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Optimizing Pelton Turbine Efficiency through Variable Flow Rates: An Experimental Study

Rahmad Hidayat Boli*, Rifaldo Pido, Wawan Rauf

***Abstract*—This study experimentally investigates the efficiency characteristics of a laboratory-scale Pelton turbine under variable water flow rates and mechanical loading conditions. Five flow rates (0.04 m³/s, 0.035 m³/s, 0.029 m³/s, 0.024 m³/s, and 0.021 m³/s) were tested by measuring rotational speed, torque, shaft power, and turbine efficiency. The results reveal a nonlinear relationship between load and efficiency for all tested flow rates, with maximum efficiency occurring at intermediate loading conditions. The highest efficiency of 52.727% was obtained at a flow rate of 0.04 m³/s and a load of 12 kg. Were associated with reduced efficiency, which is commonly linked to decreased jet momentum. These findings provide experimental insight into Pelton turbine performance under non-design operating conditions at laboratory scale.**

***Index Terms*—Efficiency Improvement, Experimental Analysis, Hydropower Optimization, Pelton Turbine, Variable Flow Rates**

I. Introduction

HYDROPOWER is a well-established and sustainable renewable energy source, essential for fulfilling global energy requirements and mitigating carbon emissions [1]. Pelton turbines are extensively utilized in this field for their effectiveness in transforming high-head, low-flow water sources into mechanical energy [2]-[3]. The potential advantages of hydropower include its renewability, reliability, and low environmental impact, making it a desirable alternative to fossil fuels [4]-[5].

Pelton turbines are engineered for optimal energy conversion efficiency in conditions characterized by elevated water pressure and reduced flow rates [6]-[7]. The effectiveness of these turbines is greatly affected by operational parameters, particularly the water flow rate and load conditions [8]-[9].

Although Pelton turbines are extensively utilized, there is still limited understanding of how variations in water flow rate affect turbine efficiency under different loading conditions in water flow rates affect turbine efficiency across various load scenarios [2]-[3]. Current research frequently emphasizes static situations, resulting in a deficiency of understanding concerning dynamic adjustments and optimization [10]-[11].

This research investigates the correlation among varying flow rates, load conditions, and the efficiency of Pelton turbines using controlled trials [12]. Through the systematic modification of flow rates and loads, we seek to determine the ideal operational parameters that enhance turbine performance [13].

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These findings offer significant insights for enhancing the design and functionality of Pelton turbines in hydropower plants. Integrating adaptive control systems and optimizing flow rates and load circumstances can boost energy output, resulting in more efficient and sustainable power generation. Subsequent research should concentrate on practical applications and enhanced turbine materials to enhance adaptation and robustness in varied environmental situations.

Although Pelton turbine performance has been widely investigated, most previous studies focus on design or near-design operating conditions, often using numerical simulations or industrial-scale systems. Systematic experimental investigations of laboratory-scale Pelton turbines operating under off-design combinations of flow rate and mechanical load remain limited. Therefore, this study aims to experimentally characterize the efficiency behavior of a laboratory-scale Pelton turbine under controlled variations of flow rate and load. The novelty of this work lies in its detailed experimental evaluation of load–speed–efficiency relationships under non-design conditions, providing reference data for educational applications and future numerical validation.

In this study, the term “optimizing” is used to describe the experimental identification of operating conditions associated with higher turbine efficiency, rather than the application of a formal optimization algorithm or design optimization methodology.

II. Math

The research utilized a controlled experimental framework to replicate actual operational circumstances for a Pelton turbine [14]-[15]. The characteristics measured included angular velocity, torque, power output, and efficiency at five distinct flow rates (0.04 m³/s, 0.035 m³/s, 0.029 m³/s, 0.024 m³/s, and 0.021 m³/s) under diverse load circumstances from 0 kg to 24 kg [3]-[15].

A. Experimental Setup

The experimental configuration comprised:

1) A laboratory-scale Pelton turbine.
2) A variable flow water pump for flow rate regulation.
3) Accurate instruments for quantifying angular velocity (rpm), torque (Nm), and power output (W).
4) A data-collecting system for the recording and analysis of outcomes.

