DESIGN AND IMPLEMENTATION OF AN EXPERIMENTAL TEST RIG FOR PELTON TURBINE PERFORMANCE STUDY

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Abstract. *This study aims to design and implement a laboratory-scale experimental test rig to evaluate the performance of a Pelton turbine. The Pelton turbine is a type of impulse turbine ideal for hydroelectric power plants (HEPP) operating under high head and low flow conditions. In engineering education, the lack of practical facilities often hinders students from gaining a direct understanding of turbine working principles. Therefore, this test rig is designed to provide an experimental platform that allows students to observe the effects of varying water flow rates and pressures on the turbine's power output and efficiency. The research process includes mechanical system design, material selection, integration of measurement instruments (flowmeter, manometer, tachometer), and performance testing. Experimental results are analyzed based on hydraulic power, mechanical power, and energy conversion efficiency. This test rig is expected to serve as an effective educational tool that enhances student understanding of water energy conversion systems and improves the quality of hands-on learning in mechanical engineering.*

Keywords: *Experimental test rig, Fluid pressure, Pelton turbine, Turbine efficiency, Water flow rate.*

1. INTRODUCTION

The Pelton turbine is a type of impulse water turbine designed to harness the potential energy of high-head water and a relatively small discharge. The working principle of this turbine is based on the change in momentum of a high-pressure water jet directed toward the bowl-shaped turbine blades (bucket). When the water jet hits the bucket surface, the resulting impulse force rotates the turbine runner, and the mechanical energy from this rotation can be converted into electrical energy through the shaft and generator (Hariadi et al., 2021). Thanks to its efficient performance characteristics in harnessing energy from high-head water flows, the Pelton turbine is the main choice in Hydroelectric Power Plant (PLTA) systems located in mountainous areas or areas with high-pressure water resources (Setyawan & Tetuko, 2023).

In the context of engineering education, particularly for students majoring in Mechanical Engineering and Renewable Energy Engineering, understanding the working principles and operational characteristics of Pelton turbines is a core competency that must be mastered. Various concepts related to energy transformation, fluid flow and pressure analysis, and turbine efficiency evaluation are included in the scope of learning about hydro energy conversion theory. However, a purely theoretical understanding is insufficient to provide students with practical experience related to the fluid mechanics phenomena that occur in Pelton turbines. Therefore, an experimental approach is needed to deepen understanding and mastery of these concepts (Tarigan et al., 2024).

Many educational institutions, including small-scale campus laboratories, face limitations in the availability of experimental test equipment that can accurately represent the workings of a Pelton turbine. This limited testing facility forces the learning process to rely heavily on theoretical aspects, without providing students with the opportunity to directly observe and measure turbine operating parameters. Furthermore, field trips to full-scale hydroelectric power plants face various technical and logistical challenges, including cost, time, permits, and other complexities (Mahayana et al., 2020).

In response to these needs, it is necessary to develop a laboratory-scale Pelton turbine experimental tester that can be used to simulate turbine operation with a sufficient level of simplicity, safety, and efficiency. This tool is expected to be used to measure turbine operating parameters, such as rotational speed, water flow, pressure, power, and mechanical efficiency. With this device, students can conduct practical work and testing directly, observe the effects of changes in water flow and pressure on turbine performance, and compare test results with theoretical concepts they have learned (Purwantono et al., 2018).

This research focuses on answering several problems related to the design and implementation of experimental testing equipment for Pelton turbines on a laboratory scale. Several aspects studied include the design and manufacture of experimental testing equipment that can effectively represent the working conditions of Pelton turbines, technical considerations in the design process, including material selection, water flow systems, and the integration of accurate measuring instruments, as well as an analysis of the effect of variations in water discharge and pressure on the output power and working efficiency of the turbine. In addition, this research also aims to evaluate the extent to which the developed experimental testing equipment can produce valid and systematic data in assessing the performance and efficiency of Pelton turbines (Salam et al., 2019).

2. LITERATURE REVIEW

2.1 Basic Concepts of Water Energy and Hydroelectric Power Plants (PLTA)

Hydropower is a form of renewable energy that can be harnessed from the movement of water masses, whether from rivers, waterfalls, or water stored in dams. Through hydroelectric power generation (PLTA) technology, water energy is converted into mechanical energy and then converted into electrical energy (Putra et al., 2019). The working principle of a PLTA is based on utilizing the potential and kinetic energy of water to drive a turbine, which is then coupled to a generator to produce electrical energy (Utiarahman et al., 2024).

