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Development of a Model of Pelton Runner for Laboratory Testing

Raman Budhathoki[1], Indra Tamang[1], Ram Bishwas Yadav[1], Sabin Oli[1], Biraj Singh Thapa[1]

[1] Department of Mechanical Engineering, Kathmandu University, Dhulikhel, Nepal

Raman Budhathoki (itsramanbudhathoki@gmail.com)

Biraj Singh Thapa (bst@ku.edu.np)

Abstract. Pelton turbines are less sensitive to head variation and are commonly used from medium to high head sites. The most common and conventional technique used for manufacturing Pelton Turbine is Casting, for which a metal pattern with the correct shrinkage allowance is required. The casted turbine to be within the tolerance with the hydraulic design is often a challenging and costly process. Different techniques used for the development of model Pelton runner for testing in laboratory conditions have shown different scenarios of cost-time-accuracy trade-off. The rapid prototyping unlike casting does not require surface finishing using dies, hammers and presses. The tolerances and accuracy of the prototype depends upon the printer's resolution usually measured in Dots per inch (DPI) or micrometres (µm) and its use is both time and cost efficient. The paper discusses the standard practices followed for laboratory testing of model Pelton turbines with the use of rapid prototyping manufacturing technique. Experiences of a case of design and model testing of a Pelton runner developed by rapid prototyping techniques using Acrylonitrile *Butadiene* Styrene (*ABS*) material will be presented.

1. Introduction

The Pelton is a type of tangential flow impulse turbine used to generate electricity in the hydroelectric power plant. This turbine was discovered by the American engineer L.A. Pelton. Here, the potential energy of the water is completely converted into kinetic energy before it strikes the bucket. Also, the pressure before and after the water strikes the bucket is same, i.e. atmospheric pressure. This type of turbine is used for high head (>100m) although it is used also at low heads extensively because of the following reasons: low excavation costs, better for erosive water, better part load efficiency, less sensitive to head variation, wide operating range, lower maintenance cost. [1]

Selection of turbine can be done on the basis of Head and discharge using Turbine selection chart 1 shown below.

