Performance of Undershot Water Wheel in Low Head Water Resources For Pico Hydropower

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***Abstract*—The growing demand for renewable energy sources has sparked interest in using low-head, low-flow water resources for small-scale hydropower generation. This study investigates into the performance of undershot water wheels as a potential technology for producing pico hydropower in such circumstances. Water resources with low head and low flow, although possessing less power potential compared to large rivers and high head sites, have substantial prospects for sustainable and decentralized energy generation. The study focuses on determining the efficiency, generation of power, and operational feasibility of undershot water wheels under varied flow circumstances found in low head, low flow sites. Experimental setups were created to simulate real-world situations, and performance metrics were gathered for various water flow rates and wheel configurations. Key parameters such as number of blade and rotational speed were systematically varied to maximize energy capture. The study also investigates the environmental consequences, installation obstacles, and maintenance requirements of deploying undershot water wheels in rural and distant areas. The proposed design prioritizes the use of inexpensive and easily accessible materials, resulting in simplified installation and maintenance processes compared to previous studies. This improves the practicality of the design. The findings show that, with correct design and site selection, undershot water wheels can provide a long-term, cost-effective alternative for localized renewable energy generation.**

***Keywords*—low-flow, low-head, undershot water wheel, pico hydropower**

I. INTRODUCTION

Water covers approximately 70% of the Earth's surface, with 97.5% being salt water and 2.5% being fresh water[1]. Surface water, particularly rivers, plays a crucial role as a daily source of water supply and a great source of hydropower[2]. Hydropower has been used for over 2,000 years, with the first hydropower station in 1882 in Wisconsin. As fossil fuels deplete, regenerative energy sources are becoming increasingly important in the world's energy supply[3], [4].

China is the largest contributor to hydropower deployment and remains the world leader in small-scale hydropower development[5]. Malaysia, with its high temperatures, humidity, and abundant rainfall, has significant hydroelectric potential[6]. Electricity is essential for human development, but a significant percentage of the public still lacks access to it, especially in impoverished rural areas[7]. Small hydro, mini hydro, micro hydro, and pico hydro have emerged as the best alternatives to generate power without negatively impacting the environment.

Pico hydro power is the most prevalent type due to its high reliability and inexpensive operating costs. It converts the potential energy and kinetic energy of water into electrical or mechanical energy[8]. Malaysia has a lot of pico hydro potential due to its vast natural water resources, high temperatures, humidity, and high rainfall volume[6].

Pico hydro systems can be configured to accommodate various situations and demands, enabling adaptability in design, operation, evaluation, and installation. In areas with limited water pressure, hydro technology shows potential as a sustainable energy source due to technological developments and cost-effectiveness. These systems leverage the natural flow of water to generate electricity on a small scale, offering a reliable energy solution for remote or off-grid communities. Further advancement and investment for pico hydro technologies have substantial prospects for meeting energy demands and fostering sustainability in locations with limited resources.

II. PICO HYRO SYSTEM

Pico hydro is a suitable hydroelectric plan for off-grid areas, particularly in isolated and hilly areas. It uses water from a small river to generate energy, which is used to power electrical devices and recharge batteries[9]. Malaysia has significant pico hydro potential due to its vast natural water resources, high temperatures, and high rainfall volume. With approximately 189 river basins, Malaysia has a wide hydropower potential, ranging from mini to pico hydropower plants[10]. The feasibility and viability of a pico hydro system depend on factors such as water resources, turbine type, electrical loads, and system development and operational costs.

A. Working Principle and Types of Turbine

Hydro turbines are rotating machines that convert hydro potential energy into kinetic, mechanical, and electrical energy. They are used in power generation systems to generate electricity, which is proportional to the volume and pressure of water flowing through the turbine[11]. Different types of hydraulic turbines have been developed for pico hydropower generation, each with its own operating principles. These include impulse turbines, reaction turbines, and gravity turbines. Impulse turbines use high-velocity water jets to rotate the turbine, while reaction turbines use nozzles and blades to expand the turbine[9]. Gravity turbines, powered by water's weight, convert water's potential energy into rotational mechanical energy[12]. Impulse turbines are suitable for various water head amounts, with four primary types: Crossflow, undershot water wheel, Pelton, and Turgo. Reaction turbines, such as the Propeller, Kaplan, and Francis, function at low water head, while the Francis turbine is best suited for medium water head. Gravity turbines, such as the Archimedes Screw, breastshot water wheel, pitchback water wheel, and overshot water wheel, function effectively in low water head settings.

