Design, Implementation, and Analysis of a Local Pelton Turbine

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Abstract – *This study investigates the performance characteristics of a locally designed Pelton turbine, focusing on the relationship between rotational speed, torque, and mechanical power output. Understanding these dynamics is crucial for optimizing turbine efficiency in various applications. Our experiments revealed that as the turbine's rotational speed increased to 844 RPM, the torque decreased from 0.090 to 0.079 N·m, indicating a reduction in the efficiency of energy transfer from the water jets to the turbine buckets from 39% to 33%. This decline highlights the importance of maintaining an optimal speed range to maximize energy conversion. Furthermore, while power output initially increases with speed, operating the turbine beyond its optimal range can lead to diminishing returns due to mechanical and efficiency losses. These findings provide valuable insights for improving the design and operational strategies of Pelton turbines, ensuring enhanced performance and reliability.*

Keywords: Efficiency, Torque, Speed, Mechanical power, hydraulic power

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I. Introduction

The Pelton turbine is a well-established and highly advanced hydraulic impulse turbine for over a century. Despite its long history of success, there remains potential for improvement in the design of Pelton turbine hydraulic flow components. As the most efficient impulse turbines available, Pelton turbines are widely used in high-head hydroelectric power plants and various other high-pressure energy harvesting applications [2].

In Europe, around 16% of installed hydroelectric capacity uses Pelton turbines. Among European hydroelectric plants with a capacity greater than 50 MW, around 31% are equipped with Pelton turbines. These turbines are particularly popular in mountainous regions due to their ability to operate efficiently under high head conditions and with lower water flow rates, making them more suitable than Kaplan and Francis turbines for such environments. Water flow is regulated by nozzle control, maintaining efficiency above 90%, even when turbine loads fluctuate [3].

The Pelton turbine has been studied by several researchers and in several ways. one study performed a comprehensive analysis of hydraulic performance combined with visualization in a Pelton turbine wheel model. The study identified two types of jet interference that can occur in multi-jet Pelton turbines. The first type involves the flow of water flowing near the bucket cutout, which can be disrupted by the subsequent jet of water. The second type occurs when the water discharged from the bucket splashes radially and is deflected by the nozzle or baffle onto the surface of the second jet. This second type of interference is particularly problematic, as it can cause severe jet disturbances, leading to significant deterioration of efficiency under high flow rates and specific velocities [4].

A group of researchers focuses on understanding sand erosion mechanisms in Pelton turbines, identifying erosion-prone areas, and quantifying erosive wear. Experiments were conducted on Pelton buckets made of aluminum, carbon steel, stainless steel, PLA, and ABS under solid-liquid flow conditions. Erosion-prone areas were identified using a multi-layer paint modeling technique, while optical profilometry and scanning electron microscopy assessed surface damage. The study found that erosion rates for aluminum, carbon steel, stainless steel, and ABS were significantly higher compared to PLA, with both PLA and ABS showing strong erosion resistance [5]. Meanwhile, another group studied how turbine casing dimensions influence the efficiency of a Pelton turbine design, highlighting the impact of physical design on performance [6]. An investigation evaluated the performance of a traditional flume versus a rimmed flume using different nozzle openings on a model test stand. They found that at higher specific speeds, the interaction of the water with the hoop reduced the power of the circled runner [7].

For the hydraulic design of a Pelton turbine, two fundamental parameters are the net pressure side height and the desired flow rate. These parameters determine the available hydraulic power, which in turn dictates the size of the turbine. The design process begins with sizing the Pelton wheel, selecting the appropriate rotational speed, and determining the number of injectors. Practical information gained from the operation of Pelton turbines serves as a guide to establishing an effective design procedure [8].

Model and mock-up design play a crucial role in research laboratories, serving as fundamental tools facilitating in-depth studies and experiments. By creating accurate, detailed representations of systems or components, researchers can simulate real-world conditions, test hypotheses, and analyze the performance of different design configurations. These models and mock-ups help create a controlled environment in which variables can be systematically adjusted and observed, leading to valuable information that informs the development and optimization of the final product or system [9-12].