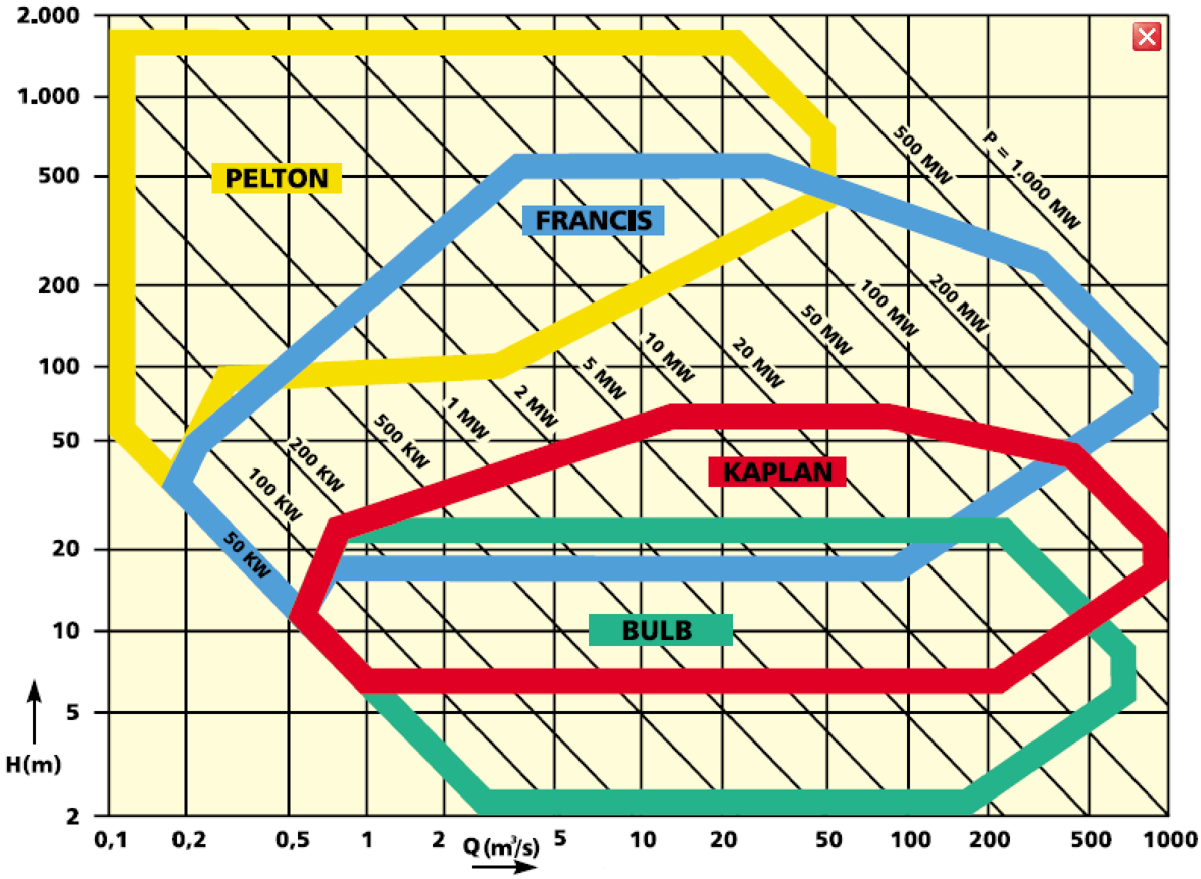

Figure 1 Turbine Selection Chart based on Head and flow rate [2]

The Pelton turbine is known as an impulse turbine. This simply means that instead of moving as a result of a reaction force, water creates some impulse on the turbine to get it to move. [3] A large circular disk is mounted on some sort of rotating shaft known as a rotor in a Pelton runner. Mounted on this circular disk are cup shaped blades known as buckets evenly spaced around the entire wheel. Generally, the buckets are arranged in pairs around the rim. [4] The Pelton turbine unit comes in two shaft axis arrangements: horizontal and vertical. The horizontal shaft turbine (maximum of 4 jets) is more conducive for maintenance activities but requires a larger powerhouse. Alternatively, the vertical shaft turbine (maximum of 6 jets) is more difficult to perform maintenance but allows a narrower shape of the power station footprint. [5] Several studies [6, 7, and 8] have suggested the use of less corrosive and easy to cast material such as aluminum for the fabrication of model Pelton Turbine. The rapid prototyping using ABS material is one alternative to aluminum since it is corrosion free and avoids the hassle of casting.

1.1 Runner and Buckets

Runner is a rotating part of the turbine. It is a circular disc on the periphery of which a number of buckets evenly spaced are fixed. The buckets are made by two hemispherical bowl joined together. Each buckets have a wall in between two hemispherical bowls called splitter. The splitter splits the jet of water striking the buckets into two equal parts and the jet of water comes out at the outer edge of the bucket. The buckets are designed in such a way that when the jet of water strike the buckets it is deflected through

160 degree to 170 degree. The buckets of the Pelton turbine are made up of cast iron, cast steel bronze or stainless steel. [9]

1.2 Rapid Prototyping Techniques

Rapid prototyping is obtained through additive layer manufacturing technology or 3D printing on the basis of three dimensional computer aided design (CAD) data. For casting a metal pattern with the correct shrinkage allowance is required. A lot of factors such as the mix and purity of metal used, the moulding sand and additives, the design of the pattern and the feeder system that takes the metal into the cavity, the metal's melting and pouring temperature determine the quality of the finished casting. Despite all these factors, the casted turbine is subjected to be within the tolerance with the hydraulic design. This is itself a challenging and costly process. [10]

The rapid prototyping unlike conventional manufacturing process like casting does not require surface finishing using dies, hammers and presses. The tolerances and accuracy of the prototype depends upon the printer's resolution usually measured in Dots per inch (DPI) or micrometres (μm).The use of rapid prototyping in testing of the turbine is both time and cost efficient. For this, a 3D CAD of Pelton turbine was designed for a head of 4m and rapid prototyped as a single unit using Acrylonitrile *Butadiene* Styrene (*ABS*) material. The picture 1.2 below shows the rapid prototyped model with the original casted model:

Figure 1.2 Casted and Rapid prototyped model of Pelton Runner

1.3 Laboratory Testing

The testing process of the Pelton Turbine conducted on pre-established laboratory conditions are controlled and economic. The testing was done at controlled laboratory conditions in a test rig available at Kathmandu University. The prototype was tested for its efficiency under varying conditions of flowrate and the data was recorded. The laboratory test conditions data is subjected to accuracy due to the use of calibrated devices and the supervision of experts. The data obtained from laboratory test of Pelton Turbine is first hand data.
In this research, we have designed and rapid prototyped a Pelton runner using ABS material for a given head and discharge. We have then studied the performance of the prototype when tested against variable flow under constant head. We have performed this research to see in what ways the performance of the prototype differs or coincides with the casted model.

2. Analytical Design

With the net head and the number of revolutions per second fixed, the Parameters for turbine design are calculated and based on the empirical and pre-established standards the runner is designed and fabricated.
Notations:

N	Revolutions per minute	g	Acceleration due to gravity($9.81 m/s^2$)	T	Thickness
η	Efficiency	r	Radius	f	frequency of alternator in cycles/sec (generally taken to be 50)
N_s	Specific Speed	d_1	Least diameter of jet	p	number of pair of poles
P_a	Turbine Power (HP)	K_{v1}	Coefficient of velocity(0.985)	m	Jet ratio
P_t	Turbine Power in (BHP)	D_1	Mean diameter of runner		
Q	Discharge	N(s)	Synchronous speed of magnetic field		
γ	Density of water ($1000 kg/m^3$)	N(r)	Rotor Speed		
A	Area	L	Length		
V	Velocity of flow	B	Breadth		

RPM = 1500 (for our case)
Net Head = 3.77m
η = 0.92 (assumed)
$N_s = N\sqrt{P_t}/H^{5/4}$ (1)
$P_a = \gamma \times Q \times H / 75$ (2)

$P_t = P_a \times \eta$ (3)
On solving equations 1, 2 and 3 we get,
$Q = (Ns^2 \times H^{1.5} \times 75)/ (N^2 \times \gamma \times \eta)$ (4)
From the right hand side of equation (4) Q required can be calculated.
We know,

$Q= A\times V$ (5)

We know, $V= \sqrt{2gh}$ (6)
For a circular pipe $A= \pi r^2$ (7)
From equations (5), (6) & (7) we can calculate value of diameter of penstock pipe by multiplying diameter with 2.

2.1 Nozzle and Jet diameter
Least diameter of Jet:
$d_1= \sqrt{} (4\times Q)/ (\pi \times K_{v1}\times \sqrt{2}\times g\times \sqrt{H})$ (8)

2.2 Mean diameter of Runner
$D_1 = (38.6 \times \sqrt{H})/N$ (9)

2.3 Jet ratio
$m= D_1/ d_1$ (10)

2.4 Slip:
Slip(s) = (N(s)-N(r))/N(s) x100% (11)
Generally slip lies between 2-6% of induction generator

2.5 Bucket Dimensions:
Dimensions of bucket depends on d_1
Length (L) = (2.30- 2.8) ×d1 (12)
Breadth (B) = (2.8-3.2) ×d1 (13)
Thickness (T) = (0.6-0.9) ×d1 (14)

2.6 Number of pole pairs of generator:
$f= (p \times N)/60$ (15)

2.7 Minimum Number of Buckets:
Z= 0.5 x m +15 (16)

2.8 Final Results from calculation:
Using above formulas:
$N_s = 26.22$
H =3.77 m
Q=0.00084m^3/s, P_t = 0.0218KW, Velocity of flow= 8.43m/s^2
Radius of penstock= 0.0056m
Least diameter of Jet (d_1) = 0.0113m
Diameter of nozzle at outlet (d_0) = 0.012m
Mean diameter of Pelton runner (D_1) = 0.15m
Number of poles pair (p) = 6
Jet ratio (m) = 13.21
Bucket Length (L) = 0.028 m
Bucket Breadth (B) = 0.0340 m
Bucket depth (T) = 0.0068 m

Minimum Number of Buckets (Z) = 22
Turbine Power (P_t) = 0.0762KW, at 92% design efficiency

3. Prerequisites for Testing

Before the testing process is initiated, there are a few prerequisites. One of them is the production of prototype and another is the preparations for the testing process.