Essentially, water flowing from a higher elevation stores potential and kinetic energy. This energy conversion process consists of three main stages: first, the potential energy of the water is converted into kinetic energy as it flows through the penstock. Second, the kinetic energy of the water is converted into mechanical energy by the turbine through the impact or reaction effect of the water hitting the turbine blades. Third, the mechanical energy from the turbine is transmitted to the generator shaft to be converted into electrical energy. The efficiency of this process is greatly influenced by the design and type of turbine, the head value, the water discharge, the quality of the flow pattern, and various energy losses that may arise from friction, turbulence, and leakage (Astro et al., 2020).

2.2 The Role of Turbines in Microhydro or Laboratory Systems

Turbines serve as a core component in hydroelectric power generation systems, both large-scale and small-scale (micro-hydro). In the context of laboratory-scale testing, turbines are used to study the phenomenon of converting energy from flowing water into mechanical energy in a more measurable and controlled manner. Turbines receive energy from flowing water at a specific height and flow rate, then convert this energy into rotational energy that can be used to turn the generator shaft (Maridjo et al., 2020).

In microhydro systems or laboratories, turbines play a significant role in three main aspects: first, as a converter of water energy into mechanical energy with high efficiency; second, as a power regulator according to the load requirements or test patterns used; and third, as a testing and research device to analyze turbine performance, including efficiency, work patterns, and the effects of variations in flow parameters. In the context of learning, turbines are also used as educational and research media to understand the working characteristics and water flow patterns in turbines, evaluate design parameters, and study the integration of modern control and instrumentation technologies (Firdausi et al., 2020).

2.3 Types of Water Turbines

Water turbines can be classified into two main categories based on their working mechanism and the energy conversion principle used, namely impulse turbines and reaction turbines.

1. Impulse Turbine

This turbine works by utilizing the full kinetic energy of water. The water flow from a high-pressure nozzle hits the turbine blades at atmospheric pressure, producing an impulse force that rotates the turbine runner. Examples of this type of turbine are the Pelton turbine, the Turgo turbine, and the Banki (Crossflow) turbine. Characteristics of an impulse turbine include the conversion of potential energy to kinetic energy before entering the turbine, the absence of pressure changes within the runner, and its suitable application in areas with high water head and low water discharge (Kurniady et al., 2019).

2. Reaction Turbine

Reaction turbines harness the kinetic and pressure energy of flowing water. The water flows into a runner enclosed in a closed casing and experiences pressure changes as it passes over the turbine blades. Examples of reaction turbines include the Francis turbine, the Kaplan turbine, and the propeller turbine. This type of turbine is suitable for areas with low to moderate water fall heights but high-water discharge (Yani et al., 2017).

2.4 Comparison of Pelton, Francis, and Kaplan Turbines

The Pelton turbine is an example of an impulse turbine used in areas with very high-water heads and low water discharge. The high-pressure water flow is converted entirely into kinetic energy before it hits the bucket-shaped turbine blades. The speed of the water jet produces an impulse force that rotates the turbine runner, making this turbine efficient and ideal for mountainous areas or areas with high water pressure.(Liem, 2017).

Francis turbines are reaction turbines and are used in areas with moderate water fall heights and discharges. The water flows in a spiral, converting its energy into pressure and velocity. They are highly efficient and suitable for medium- to large-scale power plants (Karudin et al., 2025).

The Kaplan turbine is also a reaction turbine and is used in areas with low water fall but very high-water discharge. Its blades can be adjusted to suit flow requirements, making this turbine highly efficient for a wide range of water discharge levels and varying power requirements (Sihombing & Pattipawaej, 2024).

2.5 Theory and Working Principles of Pelton Turbines

The Pelton turbine is an example of an impulse turbine specifically designed for areas with significant water fall heights and relatively small discharges. A high-pressure stream of water is directed through a nozzle, producing a high-speed jet of water that then strikes the double-bucket turbine blades. As the jet strikes the blades, the water's kinetic energy is converted into mechanical energy, and the change in momentum of the water flow produces an impulse force that rotates the turbine runner (Susanto et al., 2019).

The main components of a Pelton turbine consist of a nozzle (water jet guide), specially shaped blades (buckets), a runner as a place for the blades to be attached, a shaft as a transmission of energy from the runner, and a casing as a protector and a place to direct the water out of the turbine. The efficiency of a Pelton turbine can reach more than 90% under ideal conditions and is greatly influenced by the quality of the nozzle shape, water flow pattern, and blade design.

The Pelton turbine is also highly relevant for laboratory-scale research and microhydro technology applications, as it can be used to understand fluid flow patterns, the effects of changes in discharge and water fall height, and turbine performance in various design and test configurations.