The hydrodynamic design and performance evaluation of a Pelton-type energy recovery turbine (ERT) has been adapted to pressure-retarded osmosis (PRO) systems. We describe the process of selecting the type of ERT most suitable for the specific operating conditions of the PRO system (i.e. 400 tonnes per day at 30 bar) and discuss the design methodologies applied to develop the ERT Pelton type. Additionally, we examine performance characteristics under design and off-design conditions, analyzing how performance varies with changes in Pelton wheel diameter, based on experimental testing conducted on the fabricated ERT. At the design point, the Pelton-type ERT achieved an efficiency of approximately 85%, with the overall efficiency, including the electric generator, reaching approximately 77.2%. The efficiency of the turbine and overall system was higher when the impeller diameter was optimized according to the design specifications, thereby validating the design process through performance testing. This study is expected to contribute significantly to future efforts in the selection, design, and testing of ERTs for PRO systems [13].

The Pelton turbine remains the most widely used and efficient impulse hydroelectric turbine. A crucial but static component of this turbine is the Pelton casing, where internal hydrodynamic phenomena significantly influence plant performance, equipment vibration and water quality, particularly in terms of downstream dissolved oxygen. . Despite its importance, information in the literature is often fragmented and disorganized, leading to designs based primarily on rules of thumb and the specialized knowledge of hydropower companies. This article reviews and organizes the state-of-the-art knowledge of Pelton housings into three key areas: hydraulics, mechanics (including vibration and weight), and aeration. The preliminary design procedure is discussed in the context of recent scientific discoveries, with open questions and research challenges highlighted. The article also discusses innovative case studies, such as back-pressure operation, and presents a dataset of installed enclosures (not previously available in the literature) to derive an empirical equation for estimating the weight of the housing. The results suggest that efficiency can be improved by 3% through optimal fluid dynamic design and a better understanding of internal hydrodynamics. Additionally, appropriate inserts can improve hydraulic efficiency by 2%, reduce crankcase weiht by approximately 12%, and improve vibration tolerance. Several scientific questions remain unanswered, in particular concerning fluid-structure interaction, crucial to further improve efficiency, operational performance and water quality [14].

Our work involves the development of a Pelton turbine using locally available resources, followed by rigorous laboratory testing. The objective is to compare the performance of our locally produced turbine with that of an original commercially manufactured turbine. Through this comparison, we aim to demonstrate that our model not only works effectively, but also serves as a valuable educational tool for research purposes. This project highlights the potential for local manufacturing of hydraulic turbines, providing an accessible and practical resource for academic study and experimentation. By validating the functionality and performance of our model, we seek to contribute to the advancement of educational tools in the field of hydroelectric research.

II. Methodology

II.1. Pelton turbine

The Pelton turbine, invented by Lester Allan Pelton in the late 19th century, transformed hydroelectric power with its innovative split-bucket design. This design efficiently harnessed high-velocity water jets, making it ideal for high-head, low-flow conditions. Patented in 1880, the Pelton turbine became essential in hydroelectric plants, especially in mountainous areas, and remains widely used today. The Pelton turbine converts the kinetic energy of a high-velocity water jet into mechanical energy. The water jet strikes split buckets on a wheel, causing it to spin and drive a generator. It's particularly efficient for high-head, low-flow water sources.

As illustrated in the Figure 1 [15], the hydraulic performance of Propeller turbines is more sensitive to flow variations compared to Francis, Kaplan, Pelton, and Crossflow turbines. The Pelton turbine, recognized as one of the most efficient turbines with an efficiency of around 90%, is also capable of maintaining optimal efficiency across a variable range of flows. In contrast, the Crossflow turbine, while having a slightly lower efficiency of around 80%, can still sustain optimal efficiency levels over a broader range of flow conditions.