Fig. 1–3 illustrate the experimental Pelton turbine configuration and operating principle. Fig. 1 presents the turbine schematic, Fig. 2 shows the water jet impact position on the bucket, and Fig. 3 depicts the water flow distribution process after jet impingement, demonstrating the energy transfer mechanism responsible for turbine rotation and power generation.

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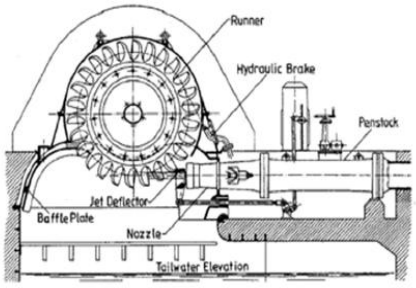


Fig. 1. Schematic turbine

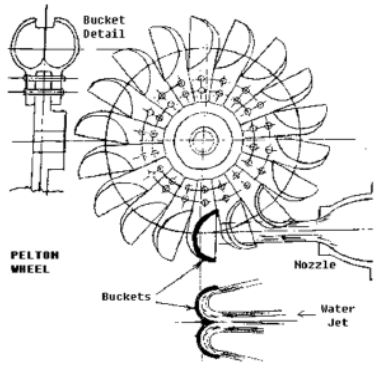


Fig. 2. Water impact position

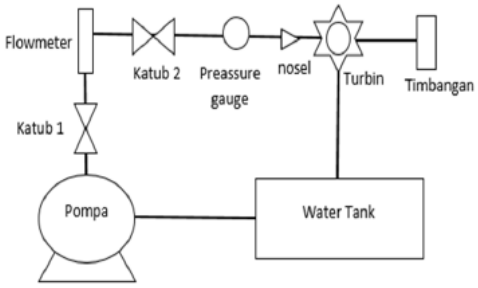


Fig. 3. Schematic of the water flow distribution process

B. Procedure

1) The turbine was operated at all five flow rates.
2) For each flow rate, loads varying from 0 kg to 24 kg were systematically applied in increments.
3) Angular velocity, torque, power output, and efficiency were documented for each combination of flow rate and load.
4) Efficiency was determined utilizing the formula

The amount of mass that comes out per unit time is expressed as the mass flow rate, as long as there are no flow losses, which is expressed as follows $m = \rho \; x \; v \; x \; A$ This equation is said to be a function of the flow rate so it can be simplified to $m = \rho \; x \; Q$ (1) [16]–[17].

The water power (p_w) received by the turbine shaft highly depends on the flow velocity and discharge rate. Therefore, the power generated can be calculated using the kinetic energy equation:

$$KE = \frac{1}{2} \; x \; m \; x \; v^2 \tag{2}$$

Substituting eq 1 and eg 2:

$$p_w = \frac{1}{2} x \; \rho \; x \; Q \; x \; v^2 \tag{3}$$

Where, according to the continuity equation

$$Q = A \; x \; v \tag{4}$$

According to Eqs. 3 and 4, the power becomes

$$p_w = \frac{1}{2} x \; \rho \; x \; A \; x \; v^3 \tag{5}$$

In the experimental testing, there is a relation between the torque and the power generated by the turbine, expressed as

$$T = r \; x \; F \tag{6}$$

The turbine blades are the main components responsible for converting the water flow's kinetic energy into mechanical energy on the turbine shaft. When force F acts on the turbine blades, the resulting torque T on the turbine shaft causes it to rotate accordingly.

The turbine power (P_t) the power transferred by water to the turbine blades, generating torque on the turbine shaft. It is expressed as:

$$P_t = T \; x \; \omega \tag{7}$$

Where,

$$T = r \; x \; F \tag{8}$$

and

$$F = m \; x \; g \tag{9}$$

Where,

$$\omega = \frac{2 \; x \; \pi \; x \; n}{60} \tag{10}$$

Substituting the eq 10 and eq 7 becomes

$$P_t = \frac{m \; x \; g \; x \; r \; x \; 2 \; x \; \pi \; x \; n}{60} \tag{11}$$

where ω represents the angular velocity of the water turbine.