2.6 Design of Experimental Test Equipment and Measurement Instruments

The development of a laboratory-scale Pelton turbine experimental test rig aims to simulate turbine operating conditions in a controllable and measurable manner. This tool allows for evaluation of turbine performance across various parameters, such as rotational speed, water flow, mechanical power, and turbine efficiency, in order to understand operating patterns and the effects of design parameter variations (Gustiawan et al., 2022).

Aspects that need to be considered in designing experimental test equipment include selecting materials with high durability, determining system dimensions based on a geometric similarity scale to the real system, designing water circulation with a reservoir tank and circulation pump, and designing nozzles that allow water flow at speeds and patterns according to test requirements. The entire system must also ensure safety and ease of operation.

Furthermore, the measurement system plays a vital role in obtaining valid and reliable data. Some of the instruments used include a flowmeter to measure flow rate, a manometer to measure water pressure before and after the nozzle, a tachometer to measure turbine rotational speed, and a torque sensor to evaluate the mechanical power generated. With the integration of a data logger system and data processing software, testing can be carried out efficiently and allow for a comprehensive analysis of the performance and efficiency of the Pelton turbine in various operational scenarios.

3. RESEARCH METHODS

This research is an experimental study using a quantitative approach aimed at designing, manufacturing, and testing a Pelton turbine tester. Testing was conducted to analyze turbine performance based on variations in water flow and pressure, thus determining efficiency and power output.

This research was conducted at the Energy Conversion Laboratory, Mechanical Engineering Study Program, Faculty of Engineering, Muhammadiyah University of West Sumatra, from February to July 2025. The research stages starting from literature study, design, manufacture and installation of tools, implementation of experiments, to data processing and preparation of the final report can be seen in Figure 1.

Figure 1. Flow chart

1. Identification of Problems

This stage is carried out after the initial research objectives have been established. The problem identification process includes initial observations of technical phenomena, such as the performance of the braking system on a particular vehicle or machine. The identified problems are then formulated into research questions or specific objectives to be achieved.

2. Literature Study

This stage aims to gather scientific references relevant to the research topic, such as journals, books, research reports, and other scientific sources. The information reviewed includes basic braking system concepts, axle types, simulation methods using SolidWorks, and related previous studies. The primary goal is to establish a strong theoretical foundation and avoid duplication of research.

3. Design
   Based on the results of the literature study, the technical design of the object to be tested, namely the drum brake system axle, was carried out. This stage consisted of creating a 3D model using SolidWorks software and determining simulation parameters, including material selection, compressive force values, and loading points. This stage served as the basis for the technical simulation and subsequent data analysis.

4. Tool Making
   If the research involves experimental testing, this stage involves creating or modifying test equipment as needed. In the context of simulation-based research, this stage can be defined as the process of creating a digital model that aligns with the technical design to ensure the simulation accurately represents real-world conditions.

5. Data Collection and Results
   Once the model is complete, a simulation process is performed using SolidWorks to obtain technical data related to maximum stress values, deformation patterns, force distributions, and safety factors. The simulation results are systematically recorded in a table to facilitate further processing and analysis.
   Next, from the test data, power value calculations are carried out to evaluate system performance, namely:

a. Hydraulic Power (Ph):

Used to calculate the power from water energy with equation (1):

$Ph=\rho \cdot g \cdot Q \cdot H$ ……………………………………………………………………………(1)

where: ρ = Masswater type (kg/m^3)

g =Acceleration due to gravity (9.81 m/s^2)

Q = Water discharge (m^3/s)

H = Heightwater pressure (m)

b. Mechanical Power (Pm):

Used to calculate the power from the shaft work with equation (2):

$Pm=(T \cdot \omega)/1000$ ……………………………………………………………………,(2)

where:

T = Torque (Nm)

ω =Angular velocity (rad/s)

The data obtained from these calculations is then processed using Microsoft Excel or other statistical software to facilitate analysis, table creation, and graphical visualization. This allows for a comprehensive evaluation of the system's performance and efficiency, as well as comparisons with relevant standards or references.

6. Conclusion
   The final stage of this research is drawing conclusions based on the data and analysis performed. The conclusions address the research problem formulation and evaluate the level of achievement of the research objectives. Furthermore, interpretations regarding the performance of the drum brake system axle are outlined, including suggestions for future development or further research.

4. RESULTS AND DISCUSSION

This study aims to design and implement an experimental test rig to evaluate the performance of a Pelton turbine based on variations in water pressure and valve openings. The test rig design was created using CAD software to produce an efficient and structured system configuration, as shown in Figure 2. This design includes the main components of a water storage tank, a pressure regulating valve system, water pipes, jet nozzles, a Pelton turbine runner, and a dynamo as a conversion of mechanical energy into electrical energy.