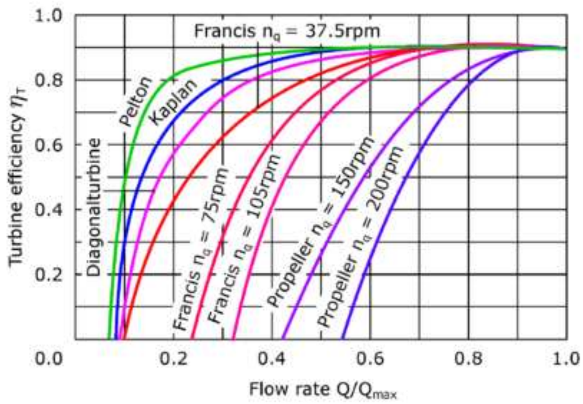

Figure 1. Hydropower turbines curves

II.2. Performance analysis

The key parameters that significantly influence the performance of a Pelton turbine are the flow rate (Q), head (H), torque (T) exerted on the turbine shaft and Speed of the turbine (N). Accurate measurement of these parameters, especially when using different nozzle diameters (d), requires the application of several mathematical equations. Assuming incompressible flow and neglecting frictional losses in the pipe and nozzle, the hydraulic power (P_{hyd}) generated by the water can be determined using the flow rate (Q) and head (H) as follows [16]:

$$P_{hyd} = p. g. Q. H \qquad (1)$$

The produced mechanical power (P_{mec}) on the turbine shaft can be estimated as follows:

$$P_{mec} = T. \omega \qquad (2)$$

Where $\omega = \frac{2\pi n}{60}$ is the angular speed and T is represents the torque that applied on the turbine shaft from the brake load. The T can be calculated as [16]:

$$T = F. R \qquad (3)$$

F is the brake force that measured by using a scale meter and R represents the arm force which is considered constant.

The overall efficiency (η) of the turbine can be evaluated as the ratio between the output power and input power as follows [16]:

$$\eta = \frac{P_{mec}}{P_{hyd}} \times 100 \qquad (4)$$

The rate of runner tangential velocity (U) of rotational wheel buckets of Pelton turbine at the mean wheel diameter (Dmean) can be obtained as follows:

$$U = \frac{\pi\, N\, Dmean}{60} \qquad (5)$$

D_{mean} can be written as follows:

$$Dmean = \frac{D_{tip} + D_{hup}}{2} \qquad (6)$$

The velocity at the nozzle outlet [16]:

$$V = \frac{Q}{A} \qquad (7)$$

With, $A = \frac{\pi}{4}\, d^2$

II.3. Pelton turbine design

Figures 2 through 6 illustrate the detailed steps involved in the design and construction of a Pelton turbine.

The Pelton turbine was designed and built using materials sourced entirely from local markets, showcasing the practicality of locally available resources. By purchasing all components locally, the project minimized costs and ensured that materials were well suited to environmental conditions. The assembly was carried out in a university laboratory, where students and researchers collaborated to bring the design to life. This hands-on experience allowed participants to bridge the gap between theory and practice, thereby improving their understanding of engineering principles.

The university laboratory provided a controlled environment for precise assembly and immediate problem resolution. Despite the challenges that often accompany locally manufactured projects, the turbine was successfully built and completed without any operational issues. The smooth operation of the turbine highlighted the reliability and efficiency of locally sourced materials as well as the skills of those involved.

The process begins with manufacturing the turbine casing, as shown in Figure 2, followed by assembly of the impeller. This essential component, at the heart of turbine operation, is meticulously assembled to ensure precise alignment and functionality as shown in Figure 3.

Figure 2. Machining and finishing of Pelton turbine casing

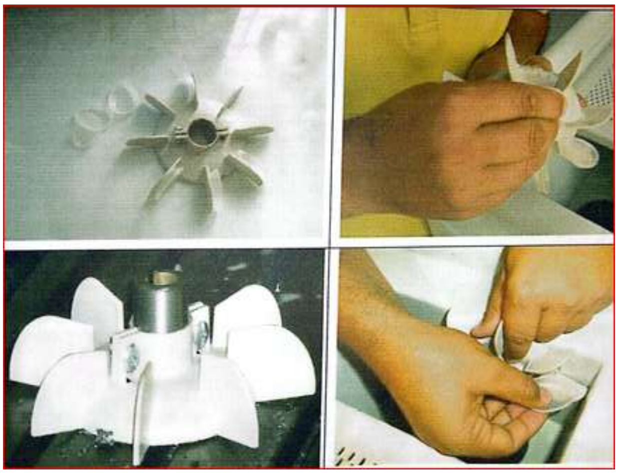

Figure 3. Mounting the magnifying wheel on the axle

Figure 4 highlights the preparation of the variable injector, an essential part of the turbine that regulates the water flow, thereby optimizing the efficiency of the turbine under different operating conditions.

