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Performance evaluation of a laboratory-scale Pelton turbine under variable nozzle distance and valve opening

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Abstract

Pelton turbines are impulse turbines widely used in micro-hydro power systems operating under high-head and low-flow conditions. Their performance depends strongly on the quality of the water jet impacting the runner buckets, which is influenced by nozzle distance and valve opening. This study experimentally investigated the effects of nozzle distance (60, 70, and 80 mm) and valve opening (30°, 60°, and 90°) on the hydraulic power, turbine power, electrical power, and efficiency of a laboratory-scale Pelton turbine. Turbine rotational speed was measured using a tachometer, while voltage and current were measured using a multimeter to determine power output. The results showed that increasing the valve opening increased hydraulic, turbine, and electrical power due to higher flow rate and jet kinetic energy. However, the turbine efficiency showed non-linear behavior because it was influenced by the quality of the jet and the effectiveness of momentum transfer. The maximum turbine power of 10.52 Watts and electrical power of 10.58 Watts were obtained at a nozzle spacing of 80 mm and a valve opening of 90°. Meanwhile, optimum efficiency was achieved at a nozzle distance of 80 mm and a valve opening of 30%, indicating that optimum conditions do not always occur at maximum flow. The results of this study indicate that the combination of nozzle distance and valve opening significantly influences Pelton turbine performance and is important for optimizing laboratory-scale micro-hydro systems.

Keywords:
Pelton turbine, nozzle distance, valve opening, turbine power, efficiency.

1 Introduction

Renewable energy has become a major focus in the transition to a sustainable energy system, particularly in providing electricity to remote and rural areas. Micro-scale hydropower plants (PLTA) play a strategic role because they are environmentally friendly, sustainable, and can efficiently utilize local water resources [1-4]. In this context, the Pelton turbine is one of the most widely used impulse turbine types in high-head and low-flow conditions due to its high kinetic energy conversion efficiency [5].

Pelton turbine performance is not only determined by the geometric design of the runner and blades, but is also significantly influenced by operational parameters, particularly the characteristics of the nozzle and flow control system. Recent research shows that nozzle optimization is a critical aspect in improving Pelton turbine efficiency, including nozzle diameter, nozzle angle, jet direction, and nozzle-blade spacing. [6] showed that the deviation of the nozzle jet direction from the blade pitch circle significantly affects the flow stability and efficiency of the Pelton turbine, making water jet alignment a crucial factor in turbine design and operation.

Theoretically, the working principle of the Pelton turbine is explained by the law of conservation of momentum, where a high-speed water jet is directed at the blade to produce impulse and torque. Maximum efficiency is generally achieved when the ratio of blade speed to jet speed is in the range of 0.46–0.50 [7-10]. A nozzle that is too close to the blade can cause the jet to develop incompletely, leading to splashing and energy loss. While a distance that is too far causes a decrease in kinetic energy due to air resistance before the jet hits the blade [11-13]. Recent experimental studies have also confirmed that suboptimal nozzle spacing can cause an uneven impulse force distribution on the blades and reduce turbine efficiency [14-15].

In addition to nozzle spacing, valve opening also affects the flow rate and pressure of water entering the nozzle, thus directly affecting the hydraulic power and output power of the turbine. [16] showed that variations in valve opening and nozzle diameter simultaneously have a significant effect on the torque and power of the Pelton turbine, while [17] reported that increasing valve opening is not always followed by an increase in efficiency, especially when the increase in flow rate does not produce optimal jet quality. In addition, other studies also highlight the importance of nozzle parameters, where [15] stated that variations in nozzle diameter have a significant effect on jet speed and Pelton turbine efficiency, while [18] showed that an inappropriate nozzle angle can reduce the effectiveness of jet impingement on the blades even though the flow rate increases. These research results indicate that nozzle parameters and valve openings play a significant role in Pelton turbine performance. However, the simultaneous relationship between nozzle spacing and valve openings in terms of power and efficiency characteristics based on energy transfer mechanisms still requires further study. Although various studies have examined the effects of head, flow rate, nozzle diameter, nozzle angle, and valve opening separately, those that comprehensively analyze the interaction between nozzle-blade spacing and valve opening simultaneously are still relatively limited. Therefore, optimization of these operational parameters remains a research gap that requires further experimental study.

Based on this description, this research focuses on analyzing the effects of variations in nozzle-blade spacing and valve openings on hydraulic power, turbine power, electrical power, and Pelton turbine efficiency, as well as determining the combination of operating parameters that produces optimal performance. The results of this study are expected to provide technical recommendations for improving the efficiency of laboratory-scale Pelton turbines in microhydro applications.

2 Research methodology

2.1 Tools and materials

Fig. 1 shows the Pelton turbine simulator used in this study, where the main component observed specifically in this study is the nozzle (item number 1), because the nozzle functions to convert fluid pressure energy into kinetic energy in the form of a high-speed water jet that directly affects the energy transfer process on the turbine blade. Other components that support the test system include a reservoir tank, jet pump, runner, flow control valve, pressure gauge, fitting, frame, and generator mount, which together, function as a support system for testing turbine performance.

The materials used in this study included the nozzle and runner. The nozzle was fabricated from Polylactic Acid (PLA) using a 3D printing method [3]. PLA was chosen for its ease of fabrication, good dimensional stability, and suitability for the experimental prototype. The runner was fabricated from acrylic using a laser-cutting method. Acrylic was chosen for its lightweight, corrosion-resistant properties, and for its ability to maintain its shape and structural strength during testing. The runner was manufactured by an external vendor in accordance with a predetermined design.