B. Water Head and Water Flow

Pico hydropower operates similarly to traditional hydropower, with the turbine revolving when pushed by flowing water. The head and flow of water are crucial parameters in generating energy from water potential energy in a hydro system. Water head is the vertical height between the point where it enters and exits the hydro system, while water flow rate is the amount of water falling or flowing through the turbine as shown in Figure 1. In Malaysia, small rivers with less than 10m of water head could be exploited for pico hydropower[12] due to the country's tropical climate and abundance of waterfalls, streams, and irrigation channels[13]. Researchers are now focusing on enhancing low head pico hydro technologies, as low head areas are more common than high head locations. The type of water turbine used in a project at a specified location depends on the head and flow rate of water.

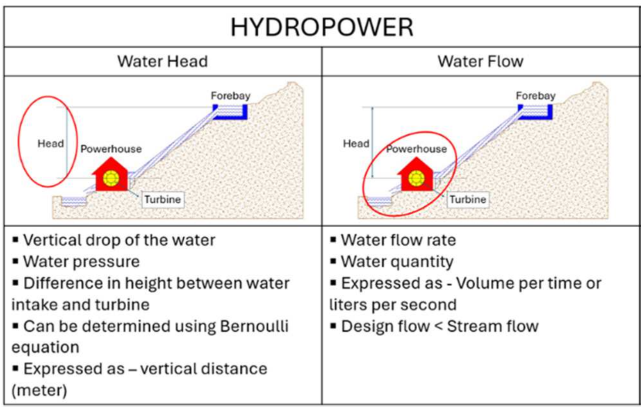

Figure 1. Head and flow rate diagram for pico hydro

C. Water Wheel Turbine

Ancient, traditional, and modern water wheels have significant differences in manufacturing methods, design specifications, working principle, and efficiency levels. Traditional water wheels were built in massive sizes but had lower efficiency than modern ones[14]. Water wheels are classified into three types based on how water approaches the wheel: wholly dependent on water gravity, partially dependent on water gravity and partially dependent on water flow rate, and solely dependent on water flow rate.

Water wheels are simple hydropower machines consisting of vertically mounted wheels wrapped around a horizontal axle. The undershot water wheel does not have a penstock because it is rotated by the kinetic energy of the water flow. Undershot water wheels operate when flowing water strikes the blade wall at the bottom of the waterwheel as shown in Figure 2, providing simple construction, lower cost, and ease of movement[15]. They are the best hydropower machines for use in low head areas and do not require the assistance of a technological irrigation system.

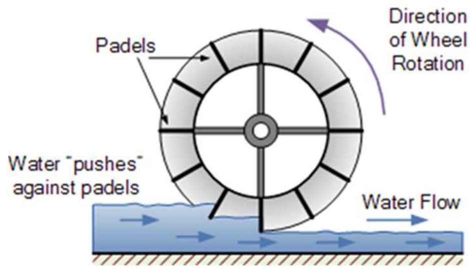

Figure 2. Undershot water wheel shcematic

The proposed pico hydro in this study employs earlier studies' approaches for undershot water wheel such as the Prony braking system, the float method, and Bernoulli equations[16]. The undershot water wheel's performance was examined using run-of-river conditions in rural areas of Bengkulu, Indonesia, with water discharges of $0.105m^3/s$ and 0.04m of head. The system achieved a peak efficiency of 24% at a U/v ratio of 0.39 and 22% at 0.41 using the Gaussian fit approach[16].

III. EXPERIMENTAL SETUP

This study presents an undershot water wheel, specifically the pico hydro undershot water wheel, which uses plastic soda bottles as its blades. The geometrical design of the water wheel turbine is identical to the typical undershot water wheel design, but the blade parts have been redesigned. The plastic soda bottle is lightweight, durable, and inexpensive, making it an ideal choice for blade turbines. The performance of the pico hydro undershot water wheel is predicted and analyzed using governing equations based on mass, momentum, and energy conservation principle.

The project focuses on developing and testing the water wheel, which features plastic soda bottle blades, a plug-in design for optimal portability, and a simple geometrical design. These features allow the turbine to operate under low-head and flow conditions. Experiments were conducted using a water test rig to verify consistent and reliable turbine performance. The experimental results were compared to published data from previous studies for theoretical validation.