Thermodynamic Efficiency and Water Turbine Efficiency can be expressed as:

$$\eta_{turbin} = \frac{p_{turbin}}{p_{water}} x \; 100\% \tag{12}$$

$$\eta_{termodinamika} = \frac{p_{turbin}}{E_P + E_k} x \; 100\% \tag{13}$$

In this study, efficiency refers exclusively to the mechanical efficiency of the Pelton turbine, defined as the ratio between shaft power output and available hydraulic power. Thermodynamic efficiency is introduced only for theoretical completeness and is not used in experimental data evaluation.

C. Data Analysis

Data were examined to discern trends, ideal conditions, and the correlation among the operational factors [18]-[19]. Graphs were constructed to illustrate efficiency fluctuations in relation to load and flow rate [20]-[21].

III. Results and Discussion

The selected flow rates were determined based on the operational limits of the laboratory pump, jet stability considerations, and their relevance to high-head, low-discharge characteristics typical of small-scale Pelton turbines.

It should be noted that this experiment was conducted at laboratory scale, and the results are subject to measurement uncertainty arising from sensor accuracy, mechanical friction, and minor flow fluctuations. Detailed uncertainty quantification was beyond the scope of this study and is recommended for future work. Despite these limitations, the experimental setup provides a reliable platform for evaluating the qualitative performance characteristics of small-scale Pelton turbines and offers valuable benchmark data for future design optimization and comparative experimental investigations.

A. Summary of Findings

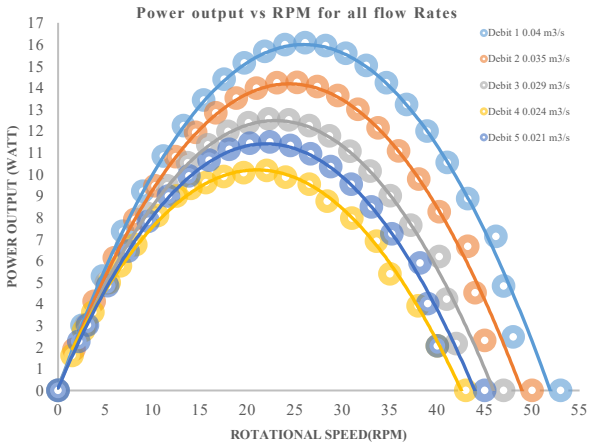


Fig. 4. Power output vs rotational speed

Fig. 4 illustrates the variation of turbine rotational speed as a function of mechanical load for different flow rates. For all tested flow conditions, the rotational speed decreases monotonically with increasing load. This behavior is consistent with the fundamental operating principle of impulse turbines, where higher mechanical resistance at the shaft requires greater torque, resulting in reduced rotational speed.

At higher flow rates, the turbine maintains relatively higher rotational speeds under the same load conditions, indicating the availability of greater jet momentum. Similar trends have been reported in previous experimental studies on Pelton turbines operating under laboratory-scale conditions [2]-[9]. Minor deviations in absolute speed values can be attributed to differences in nozzle geometry, bucket shape, and mechanical transmission losses.

1) Efficiency at 0.04 m³/s

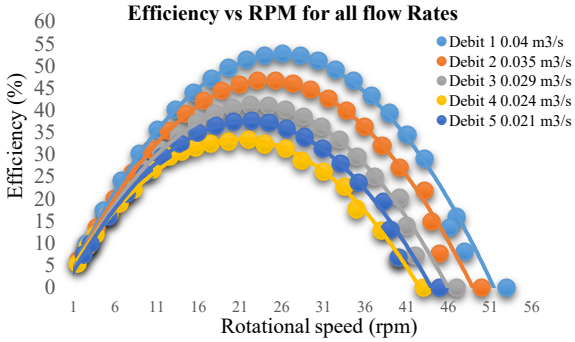


Fig. 5. Efficiency vs rotational speed

The relationship between shaft power and mechanical load is presented in Fig. 5. Shaft power initially increases with load due to the combined effect of decreasing rotational speed and increasing torque. Beyond a certain load threshold, however, the power output begins to decline, indicating that excessive loading indicating a reduction in effective energy conversion under excessive loading conditions.