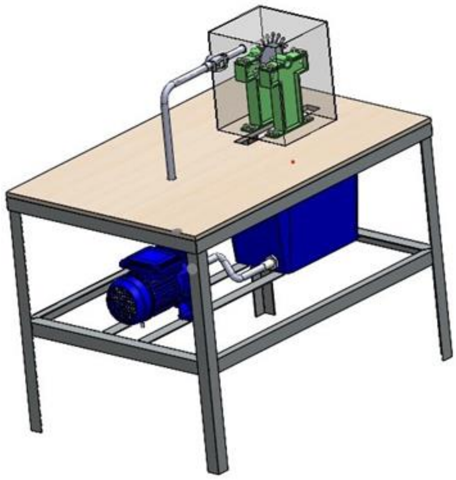

Figure 2. Platoon Turbine Design

After the design phase, the system is realized into a physical form using materials and components that comply with the technical design. The implementation of this test rig is arranged modularly for easy observation and operation, as seen in Figure 3, where the entire system is installed in an actual test configuration in a laboratory environment. The test rig is designed to be able to regulate the inlet water pressure through a valve system that can be opened in stages (¼, ½, ¾, and full), and flowed through a focused nozzle to drive the turbine blades.

When the water jet hits the turbine blades, the water's kinetic energy is converted into rotational mechanical energy. This rotation is transmitted to the dynamo shaft, which then generates electrical power. System performance parameters were measured using a digital tachometer to record the turbine's rotational speed (rpm), and a digital multimeter to measure voltage and electric current as the basis for calculating power (Watts). Data collection was carried out systematically for each valve opening variation, recording water pressure, rotational speed, and power generated.

1. Test Rig Valve Opening ¼

Table 2. ½ Valve Opening

Stage	Water Pressure (Psi)	Rotation (Rpm)	Power Generated (Watts)
1	164	137.2	30.56
2	168	143.2	31.13
3	174	146.6	31.25
4	180	147.8	32.65

From the test results with a valve opening of ¼, a positive correlation was seen between water pressure, turbine rotation, and power generated. When the water pressure was increased from 164 Psi to 180 Psi, the turbine rotation gradually increased from 137.2 Rpm to 147.8 Rpm. This increase reflects that the kinetic energy of the fluid flow entering the turbine increases with increasing pressure, resulting in a greater thrust on the turbine blades.

As a result, the electrical power generated also increased, from 30.56 Watts to 32.65 Watts. Although the power increase is relatively small, this trend indicates that the system can respond to increased pressure with fairly good energy conversion efficiency, even at a still limited valve opening (¼ full opening). This performance indicates that the system has begun to enter the optimal operating zone, although not yet at maximum capacity. The increase in power does not occur linearly, which is caused by factors such as the turbine's hydraulic efficiency, flow turbulence, or mechanical resistance that begins to increase at certain speeds.

2. Test Rig Valve Opening ½

Table 2. ½ Valve Opening

Stage	Water Pressure (Psi)	Rotation (Rpm)	Power Generated Watts)
1	197	176.7	39.75
2	198	180.9	40.56
3	205	185.7	42.46
4	208	207.8	43.55

Test data shows a strong correlation between increasing water pressure and turbine performance, both in terms of rotation (Rpm) and electrical power generated. In stages 1 to 4, water pressure increases from 197 Psi to 208 Psi. In response to this increase in pressure, turbine rotation speed increases from 176.7 Rpm to 207.8 Rpm, while power output increases from 39.75 Watts to 43.55 Watts.

The 3.8-Watt (approximately 9.6%) power increase during the 11 Psi pressure increase indicates that the turbine system responds to high pressure with better energy conversion efficiency than at low pressure (as at ¼ valve opening). This may indicate an approach to the optimal operating zone or even near the maximum capacity of the system.

Furthermore, power growth is not linear. For example, the power increase from stage 2 to stage 3 is greater than from stage 1 to stage 2, even though the pressure difference delivered is nearly the same. This indicates that at a given pressure, the fluid flow becomes more effective in transferring energy to the turbine, possibly due to more stable turbulence or better fluid penetration into the turbine blades.

Overall, these data indicate that the turbine system's performance is highly dependent on water pressure, and high pressure provides a significant increase in power output.