The water wheel is expected to make significant advancements in terms of operating under limited water resources and alleviating the problem of previous undershot water wheels. The project also addresses concerns about the cost and suitability of the technology to limited water supply.

A. Governing Equations

Before measuring mechanical power, the force, F, on the water wheel must be determined. As a result, the Prony break method is essential for determining the force, F, on a wheel[16]. The force, F generated by the wheel is determined using (1).

$$F = F_2 - F_1 \tag{1}$$

F_1 indicates the applied weight given to the device until the wheel stops rotating, while F_2 is the result of the force meter. Next, the torque, τ is calculated once the force, F is obtained using (2).

$$\tau = F \cdot r \tag{2}$$

where r is the radius of the pulley. Hence, the mechanical power of wheel can be calculated using (3).

$$P_{mech} = \tau \cdot \omega \tag{3}$$

meanwhile, the angular velocity, ω can be calculated using(4).

$$\omega = 2\pi n / 60 \tag{4}$$

where n denotes the tachometer-measured rotating speed (rpm) of the wheel turbine. Furthermore, using (5), the potential power, $P_{potential}$ can be calculated[11]

$$P_{potential} = \rho \cdot g \cdot Q \cdot H \tag{5}$$

water discharge is monitored, Q is based on the volume of water passing through an area over time. As a result, the value of Q was determined using (6).

$$Q = v \cdot A \tag{6}$$

where A is the surface area of the water in the gutter. As a result, A can be determined using the parameters in Figure 2.15, as shown in (7).

$$A = L \cdot T \tag{7}$$

T and L are the breadth and height of the water in the gutter, respectively. Meanwhile, the Bernoulli equation is used to approximate H in the system, as shown in (8), where water velocity, v, is measured using the float method.

$$H = \frac{v^2}{2g} \tag{8}$$

The water velocity, v, is calculated using the float method. A float object is transmitted from the first measurement point to the second measurement point, ℓ, in a float procedure. The time it takes for the object to travel, t, is then recorded using a stopwatch. Thus, (9) can be used to calculate v.

$$v = \frac{\ell}{t} \tag{9}$$

The multimeter is then used to determine the voltage, V, and current, I values. As a result, (10) is used to calculate the system's electrical power, P_{elec}.

$$P_{elec} = VI \tag{10}$$

Finally, the mechanical and electrical efficiencies were determined using (11) and (12), respectively.

$$\eta_{mech} = \frac{P_{mech}}{P_{potential}} \cdot 100\% \tag{11}$$

$$\eta_{elec} = \frac{P_{elec}}{P_{potential}} \cdot 100\% \tag{12}$$

B. *Testing Parameters*

This section discusses in detail the testing processes required to gather correct experimental results. These procedures are critical for ensuring compliance with the defined methodology and assisting in the evaluation of output performance in order to produce accurate results. The study of the pico hydro undershot water wheel turbine's performance requires assessing eleven critical parameters:

a. Potential power ($P_{potential}$)
b. Rotational speed of water wheel turbine (ω)
c. Voltage and current at the generator output (V, I)
d. Water flow rate through the turbine (Q)
e. Torque (τ)
f. Water velocity (v)
g. Available force (F)
h. Applied force (F_1)
i. Force meter from Prony brake scheme (F_2)
j. Mechanical power (P_{mech})
k. Electrical power (P_{elec})

C. *Preliminary Design*

The preliminary design serves as a blueprint, guiding the subsequent detailed engineering, fabrication, and installation processes. By meticulously planning and optimizing these elements, the preliminary design ensures that the final system will be both functional and efficient. The preliminary design of the pico hyro undershot water wheel are shown in Figure 3.