Figure 5 shows the axles and pulleys, which are an integral part of the mechanical operation of the turbine, ensuring smooth transmission of rotational forces.

The turbine assembly, shown in Figure 6, brings all the components together and aligns them to create a fully functional unit. Finally, Figure 7 shows the painting of the turbine, marking the completion of the assembly process and ensuring that the turbine is both protected from environmental factors and aesthetically finished.

Figure 4. Variable area injector

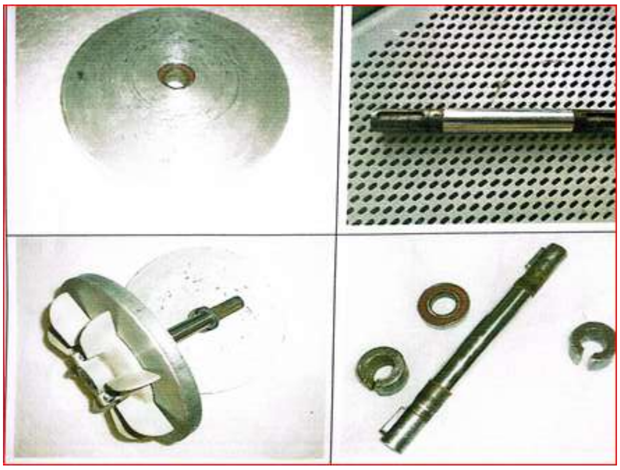

Figure 5. Blades and the turbine shaft

Figure 6. Turbine assembly

Figure 7. Final state turbine

III. Experimental results

III.1. Experiment preparation

Figure 8 shows the turbine during experimental testing, where it is connected to a range of measuring instruments. These tools are crucial for monitoring various parameters, such as efficiency, flow rate and mechanical performance, under different operating conditions. The data collected from these experiments are analyzed and discussed in the following section, providing insight into the performance of the turbine and validating the design choices made during its development.

Figure 8. Turbine under test

Table 1 summarizes all the results of the experiment on the locally designed Pilton turbine.

Based on the results presented in Table 1, we have the flexibility to generate a variety of curves that illustrate the relationships between different parameters. By manipulating these parameters relative to one another, we can explore and visualize a wide range of interactions and effects. This capability is demonstrated in the series of figures from 8 to 20, where each figure highlights a specific aspect of these relationships, offering deeper insights into the system's behavior under various conditions.

Table 1. Pelton turbine parameters

Mesure	P (Kpa)	N (tr/min)	Qv (l/s)	V (m/s)	T (N,m)	P_{hys} (W)	P_{mec} (W)	η (%)
1	35,4	564,000	0,037	8,08	0,068	4,06	1,28	31
2	45,5	636,000	0,086	9,16	0,078	5,04	1,65	32
3	59,4	740,000	0,099	10,47	0,088	5,78	2,18	37
4	76,3	844,000	0,113	11,87	0,09	6,43	2,53	39
5	94,7	860,000	0,117	13,22	0,079	6,81	2,28	33

III.2. Efficiency

Figure 9 shows the evolution of the Pelton turbine efficiency as a function of flow. The efficiency of a Pelton turbine varies with flow rate due to the relationship between hydraulic energy conversion and turbine operation. At low flow rates, the turbine may not harness enough energy from the water, resulting in lower efficiency. As the flow rate increases between 0.086 - 0.099 l/s, the turbine captures more hydraulic energy, improving its efficiency until it reaches an optimal flow rate where the turbine operates at its maximum efficiency with n = 39 %. Beyond this point, the flow rate continues to increase to 0.117 l/s, the efficiency continues to decrease to 31% due to factors such as excessive speed leading to energy losses or poor alignment of the jet with the buckets, leading to inefficiencies in energy conversion.