3. ¾ Valve Opening Test Rig

Table 4. Valve Opening Data Testing

Stage	Water Pressure (Psi)	Rotation (Rpm)	Power Generated (Watts)
1	232	233.2	83.58
2	238	236.6	85.97
3	240	486.8	90.83
4	242	491.7	93.65

Test results show the turbine system's response to very high water pressures, from 232 psi to 242 psi. Overall, there was a consistent increase in turbine performance parameters, namely rpm and power output (watts), but with one significant anomaly in stages 3 and 4.

In stages 1 and 2, when the water pressure increased from 232 psi to 238 psi, the turbine speed increased from 233.2 rpm to 236.6 rpm, and the power output increased from 83.58 watts to 85.97 watts. This increase is still within a reasonable trend, following a similar pattern to the previous stage of testing.

However, in stages 3 and 4, there is a drastic jump in turbine speed from 236.6 rpm to 486.8 rpm (stage 3), and to 491.7 rpm (stage 4), even though the pressure only increases slightly from 238 psi to 240 and 242 psi. This increase in speed is very significant and is not proportional to the relatively small increase in water pressure, thus indicating a change in flow characteristics or system conditions that cause the transition to near peak capacity.

This surge is also reflected in the sharp increase in output power from 85.97 Watts to 90.83 Watts (stage 3), and reaching 93.65 Watts (stage 4). This could indicate that at a pressure of around 240 psi, the system achieves very high energy conversion efficiency, or that a hydrodynamic resonance effect occurs, where the water flow is in optimal conditions to drive the turbine blades.

4. Full Valve Opening Test Rig

Table 4. Valve Opening Data Testing

Stage	Water Pressure (Psi)	Rotation (Rpm)	Power Generated (Watts)
1	261	287.7	98.54
2	265	293.3	104.87
3	271	303.6	119.65
4	274	311.5	127.25

Based on the data listed in Table 4, a consistent relationship is seen between water pressure, rpm, and the resulting electrical power (watts). The data shows that increasing water pressure directly affects the increase in rpm and power generated by the system.

At a water pressure of 261 psi, the resulting rotation speed is 287.7 rpm with a power of 98.54 watts. As the pressure increases to 265 psi, the rotation speed increases to 293.3 rpm and the power increases to 104.87 watts. This trend continues until the pressure reaches 274 psi, where the rotation speed reaches 311.5 rpm and the power output is 127.25 watts.

The relationship between pressure and rotational speed shows a positive linear pattern, indicating that the greater the applied water pressure, the higher the rotational speed of the system. A similar trend is observed for power, where electrical power increases with increasing pressure and rotational speed. This indicates that the conversion of mechanical energy to electrical energy is efficient in this system.

The results of this test have been validated with previous research that showed a positive correlation between water pressure, turbine rotation, and power output, where the performance spike at ¾ opening indicates the system is entering a hydrodynamic resonance phase in line with findings that show that flow at critical head and speed conditions can achieve peak efficiency. Research by Ji et al. (2023) showed a 1.8% increase in turbine efficiency on impeller blade optimization using the Box–Behnken method, confirming that flow space and blade optimization contribute significantly to performance. Meanwhile, the study "Validation of a Numerical Model for an Axial Hydraulic Turbine" (2025) confirmed that the numerical model accurately predicts the performance transition at high head conditions, making it clear that the rotation spike at 240 Psi reflects a movement into the maximum efficiency zone. Furthermore, the assessment of crossflow turbine efficiency in the review Hydro Turbine Energy Efficiency (2025) emphasized the importance of blade design and flow head to achieve energy increases of up to double-digit percent supporting the finding that system efficiency improves with valve opening and pressure increases. Overall, your experimental results are proven to be valid and consistent with the current literature which indeed shows pressure and flow velocity as the main determining variables of water turbine efficiency.

CONCLUSION

Based on the test results at various valve opening levels (¼, ½, ¾, and full), it can be concluded that there is a consistent positive relationship between water pressure, turbine rotation, and electrical power generated. Increasing water pressure generally causes an increase in rotation speed and output power, although at some stages there is a non-linear increase due to the influence of hydraulic efficiency, flow turbulence, and mechanical resistance. At valve openings of ¼ and ½, the system begins to show good energy conversion efficiency, but has not yet reached optimal performance. A significant spike occurs at opening ¾, indicating that the system has entered the critical operating zone or resonance, where efficiency increases drastically. Meanwhile, at full opening, the system operates stably and efficiently, with a linear increase in power with pressure, indicating that maximum performance is achieved at the highest flow and pressure conditions. Overall, the turbine system shows responsive performance to variations in pressure and valve opening, and has high potential to be optimized under certain head and flow conditions to generate electrical power efficiently.

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