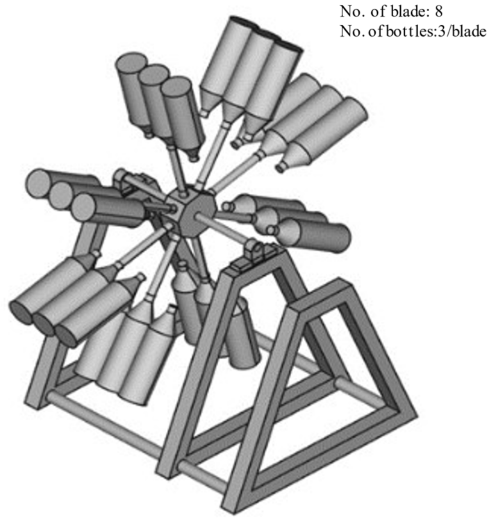

Figure 3: 3D model of the pico hydro undershot water wheel

IV. RESULTS

Before conducting the real-world tests, data are meticulously calculated to determine the ideal output of the undershot water wheel. These preliminary calculations involve the eleven parameters mentioned before: These calculated results serve as benchmarks, providing a clear understanding of the system's potential performance and guiding the experimental setup. By establishing these theoretical values, the subsequent real tests can be more effectively evaluated, ensuring that the system is configured for optimal performance under the specific conditions of the low head, low flow water resource.

The calculated results of mechanical power, P_{mech}, in relationship to angular velocity(ω) is shown in Figure 4. The results show the performance of waterwheel operating at increasing value of angular velocity for four blades and eight blades respectively. Figure 5 shows the comparison of mechanical efficiency, η_{mech}, with the efficiency achieved in [16].

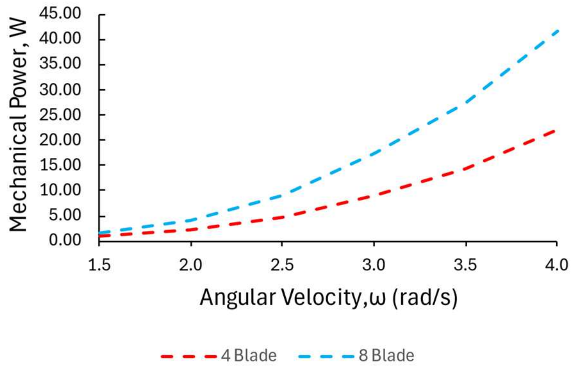

Figure 4. Theoretical mechanical power at different value of angular velocity

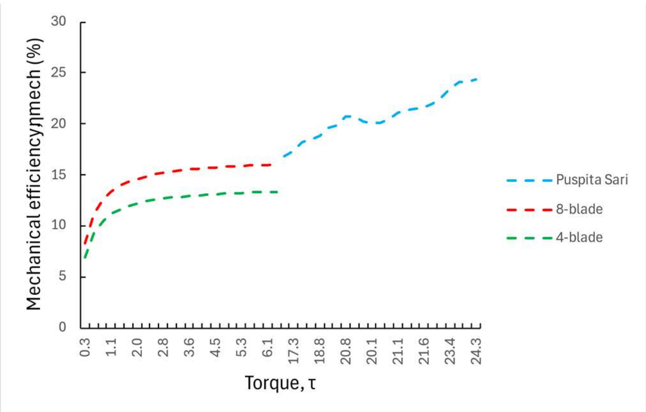

Figure 5. Comparison of mechanical power efficiency

Figure 5 shows that both the four-blade and eight-blade water wheels have lower efficiency when compared to the [16]. This is a result of the poor torque output. Reduced torque results in a decrease in the mechanical power produced by the water wheel. The eight-blade water wheel achieved a peak efficiency of 16.02%, whereas the reference value for peak efficiency is 24.31%. This can have a substantial effect on the total energy production, particularly in situations with low water flow where the water's kinetic energy is already restricted. It is essential to address the problem of insufficient torque to make undershot water wheels viable in water resources with low head and low flow. Enhancing the torque of these pico hydropower systems can greatly improve their efficiency and reliability.

V. CONCLUSION

The research aimed to develop, test, and analyze the performance characteristics of an innovative pico hydro system. Prior studies on pico hydro systems have frequently emphasized the difficulties in achieving high efficiency, specifically regarding the limited torque seen in situations with low head and low flow. This study aims to enhance efficiency and power output by optimizing turbine design and operational characteristics. The pico hydro undershot water wheel was developed with eight and four bottle blade types and evaluated under various physical parameters. However, the undershot water wheel experiences lower torque, which directly affects the mechanical power output and overall efficiency of the system. This inherent limitation underscores the need for further design optimization to enhance torque and improve performance in such conditions. Utilizing computational fluid dynamics (CFD) analysis to model various design configurations and water flow situations helps in determining the most efficient methods to improve torque. This enables the optimization of wheel and paddle designs prior to their physical execution.

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