This characteristic power curve agrees well with findings reported in [2]-[3], where maximum power output was achieved at intermediate loading conditions. The slightly lower peak power observed in the present study is attributed to the laboratory-scale configuration and non-optimized turbine geometry, as also noted in [9].

2) Efficiency at 0.035 m³/s

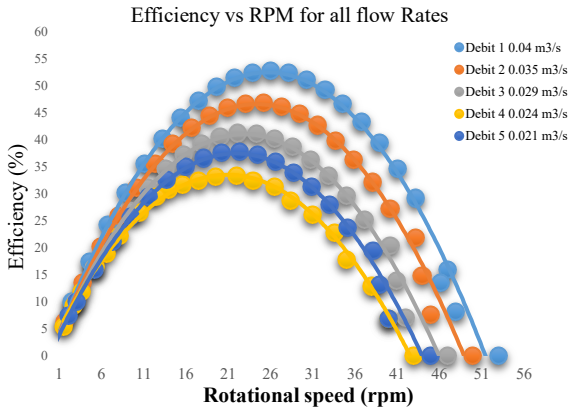


Fig. 6. Efficiency vs rotational speed

Fig. 6 shows the variation of turbine efficiency with mechanical load for all tested flow rates. A nonlinear relationship is observed, with efficiency increasing initially, reaching a maximum at intermediate load, and subsequently decreasing at higher loads and is commonly associated with the balance between momentum transfer and mechanical losses, as reported in previous studies.

The efficiency behavior observed in this study is generally consistent with previous investigations [2]-[3], [9]. However, the maximum efficiency values obtained are lower than those reported in [2], [22], which primarily investigated optimized or near-design operating conditions. The reduced efficiency in the present study can be explained by scale effects, additional mechanical losses, and off-design operation inherent to the experimental setup.

3) Efficiency at lower flow rates

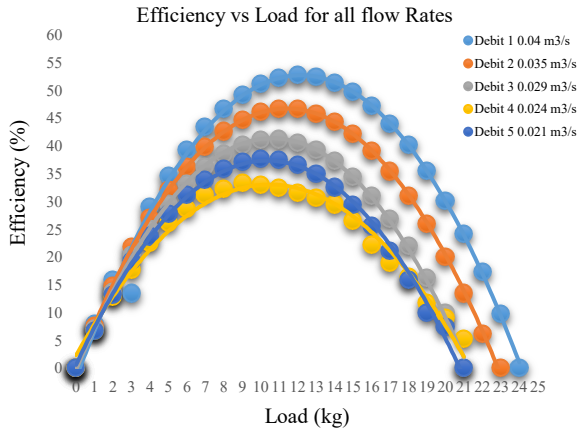


Fig. 7. Efficiency vs load

Fig. 7 compares efficiency trends at different flow rates. Higher flow rates consistently result in improved turbine efficiency, particularly at intermediate loading conditions. This behavior is commonly associated with increased jet velocity and momentum, which enhance energy transfer efficiency, which enhance energy transfer from the water jet to the turbine buckets.

At lower flow rates, efficiency reduction becomes more pronounced, especially under higher mechanical

loads. Similar observations have been reported in [3], [22], where insufficient jet momentum and increased relative hydraulic losses were identified as dominant factors affecting performance. These results confirm that adequate jet energy is essential for maintaining efficient impulse turbine operation.

4) Detailed Load Analysis

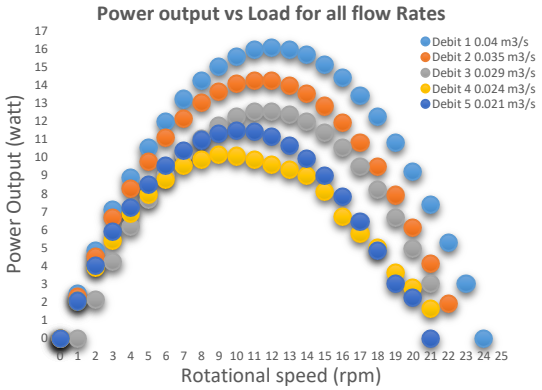


Fig. 8. Efficiency vs rotational speed

Fig. 8 summarizes the variation of turbine efficiency with flow rate across all tested load conditions. An overall increase in efficiency is observed with increasing flow rate, indicating the influence of jet momentum on turbine performance. Similar trends have been reported in previous experimental studies on Pelton turbines operating under off-design conditions [3], [9], [22]. The lower efficiency values obtained in the present study compared to Ref. [2] can be attributed to laboratory-scale effects, non-optimized geometry, and additional mechanical losses.

