Design and Field Testing of Pelton Turbine Blades for Small-Scale Hydropower Generation in High and Low Head Flow Environments

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Abstract. This paper explores the design and material selection of Pelton turbine blades, along with the installation and testing of small-scale hydropower systems in high- and low-head flow environments. A custom-designed axial flux permanent magnet generator is used to improve efficiency and stability. The study reviews the historical development of Pelton blades, focusing on how key design factors affect energy conversion efficiency. An analysis of water flow characteristics and site conditions shows that blade shape and flow angle significantly impact performance. Recommendations are made for optimizing blade design in different operational settings. The potential of Pelton turbines for renewable energy applications and their environmental impact are also discussed, with suggestions for future research. This work provides both theoretical and practical insights to improve Pelton turbine blade design for sustainable hydropower.

Keywords: Pelton turbine blade design, axial flux generator, renewable energy applications

1 Introduction

1.1 The Importance of Hydropower

With rapid technological advancements, global energy consumption has surged, exacerbating environmental pollution and climate change threats [1]. By 2050, under stringent climate mitigation scenarios, hydropower generation is projected to reach 71 to 87 terawatt-hours annually, contributing significantly to the 2°C target set by the Paris Agreement [2]. Among renewable energy sources, wind, solar, and hydropower are critical for decarbonizing the energy sector. Hydropower, with relatively low carbon emissions, is regarded as a highly promising renewable source, with average emissions estimated at 85 g CO_2/kWh and 3 g CH_4/kWh [3]. Small hydropower, defined as systems with capacities below 10 MW, differs from large-scale hydropower and is typically deployed in small rivers or irrigation channels, where its environmental and economic impacts are systematically assessed [4].

1.2 The Selection of Hydro Turbine Blades

This article identifies the impulse-type Pelton blade as the optimal choice for small-scale hydropower generation after analyzing various turbine blade characteristics. Compared to reaction blades, which require more space, and the lower efficiency of screw-type blades, Pelton blades demonstrate superior energy conversion in high-head, low-flow environments. According to the literature, Pelton blades are cost-effective and maintain high efficiency, even under fluctuating water conditions. Additionally, CFD model optimizations have confirmed their adaptability, making them suitable for a wide range of water flow environments [5].

1.3 Future Trends in Renewable Energy Installed Capacity

The article highlights that by 2050, an annual global increase of 1066 GW in renewable energy capacity is necessary to meet climate targets [6]. While green energy generation itself is cost-free, the installation and maintenance of wind turbines remain expensive [7]. In hydropower scheduling, multi-layer stochastic optimization and stochastic dual dynamic programming are the leading techniques. However, recent advancements and alternative methods hold significant potential for future applications by power system operators and policymakers [8].

2 Site Analysis and Installation

Micro-hydropower offers a sustainable energy solution with both environmental and economic benefits. This study explores the installation of a micro-hydropower device in a fishpond, which reduces operational costs (Fig. 1), lowers reliance on grid electricity, and promotes a more sustainable aquaculture system. The device is installed at the water pipe outlet, which supplies water to maintain pond levels and ensure proper operation. With stable water flow and sufficient discharge, this location was ideal for testing. The device efficiently captures the kinetic energy of the flowing water and converts it into electricity.

Fig. 1. Field Diagram

The hydropower device developed in this study is installed at the water supply pipeline outlet (Fig. 2). As water flows through the system before entering the fishpond, its kinetic energy drives the turbine blades, which is then converted into electricity by a custom-designed generator optimized for low-speed, high-torque conditions. The system operates without disrupting water supply, ensuring efficient resource utilization. Designed for stable, long-term operation, the generator provides continuous, reliable supplementary power. This dual-use design enhances resource efficiency and adds value to the overall system.

Fig. 2. Turbine Blade On-Site Installation Schematic

The favorable environmental conditions at the water pipe outlet support the long-term stable operation of the power generation device. Consistent water flow minimizes blade wear and degradation, while the design ensures minimal impact on the fishpond, promoting sustainability. The simple structure also facilitates easy maintenance, making the device ideal for low-interference, high-stability environments.The Pelton turbine, as shown in Table 1, is a specialized impulse turbine designed to convert the kinetic energy of high-pressure water into mechanical energy. It directs high-velocity water through nozzles to strike double-cupped blades, efficiently capturing momentum to drive the turbine and generate electricity. With efficiency rates up to 92%, the Pelton turbine ensures stable power generation even in low-flow conditions. Its precision-engineered components, including optimized bucket and nozzle designs, maximize energy conversion efficiency across various operational settings [9].