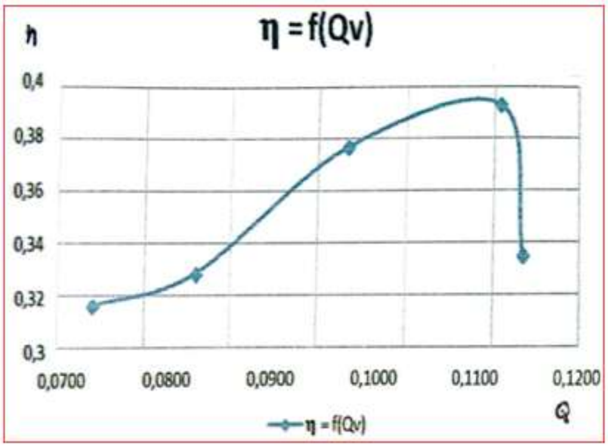

Figure 9. Efficiency as a function of flow rate

III.3. Torque

Figure 10 shows the variation of torque as a function of speed. Torque in a Pelton turbine is closely related to rotational speed, primarily due to the interaction between the water jets and the turbine blades. At lower speeds, torque is higher because the water jets have sufficient time to efficiently transfer their kinetic energy to the turbine blades. However, as the rotational speed of the local Pelton turbine increases, reaching 844 rpm, a notable decrease in torque from 0.090 to 0.079 N·m is observed. This reduction in torque occurs because the faster buckets spend less time in contact with the water jets, decreasing energy transfer efficiency. Therefore, the turbine's ability to maintain higher torque decreases as speed increases, highlighting the importance of balancing speed and torque for optimal turbine performance.

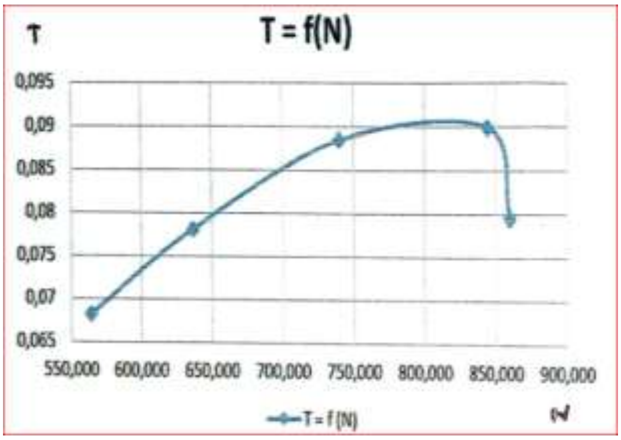

Figure 10. Torque as a function of speed

III.4. Speed of the turbine

Figure 11 shows the evolution of the speed of the turbine as a function of the flow rate. The relationship between a Pelton turbine's speed and water flow is fundamental to its operation and efficiency. As the flow rate increases, more water is directed toward the turbine blades, which in turn increases the force on the buckets, causing the turbine to spin faster. This means that a higher flow rate generally results in a higher rotational speed of the turbine. However, this relationship is not linear; as the flow continues to increase. the speed of the local turbine is increased until reaching an optimal point of 844 rpm with a flow rate of 0.113 l/s. It is noted that beyond this point, further increases in flow rate 0.117 l/s may not significantly increase velocity due to mechanical limitations and potential inefficiencies, such as splashing or energy losses. Understanding this relationship is crucial to optimizing turbine operation, ensuring that flow is balanced to achieve the desired speed without causing undue stress or inefficiency..