5) Discussion of Key Findings

The experimental results demonstrate that the performance of the Pelton turbine is governed by the combined influence of mechanical load and flow rate within the tested operating range. Across all experimental conditions, the observed trends in rotational speed, shaft power, and efficiency follow patterns that are consistent with the fundamental characteristics of impulse turbines reported in the literature [2]-[3], [9].

An increase in mechanical load consistently results in a reduction in rotational speed, while shaft power initially increases and subsequently decreases beyond an intermediate loading condition. This behavior indicates that there exists an operating region where the balance between torque generation and rotational speed leads to more effective energy conversion. Similar performance characteristics have been observed in previous experimental studies on Pelton turbines operating under laboratory-scale and off-design conditions [2], [9].

Efficiency trends exhibit a nonlinear relationship with mechanical load, where efficiency increases at low to moderate loads and decreases at higher loads. This behavior is commonly associated with the balance between momentum transfer from the water jet to the turbine buckets and increasing mechanical losses at higher resistance levels. Comparable efficiency trends have been reported in [3], [22], supporting the validity of the present observations.

Flow rate plays a significant role in determining turbine performance. Higher flow rates are consistently associated with improved efficiency and power output within the tested range, whereas lower flow rates result in more pronounced efficiency reductions, particularly under higher loading conditions. This behavior is commonly associated with variations in jet momentum and relative hydraulic losses, as discussed in previous studies[3], [9], [22]. The results confirm that adequate flow conditions are essential for maintaining stable impulse turbine performance.

When compared with optimized systems reported in the literature, the absolute efficiency values obtained in the present study are lower than those reported in Ref. [2]. This difference can be attributed to several factors, including laboratory-scale effects, non-optimized bucket geometry, mechanical transmission losses, and operation under off-design conditions. Similar efficiency levels for small-scale or experimental Pelton turbines have been documented in [9], [22], indicating that the present results are reasonable within the context of the experimental setup.

It should be noted that certain physical aspects, such as jet alignment, flow separation within the buckets, vibration, and mechanical wear, were not directly measured in this study. Consequently, interpretations related to these phenomena are based on established impulse turbine theory and findings reported in previous experimental investigations [2], [22], rather than direct observation. Future experimental work incorporating flow visualization, vibration analysis, and geometric optimization would provide further insight into these effects.

The experimental results demonstrate that the performance of the laboratory-scale Pelton turbine is highly dependent on the interaction between hydraulic input and mechanical loading. As the applied mechanical load increased, the turbine rotational speed gradually decreased due to the greater resisting torque, while shaft power initially increased before reaching an optimum value and subsequently declined. This behavior is consistent with the operating characteristics of impulse turbines, where maximum energy conversion occurs only within a specific range of load and flow conditions. Similar observations have been reported for various turbine systems, indicating that turbine performance is governed by the balance between hydraulic energy input and mechanical output under varying operating conditions [23], [24].

The nonlinear relationship between efficiency, flow rate, and mechanical load observed in this study also agrees with previous investigations on hydraulic turbine performance. The highest efficiency of 52.727% was achieved under intermediate loading conditions, suggesting that excessive loading limits rotational speed and hydraulic energy conversion, whereas insufficient loading prevents effective utilization of the available water power. Previous studies have shown that turbine efficiency is highly sensitive to operating conditions and

often declines significantly when systems operate away from their design point [24]-[26]. The higher efficiencies obtained at larger flow rates in this study further confirm that adequate hydraulic energy input improves momentum transfer from the water jet to the turbine buckets, resulting in more effective power generation.

