Parametric Optimization & Design of Pelton Turbine Wheel for Hydraulic Efficiency Improvement

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Abstract. Impulse turbine is one of the oldest methods of water power extraction. Pelton turbine is one amongst them. There is notable increase in utilization of renewable energy sources and hydropower in developed countries. The potential energy of water in hilly areas can fulfill the demands of the rural areas and can also contribute to grids. The power output of a turbine can be increased from the same input by improvising its efficiency. This paper aims to design the Pelton turbine wheel to improve its hydraulic efficiency. Parametric optimization of a Pelton turbine wheel is achieved by two methods: direct search method and efficiency optimization method. The effect of bucket exit angle, specific speed, speed ratio and nozzle opening on hydraulic efficiency is described here. The hydraulic efficiency of the turbine will be higher at the complete nozzle opening and at a higher specific speed. The maximum hydraulic efficiency is achieved for the specific speed 20.77. The theoretical hydraulic efficiency 93.9 percentage is achieved for 15 degrees of exit angle at 0.49-speed ratio

1. INTRODUCTION

With increasing population worldwide energy demand is also increasing. The conventional sources of energy on earth are decreasing rapidly. All efforts are in the direction of finding a better way to utilize renewable and free energy sources systematically and constructively. Water power is one of the most reliable and efficient energy sources. Water occupies the vital portion of the earth (75% of the total earth space), so there is an enormous source of free and renewable energy in the form of water power on earth. The mechanical device used for water power extraction is known as the “Turbine” [1]. Laster A. Pelton devised method of extracting power from water [2]. It has number of buckets attached to the periphery of a circular disc known as “Runner”. The water jet having kinetic energy flows in the tangential direction to the runner. When it strikes on the bucket, it gives its momentum to the buckets and the runner produces mechanical work in the form of rotations which can be converted in electrical energy by the use of a generator. Several attempts have been made by researchers to optimize the design to increase efficiency of Pelton turbine. It is worth noting that the Pelton turbine bucket, which is the main element of the Pelton turbine set-up, is very complex in shape and very important for the power extraction point of view from the water. So the design optimisation of Bucket’s geometry and
efficiency improvement of the turbine by conventional methods is a very tough task for the designers and researchers. The design method developed by the waterpower laboratory at NTNU is believed to be a good tool for the parametric design of Pelton turbines and gives the possibility to investigate the effects of parameters on the flow within the turbines [3]. A numerical methodology can be adopted for parametric studies and evaluate the optimal design of the inner bucket surface that maximizes the hydraulic efficiency [4]. Another kind of research has been carried out at Energy Conversion Laboratory of Sebelas Maret University to optimize the maximum efficiency through the restructuring of bucket volume, bucket angle attack, nozzle needle seat ring, and nozzle needle tip of Pelton Turbine [5]. Bucket geometry optimization has been an extensive research field using analytical and graphical methods. The design analysis for each dimension is carried out separately due to the complexity of several design parameters [6]. CFD analysis of Pelton turbines was not feasible due to the nature of the complex flow pattern [7]. But after the development of computerised Numerical models, there are more possibilities of optimizing the design of Pelton turbine bucket more cost-effectively with lower efforts. An attempt is made in this paper to carry out parametric optimization of the Pelton turbine and design of the hydraulic geometry of a Pelton turbine bucket is presented. Four independent parameters are discussed for the improvement of hydraulic efficiency. These parameters are speed ratio, bucket exit angle, nozzle opening and runner specific speed. This analysis will open new possibilities for the design and optimization of a Pelton turbine bucket. This approach could be a thrust area for design optimization of the Pelton turbine bucket leading to increased hydraulic efficiency.

1.1 Design of Pelton turbine wheel [8]

Consider bucket 1 and 2 as shown in figure 1. Bucket 2 just begins to enter in main jet stream at A while bucket 1 is in full jet stream. If all water drops are to remain within bucket 1 till the last drop reaches point B, then the time taken by water at outer stream to travel the distance AB must be equal to the time taken by bucket 1 to travel from position OC to OB as shown in figure 1. The jet is running horizontally with its centre line touching the pitch circle at a point directly under the center at D while points A and B shows the straight horizontal path of the bucket tips. The angular distance from A or B from the vertical center line of runner OD is \( \theta \).

As shown in figure 1, bucket two has arrived at A; meanwhile, the position of bucket 1 was at C at an angle \( \theta \) ahead of A. It is a limiting position. The location of a jet to right of bucket two is about to strike bucket 1. To reduce volumetric loss, not a single particle of the water jet should escape without striking bucket 1. For maximum utilization of water jet with a minimum number of buckets, it is
essential that a water particle at A, which has escaped from striking bucket 2, should be able to
overtake the bucket one before crossing the point B. The time taken by a water particle in the jet to
traverse a horizontal distance should be equal to the time taken by a bucket to move an angular
distance $\Psi$. Table 1 shows the assumptions taken for this research work.