Table 1. Performance comparison of blade types and efficiency in micro Hydropower Systems

Blade Type	Applicable Conditions	Efficiency Performance
Pelton Blade	High head conditions	Achieves over 90% efficiency, maintaining stable performance under low flow fluctuations.
Francis Blade	Medium head conditions	Wide efficiency range, typically exceeding 90%.
Kaplan Blade	Low head conditions	Best efficiency under low head, maintaining high performance.

The formula for power output of an impulse-type turbine blade can be translated as follows:

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H \tag{1}$$

The velocity of the water jet impacting the blades can be determined by the Bernoulli equation as:

$$V\omega = \sqrt{2 \cdot g \cdot H} \tag{2}$$

Assuming the turbine blades operate at a constant rotational speed, the speed (N) can be estimated using the following formula:

$$N = \frac{60 \cdot V\omega}{2 \cdot \pi \cdot r} \tag{3}$$

The efficiency η of the hydraulic turbine can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} \tag{4}$$

The relationship between the angular velocity ω of the turbine and the power P:

$$P = \tau \cdot \omega \tag{5}$$

3 Installation Design

As shown in Table 2, PETG was selected for its high durability, impact resistance, and excellent chemical resistance, making it ideal for corrosive water environments. Additionally, PETG's non-hygroscopic properties and stable 3D printing performance, with minimal warping, make it suitable for testing turbine blades under high-pressure water flow conditions.

Table 2. Comparative applications of 3D printing material

Property	PLA	PETG	ABS
Heat Resistance	60°C	75°C	100°C
Impact Resistance	Low	High	High
Wear Resistance	Low	Medium	Medium
Applications	Prototypes, teaching models, decorative items	Mechanical parts, containers, durable components	Functional prototypes, consumer product shells

In this project, a circular shape was selected for the Pelton turbine blades to ensure symmetry, allowing water to evenly impact the blade surface (Fig. 3), thereby maximizing the use of the water's kinetic energy. The shallow, bowl-shaped design provides enough depth to capture and guide the water flow without significantly reducing its velocity. This shape allows the water to glide smoothly over the blade surface and detach quickly, minimizing retention time and improving efficiency. Additionally, the disc-shaped curvature further decelerates the water as it exits the blade, converting remaining kinetic energy into rotational energy. This design ensures that water exits the blade with near-zero velocity, optimizing energy conversion. The blade design effectively captures water energy while promoting smooth and rapid discharge, minimizing energy loss, making it ideal for high-head hydropower applications.

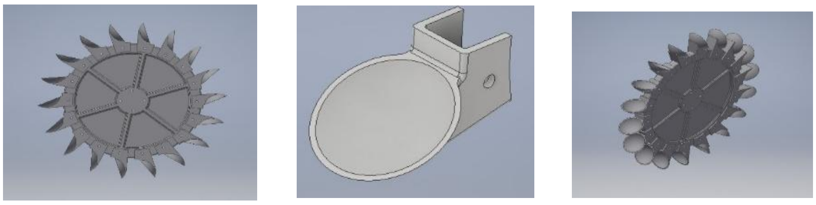

Fig. 3. Blade Diagram

To enhance the overall efficiency of the micro-hydropower system, a custom-built axial flux permanent magnet generator was chosen as the core power generation device (Fig. 4). This generator features a compact structure and performs exceptionally well at low rotational speeds, thanks to its slotless, silicon-steel-free modular design. It is particularly well-suited for integration with small hydropower systems and impulse turbine blades.

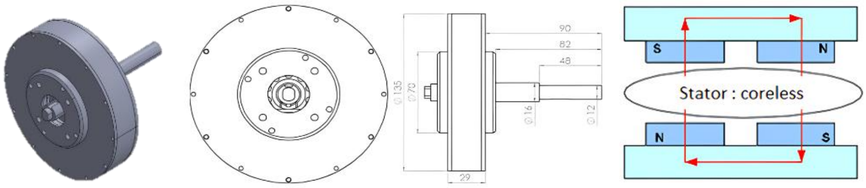

Fig. 4. Generator Dimensions Diagram

According to the test bench data in Table 3, the power output of the axial flux permanent magnet generator increased significantly with various rotational speeds. At 600 RPM, the generator produced nearly 80 watts, demonstrating high energy conversion efficiency even at low rotation.