Although the measured maximum efficiency is lower than that reported for commercial or optimized Pelton turbines, the difference is reasonable considering the laboratory-scale configuration employed. Scale effects, simplified bucket geometry, mechanical transmission losses, manufacturing tolerances, and non-optimized nozzle alignment all contribute to reduced overall efficiency. Similar influences of scale and mechanical losses have been discussed in previous studies, which emphasize that laboratory prototypes typically exhibit lower absolute efficiencies than full-scale installations while maintaining comparable performance trends [25], [27]. Furthermore, control and optimization strategies have been shown to improve turbine performance by maintaining operation closer to optimal conditions under varying loads [28]-[30].

Overall, the present findings provide experimental evidence that small-scale Pelton turbines follow the fundamental performance characteristics predicted by impulse turbine theory. Despite operating under non-design conditions, the observed trends in rotational speed, shaft power, and efficiency remain consistent with previous experimental and numerical investigations. Therefore, this study offers valuable experimental data for laboratory education, prototype evaluation, and future optimization studies aimed at improving the efficiency of micro-hydropower systems through enhanced turbine design and operating control [24], [26], [28].

6) Future Research Directions

Future studies may focus on a more detailed investigation of the flow characteristics within the Pelton turbine by incorporating flow visualization techniques and computational fluid dynamics (CFD) analysis. Such approaches would allow a clearer understanding of jet alignment, flow separation, and energy transfer mechanisms, which were not directly examined in the present experimental work.

Further research may also explore the optimization of bucket geometry and nozzle configuration to improve turbine performance under specific operating conditions. Parametric studies involving variations in bucket shape, splitter design, and jet diameter could provide insights into performance enhancement strategies for small-scale Pelton turbines.

In addition, future experiments could include detailed measurements of mechanical losses, vibration, and long-term wear to better evaluate turbine reliability and durability under varying load conditions. Scaling up the experimental setup or testing under field conditions would also be valuable for assessing the applicability of the present findings to real-world hydropower systems.

IV. CONCLUSION

This study experimentally investigated the performance characteristics of a laboratory-scale Pelton turbine under varying mechanical loads and flow rates. The results demonstrate that turbine performance is strongly influenced by operating conditions, with rotational speed decreasing as mechanical load increases, while shaft power and efficiency reach maximum values at intermediate loading conditions.

The efficiency trends observed in this study exhibit a nonlinear relationship with mechanical load and flow rate, which is consistent with the general behavior of impulse turbines reported in previous studies. Within the tested operating range, the maximum efficiency achieved was 52.727%, occurring at intermediate load conditions. Higher flow rates are generally associated with improved turbine performance, whereas lower flow rates result in more pronounced efficiency reductions, particularly under higher loading conditions.

Although the maximum efficiency obtained in this study is lower than values reported for optimized Pelton turbines in the literature, the observed performance trends show good qualitative agreement with previous experimental investigations. The differences in absolute efficiency values can be attributed to laboratory-scale effects, non-optimized turbine geometry, mechanical transmission losses, and off-design operating conditions.

Overall, the results confirm that the experimental findings are reasonable and consistent with established impulse turbine theory and prior studies. The outcomes of this research provide a useful experimental reference for understanding the performance behavior of small-scale Pelton turbines operating under non-design conditions.

NOMENCLATURE

$\boldsymbol{m}$	:	Mass flow rate [kg s^{-1}]
$\boldsymbol{\rho}$	:	Density [kg m^{-3}]
$\boldsymbol{v}$	:	Velocity [m s^{-1}]
$\boldsymbol{A}$	:	Section area [m^2]
$\boldsymbol{Q}$	:	Debit [m^3]
$\boldsymbol{KE}$	:	Kinetic energy [joule]
PE	:	Potensial energy [joule]
$\underline{\boldsymbol{P_w}}$	:	Water power [watt]
$\boldsymbol{T}$	:	Torgue [Nm]
$\boldsymbol{r}$	:	Radius [m]
$\boldsymbol{F}$	:	Force [N]
$\boldsymbol{P_{turbin}}$	:	Turbine power [watt]
$\boldsymbol{\omega}$	:	Angular velocity [rad s^{-1}]
$\boldsymbol{g}$	:	Gravity [m s^{-2}]
$\boldsymbol{\eta_{turbin}}$	:	Efficiency turbine [%]
$\boldsymbol{\eta_{thermodinamika}}$	:	Efficiency thermodynamic [%]

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