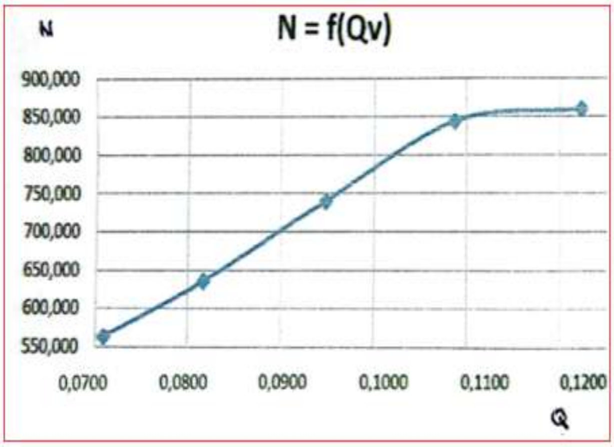

Figure 11. Speed as a function of flow rate

We note that the relationship between a Pelton turbine's speed and its mechanical power output is a key aspect of its performance. As the speed of the turbine increases, driven by the flow of the water, the power output initially increases because the turbine converts more of the kinetic energy of the water into mechanical energy. This increase in power continues as the speed increases, up to an optimal point where the turbine operates most efficiently at exactly 2.53 W with a flow rate of 0.113 l/s and a speed of 844 rpm. However, beyond this optimal speed, the output power begins to decrease to reach a value of 2.28 W, the flow rate is 0.117 l/s and the speed is 860 rpm as shown in Table 1.

This occurs because the turbine may suffer losses due to factors such as reduced torque, inefficient energy transfer from the water jets to the blades, or mechanical limitations. Therefore, although speed and power are directly linked, to achieve maximum power, the turbine must be kept in an optimal speed range to avoid a decrease in efficiency.

III.5. Mechanical power P_{mec}

Figure 12 shows the variation of the mechanical power with respect to the flow rate. The mechanical power P_{mec} of a Pelton turbine depends directly on the flow rate, because the quantity of water hitting the turbine buckets determines the mechanical energy generated. At lower flow rates, the turbine produces less power due to the limited hydraulic energy available. As the flow rate increases to 0.113 l/s, more water exerts a greater force on the buckets, resulting in a higher mechanical power 2.53 W. However, beyond a certain optimal flow rate 0.113 l/s, the P_{meca} begins to decrease slightly 2.28 W, if the turbine becomes less efficient, due to factors such as excessive water splashing or loss of control over the water jets, which can reduce the efficient conversion of hydraulic energy into mechanical power.

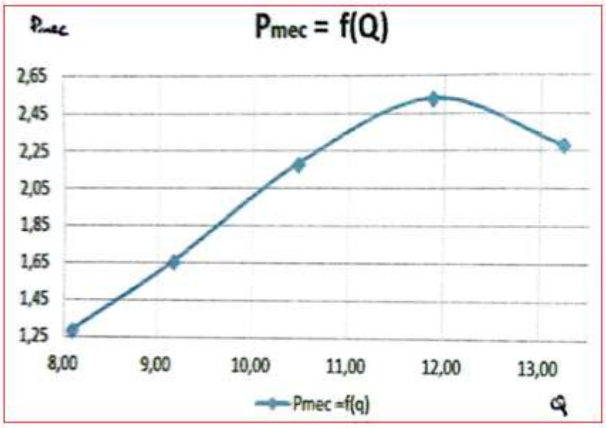

Figure 12. Mechanical power as a function of flow rate

IV. Conclusion

In our study, we explored the complex dynamics of a locally designed Pelton turbine, focusing on the relationships between rotational speed, torque and mechanical power. Understanding these relationships is crucial to optimizing turbine performance, especially in applications where efficiency and reliability are paramount. Through our analysis, we sought to determine how speed variations affect both torque and power output, providing valuable information for the design and operation of Pelton turbines.

The performance of a Pelton turbine is significantly influenced by the relationship between its rotational speed and its torque and power output. Our analysis revealed that as the turbine speed increased to 844 rpm, the torque decreased from 0.090 to 0.079 N·m, indicating a reduction in the efficiency of energy transfer from the water jets to the turbine blades. This drop in torque highlights the importance of optimizing speed to maintain efficient power production. Additionally, although an increase in speed initially improves power output, it is essential to operate within an optimal speed range to avoid decreased efficiencies. These results highlight the delicate balance required between speed, torque and power to achieve optimal turbine performance.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism.

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