3.1 Production of Runner

The runner's CAD is done using Creo parametric. The final CAD looks like figure 3.1 below:

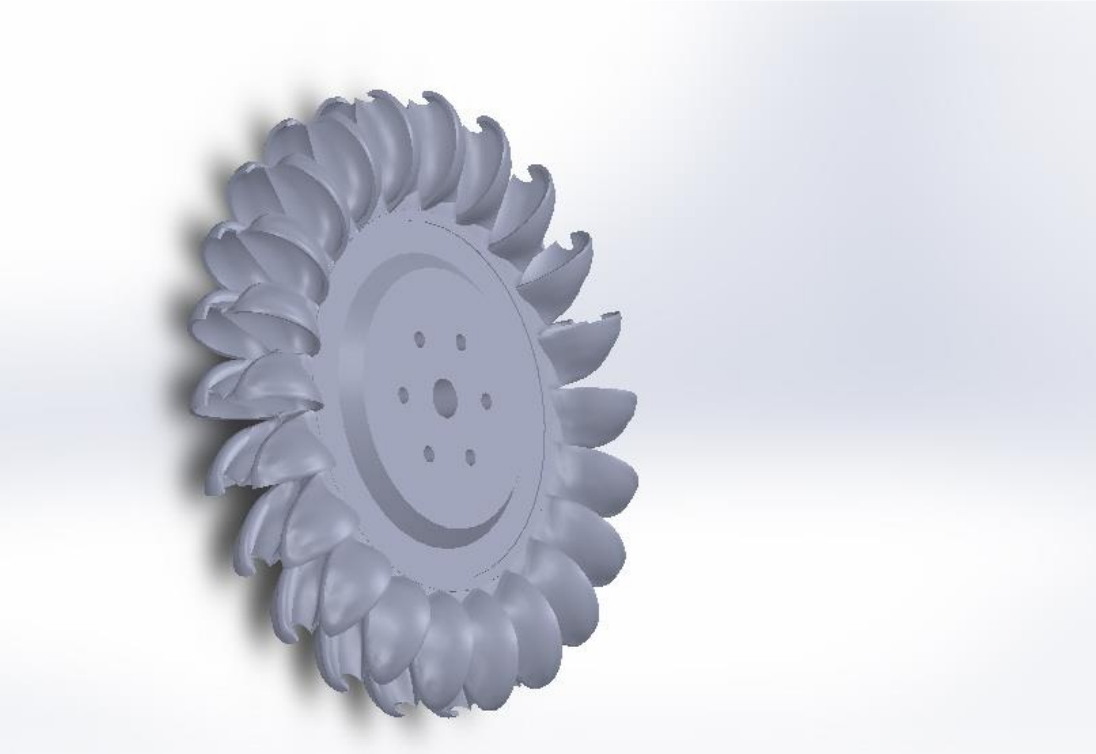

Figure 3.1 CAD of the runner

Then the CAD is used for rapid prototyping using a 3D printer. The prototype was fabricated with 0.05mm layer resolution of 3D printing and was sectioned in two halves due to the limitations of printer's capacity. The two halves were joined together with plates and bolted for the testing process.

3.2 Preparations for Testing

For the testing process the laboratory test rig available at Turbine Testing Lab (TTL), Kathmandu University was used. For the measurement of the Head a theodolite survey was done and as for the discharge measurement an ultrasonic flowmeter was used. In order to vary the discharge a spherical valve was operated manually. Likewise, tachometer was used for the rpm measurement to find the torque. Also, the standard weights of 0.5kg, 1kg, 1.5 kg, etc. were made ready for the testing.