Table 3. Testing data of AFPM generator

Speed (rpm)	Power (w)
160	5.75
300	25.00
600	74.40
800	104.39
900	126.40
1200	189.72

4 Results and Discussion

This study assesses the power generation efficiency of multiple turbine blade designs, including Pelton, Francis, and Kaplan, ultimately identifying the Pelton blade as the most optimal choice (Fig. 5). The Pelton blade demonstrated superior performance under high head and fluctuating flow conditions, maintaining stable operation even at low flow velocities. Field tests conducted at a flow velocity of 0.5 m/s revealed power outputs between 0.91W and 1.05W at 5V, reaching 1.46W at 7V, with the generator's rotational speed exceeding 100 RPM. The current remained stable at 0.2A, indicating consistent performance across varying voltages. These findings confirm the Pelton blade's ability to address efficiency challenges in low-flow environments, highlighting its strong potential for practical applications (Fig. 6).

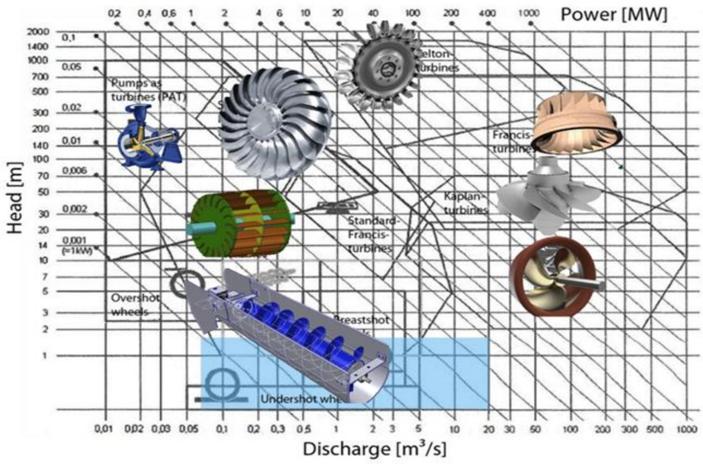

Fig. 5. Application ranges of different types of turbines under various 'Head' and 'Discharge' conditions."[10]

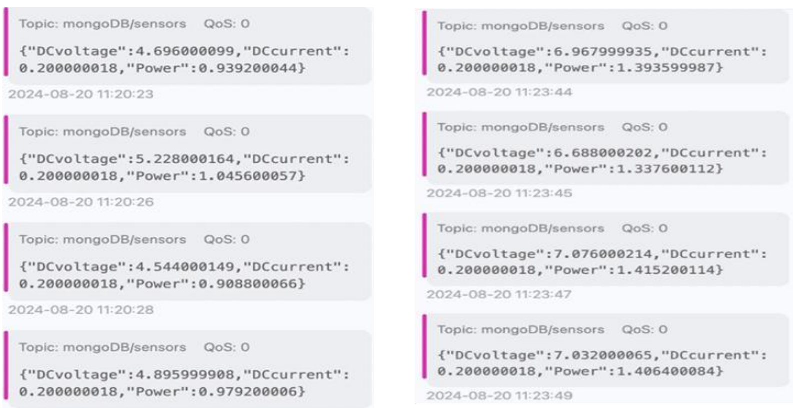

Fig. 6. Turbine Measured Data

From a technological innovation perspective, the device utilizes a lightweight aluminum alloy frame and PLA materials to enhance convenience and reduce costs. This represents a significant improvement over traditional steel used in small hydropower systems, optimizing both installation and transportation processes (Fig. 7). The device is equipped with a custom-designed permanent magnet generator, which offers high efficiency and low maintenance, and is precisely matched to the blade system. It performs efficiently at low rotational speeds, making it ideal for environments with fluctuating water flow velocities. This ensures stable and efficient operation even under low-flow conditions, significantly improving energy conversion efficiency and expanding its applicability across diverse scenarios.

Fig. 7. System Configuration and On-site Deployment Diagram

This thesis explores the potential for widespread adoption of small hydropower technology in the global market, focusing on providing stable, efficient, and cost-effective energy solutions to meet the growing demand for clean energy. Future development hinges on reducing production costs and optimizing technical design to enhance market competitiveness. By promoting commercialization, the system proposed in this thesis is expected to expand into new application areas and regions, contributing to broader energy coverage and supporting the global energy transition.

5 Conclusion

The research provides a comprehensive evaluation of a small hydropower system, identifying the Pelton turbine as the optimal choice for high head and variable flow conditions. Experimental data confirm the system's capacity to deliver stable and efficient power output across a range of voltages and flow rates, addressing inefficiencies commonly found in conventional hydropower systems under low-flow conditions. The findings also underscore the turbine's excellent energy conversion capabilities. Moreover, power output tests indicate a marked increase in efficiency with rising voltage while maintaining stable current, further validating the system's high operational performance. These results demonstrate the Pelton turbine's effectiveness in improving power generation for small-scale hydropower, offering a reliable solution for sustainable energy production.

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