### Table 1. Assumptions for design [9]

| Parameter                  | Notation | Calculated Value |
|----------------------------|----------|------------------|
| Velocity co-efficient      | $C_v$    | 0.98             |
| Relative velocity ratio    | $K_r$    | 0.99             |
| Speed ratio                | $\lambda$| 0.481            |
| Jet ratio                  | $k$      | 0.99             |
| Power                      | $P_T$    | 3.75 kW          |
| Speed                      | $N$      | 1000 rpm         |
| Head                       | $H$      | 45 m             |
| Hydraulic efficiency       | $\eta_h$ | 0.94             |
| Density of water           | $\rho$   | 1000 kg/m$^3$    |
| Number of jet              | $n_j$    | 01               |

1.2 Design Methodology

Pelton turbine wheel design is based on the experimental relations given as follow. Parameters used
for the design and optimizations are mentioned in table 2 [9].

\[
d_j = D/m \quad (1)
\]

\[
V = C_v \sqrt{2gH} \quad (2)
\]

\[
u = \pi D N/60 \quad (3)
\]

\[
\lambda = u/V \quad (4)
\]

\[
\eta_h = 2 C_v^2 \alpha (1 - \lambda)(1 + K_r \cos \beta_2) \quad (5)
\]

### Table 2. Calculated dimensions & parameters

| Parameter                  | Notation | Calculated Value |
|----------------------------|----------|------------------|
| Bucket exit angle          | $\beta_2$| 15°              |
| Angular velocity           | $\omega$ | 104.72 rad/s     |
| Non dimensional specific speed | $K_S$ | 0.1002            |
| Jet ratio                  | $m$      | 13.45            |
| Inlet velocity             | $V$      | 29.11 m/s        |
| Tangential velocity        | $u$      | 14 m/s           |
| Mean diameter              | $D$      | 0.2675 m         |
| Jet diameter               | $d_j$    | 0.0198 m         |
| Angle                      | $\phi$   | 20.53°           |
| Angle                      | $\psi$   | 22.17°           |
| Angle                      | $\theta$ | 18.89°           |
| Number of buckets (theoretical) | $Z_b$  | 19.05            |
| Number of buckets (actual) | $Z_{b\,actual}$ | 21.05         |
| Number of buckets by Tygun | $Z_{b\,Tygun}$ | 21.725         |

From equation (5), it can be seen that for theoretical hydraulic efficiency of the Pelton turbine; two
parameters are crucial: velocity ratio and bucket exit angle at the splitter section figure 2, shows the
geometrical notations for Pelton bucket. The selection of inlet and exit angles are very critical task
from design point of view to achieve the smooth flow of water over the inner surface of the bucket.
The value of the splitter angle should be less than 20 degrees to avoid a drastic variation in water jet
spray [10]. The range of bucket inlet angle should be between 10 to 20 degrees to protect the splitter of the bucket against the high enormity force applied from the water jet [11]. To preserve the torque and power generated by the Pelton wheel, the range of bucket exit angle should be between 10 to 20 degrees [1]. The water jet will impinge on the back surface of the next bucket if the bucket exit angle is below 10 degrees [12]. It would oppose the rotating speed of the bucket and eventually diminish the torque and power generated by the turbine wheel. The bucket exit angle is 15 degrees for the design and optimization of a Pelton turbine bucket [1].

Figure 2. Bucket geometry notation

Where, \( L \) = bucket length (mm), \( B \) = bucket inner width (mm), \( T \) = bucket depth (mm), \( t \) = bucket thickness (mm), \( \alpha \) = bucket inclination angle (\(^\circ\)), \( \beta_1 \) = bucket tip(splitter) inlet angle (\(^\circ\)), \( \beta_2 \) = bucket middle exit angle (\(^\circ\)), \( \beta_3 \) = bucket front exit angle (\(^\circ\)), \( \beta_4 \) = bucket back exit angle (\(^\circ\)), \( x \) = splitter tip level (mm), \( l \) = cut-out length (mm), \( w \) = cut-out width (mm), \( \xi \) = jet interaction angle (\(^\circ\))

2. PARAMETRIC OPTIMIZATION OF PELTON WHEEL TURBINE

The bucket efficiency is assumed to be 94%. Two different methods used to achieve it:

2.1 Direct Search Method

In a direct search method, a graph of bucket exit angle versus speed ratio for different efficiencies are plotted and the values corresponding to the desired efficiency are taken [13]. Both the parameters are also plotted individually against efficiency to understand the variations. The range for these parameters described in table 3.

| Parameter          | Range                        |
|--------------------|------------------------------|
| Bucket Exit angle  | 13\(^\circ\), 14\(^\circ\), 15\(^\circ\), 16\(^\circ\), 17\(^\circ\) |
| Runner speed (rpm) | 500 rpm, 750 rpm, 1000 rpm, 1250 rpm, 1500 rpm |
| Nozzle opening     | 20\%, 40\%, 60\%, 80\%, 100\% |
2.2 Efficiency Optimization (Characteristic Curves)

In characteristics curves method, the graph of bucket exit angle, runner speed and nozzle opening versus efficiency are plotted [6]. The graphs show the effect of these parameters on hydraulic efficiency.

3. RESULT & DISCUSSION

Figure 3 suggests that with lower bucket exit angles, the efficiency will be higher; for lower speed ratio the efficiency will decrease. It depicts that for 94% efficiency, bucket exit angle should be around 15 degrees.

![Figure 3](image1.png)

**Figure 3.** Effect of speed ratio and bucket exit angle on hydraulic efficiency

![Figure 4](image2.png)

**Figure 4.** Effect of bucket exit angle on hydraulic efficiency for 0.49 speed ratio

Figure 4 shows that for a given speed ratio the efficiency changes linearly with bucket exit angles. For every one degree of bucket exit angle reduction, 0.2 percentage of efficiency increment is observed. The theoretical hydraulic efficiency is 93.9 percentage for 15 degrees of exit angle at 0.49-speed ratio with consideration of losses.
For a given exit angle, the efficiency changes parabolically for different speed ratio from figure 5. The increment in the efficiency noted less than one percent when the speed ratio is varied from 0.45 to 0.5. It increases significantly below the speed ratio of 0.49.

Figure 5. Effect of bucket exit angle on hydraulic efficiency for 15 degree bucket exit angle

Figure 6 shows the relation of hydraulic efficiency for different bucket exit angles at 100% nozzle opening over a definite range of specific speed. The variation of hydraulic efficiency to the exit angle for a particular specific speed is very much lower as there is a very slight linear negative slope for each line. The hydraulic efficiency is decreasing within the range of 1% for 5º of increment in exit angle. The maximum efficiency can be achieved for the specific speed is equal to 20.77.

It is observed from figure 7, for a given exit angle and specific speed; efficiency increases in a parabolic manner with incremental nozzle opening. Figure 8 depicts that for a given exit angle and nozzle opening, efficiency increases in parabolically with increment in specific speed. The hydraulic efficiency of the turbine will be higher at the complete nozzle opening and high specific speed.

Figure 6. Effect of nozzle bucket exit angle on hydraulic efficiency
Figure 7 & 8 indicate that the maximum theoretical hydraulic efficiency of amount 93.94% achieved with 15° bucket exit angle; when the nozzle is fully open at speed ratio 0.4994 with runner speed 1250 rpm. Figure 7 and figure 8 suggest that the maximum efficiency can be achieved with a low amount of flow rate for a particular nozzle opening at a given specific speed.

The decrement in efficiency after the peak value is mainly due to the decrement in the velocity with an increase in the nozzle opening for a given flow rate. It makes the speed ratio greater than 0.5. In actual practice, the speed ratio varies from 0.46 to 0.48. The hydraulic efficiency of 93.8% with 0.48-speed ratio is achieved.

Substantial amount of work has been conceded by considering scalar parameters with 90% efficiency [5]. In this paper, a range of optimized parameters is taken to maximize the hydraulic efficiency of the Pelton turbine and provide concrete solution for the selection of the value of scalar parameters with an efficiency of 94%. This outcome persuades to perform numerical and computational fluid dynamics analysis for future work.
4. **CONCLUSION**

The design and optimization approach of a Pelton wheel is presented in a simplified way in this research paper. The procedure outlined is applicable to achieve 94 percent theoretical hydraulic efficiency of the Pelton turbine wheel. Selecting an appropriate speed ratio (0.481) and bucket exit angle (15 degrees) is obtained from this analysis. This demonstrates the virtue of simplified procedure of the design and optimization. The optimized results derived are as under.

- Maximum hydraulic efficiency is achieved when the specific speed is 20.77.
- For 20.77 specific speed, maximum hydraulic efficiency is achieved between the gate openings of 90 to 100 percent.
- For speed ratio 0.48 & 0.49, the hydraulic efficiency achieved respectively are 93.8% & 93.9%

**Hydraulic efficiency decreases with increases in bucket exit angle.**

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