4. Test Procedure

After the prerequisites were completed, the testing process was initiated.

4.1 Test Setup

The test setup was prepared at the test rig and a constant pressure was maintained in the tank by filling it with water up to a constant level throughout the testing. The test setup is represented by the picture 4.1 below:

Fig 4.1 Test setup and the undergoing testing process

4.2 Head and Flow Measurement

The head was measured with the help of a theodolite survey and the flow was measured instantaneously through a hand held ultrasonic flowmeter. The flow was varied using a manually operated spherical valve.

4.3 Revolutions per minute(RPM) measurement

For measuring the RPM a tachometer was used. The maximum RPM at a particular discharge was recorded.

4.4 Torque Measurement

Motor torque (momentum) is one of the motor ratings which is used to indicate rotary motor force produced on its output shaft. Motor torque rating is usually captured at the point when the motor is stalled. The torque measurement unit is (Nm) in the metric system or (ft-lbs) in the US system. But the principle is the same torque is a multiplication of lever length (r) and force (F) applied to lever:

T= F x R (16)

The experimental setup on how the measurement of torque was done is shown below in Figure 4.4:

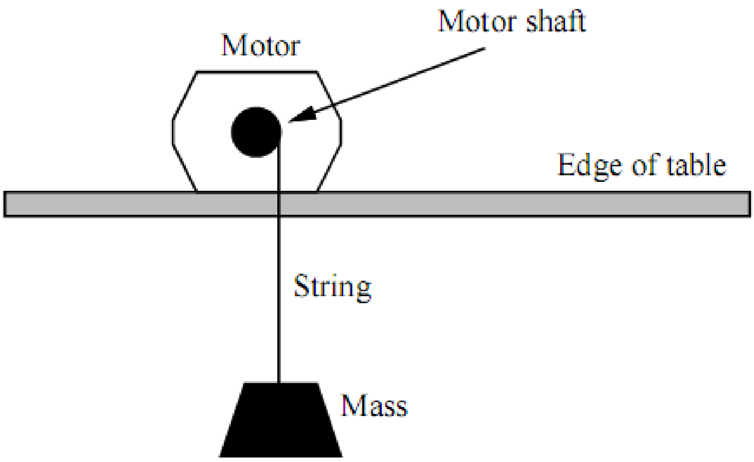

Figure 4.4 Torque measurement method

The mass was attached to one end of the string and another to motor shaft so that it could turn the windings. The motor was fixed at the edge of the table so that string with mass would hang. As the motor started and the rotating shaft was let to wind the thread while lifting the mass. In the beginning, the motor turned very easily but later when the radius of winding increased the stopping force also increased. At last, the motor was stall. At this moment the motor was stopped and the radius of winding was measured. Then the torque was calculated from the formula as mentioned below. For instance if mass m=0.1kg; radius of winding r=0.01m; acceleration due to gravity g=9.8m/s^2.

T= Fxr

T= 9.91x0.1x0.01 (Nm)

4.5 Power Output Measurement

With the torque already calculated the output power can be determined by the relation:

P= TxΩ (17)

Where, the angular velocity can be related to the RPM by the relation:

Ω= (2πN)/ 60 (18)

5. Results

The graph plotted between (i) flowrate and efficiency and (ii) flowrate and power from the obtained data is shown below in Figure 5.1 and Figure 5.2 respectively.

5.1 Flowrate vs efficiency curve

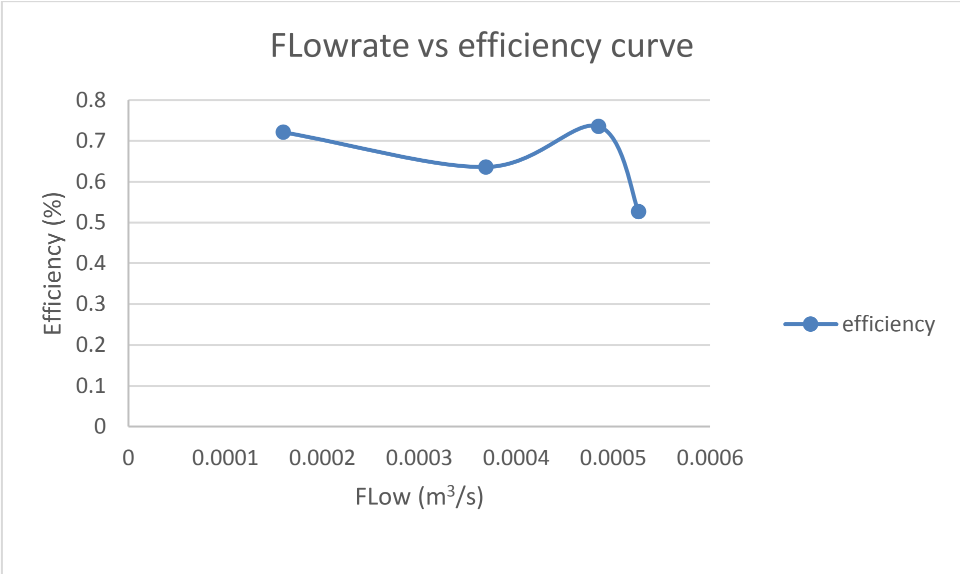

Figure 5.1 Flowrate vs efficiency curve

From the flowrate vs efficiency curve, we can see that with increasing discharge the efficiency of the prototype increases. The efficiency is maximum at 0.000485 m^3/s discharge and is 73.58%.

5.2 Flowrate vs Power curve

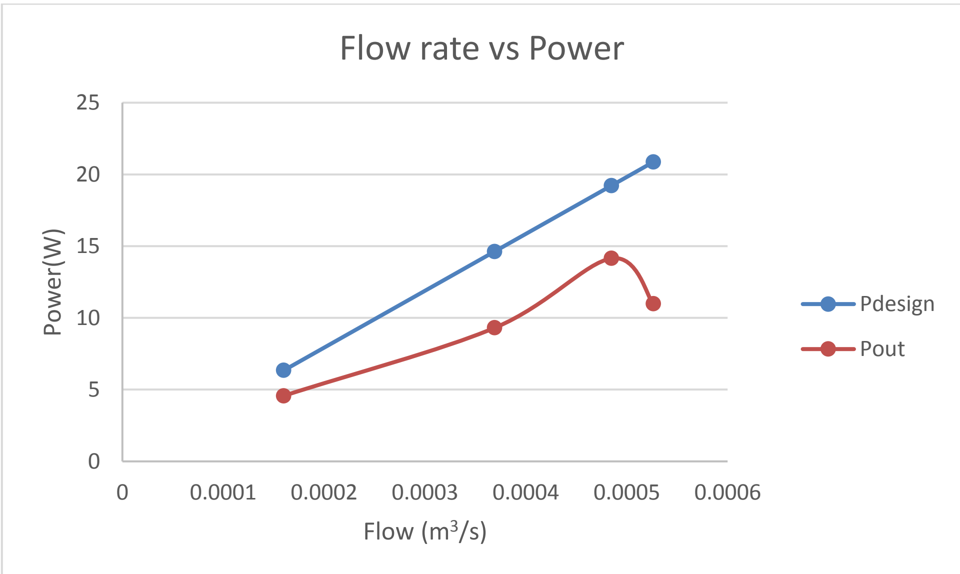

Figure 5.2 Flow rate vs Power curve

From the flow rate vs power curve, we can see that the output power increases with increasing discharge and is maximum at 0.000485 m^3/s and is equivalent to 14.16Watts. This is mainly because the hydraulic power increases with the discharge which is given by the relation:

$P = \rho gQH$ (19)

6. Conclusion

The flowrate versus efficiency curve of the rapid prototyped model with ABS material is similar to the conventional efficiency curve of a Pelton runner. [11] We hope our research will be an example for the first of many testing using rapid prototyping in Nepal. Also we hope it to be equally helpful to even the larger scale testing using rapid prototyping.

References

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