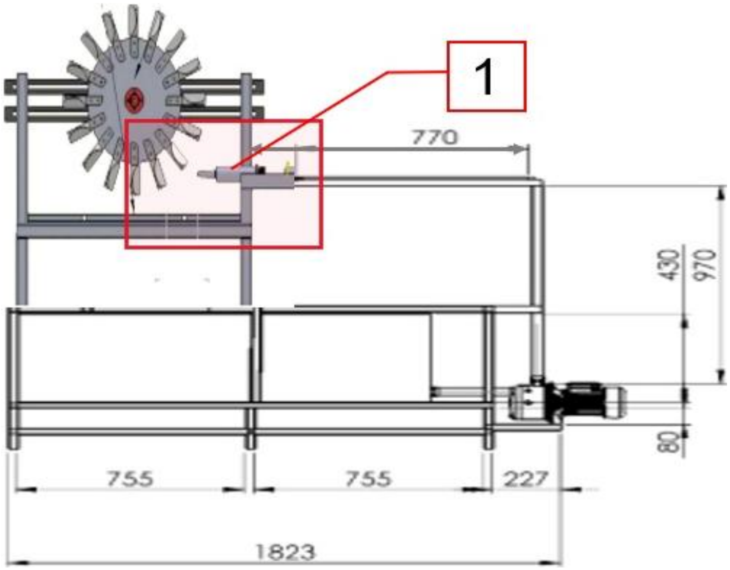

Fig. 1. Pelton turbine.

The measuring equipment used in this study included a tachometer, a multimeter, and a flowmeter. The tachometer measured the runner's rotational speed (rpm), which was used to determine the turbine's performance characteristics. The multimeter was used to measure the generator's voltage and current, thus calculating the electrical power. The flowmeter measured the water flow rate (Q), which is a key parameter in determining the hydraulic power and efficiency of the turbine.

The Pelton turbine in this study operates on the impulse principle, in which the kinetic energy of a water jet is converted into mechanical energy through changes in fluid momentum. Theoretically, the jet velocity exiting the nozzle and its interaction with the turbine blades can be analyzed using the velocity triangle concept. The nozzle-blade distance affects jet quality, the direction of the absolute velocity, and the energy loss before impact. Suboptimal nozzle distance can cause jet dispersion and reduce the effectiveness of energy transfer, thus affecting rotational speed, turbine power, and efficiency.

In this study, the test parameters used were variations in nozzle distance and valve opening. The nozzle distance variations used were 60 mm, 70 mm, and 80 mm, measured from the nozzle tip to the point of jet impact on the turbine blades. These variations were used to analyze the effect of changes in jet characteristics based on the principles of momentum transfer and the velocity triangle. Furthermore, the valve opening was varied to regulate the flow rate and the resulting jet characteristics. The combination of these two parameters was used to evaluate the performance characteristics of the Pelton turbine and determine operating conditions that produce optimum performance. The Fig. 2-Fig. 4 illustrates the variations in nozzle spray distance and valve opening angle.

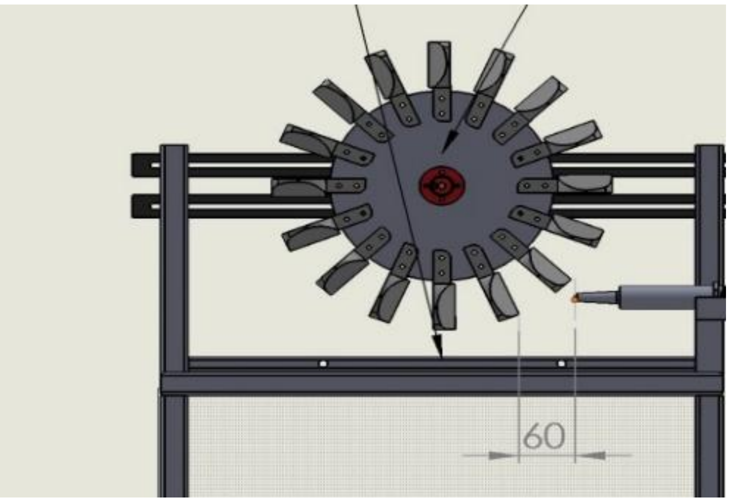

Fig. 2. Nozzle spray distance design 60 mm.

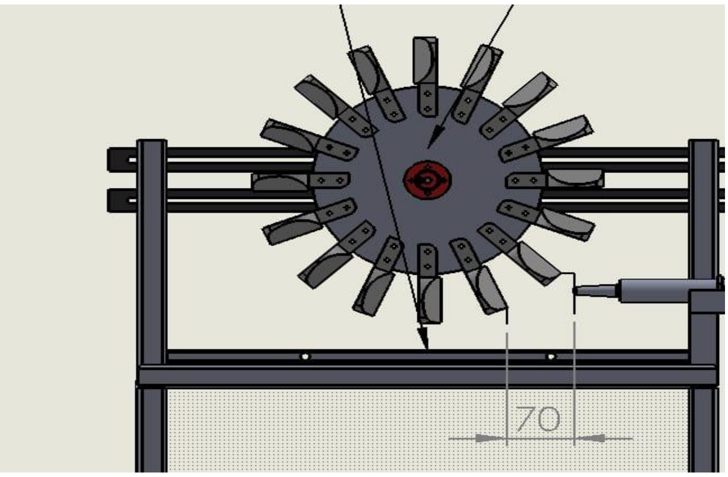

Fig. 3. Nozzle spray distance design 70 mm.

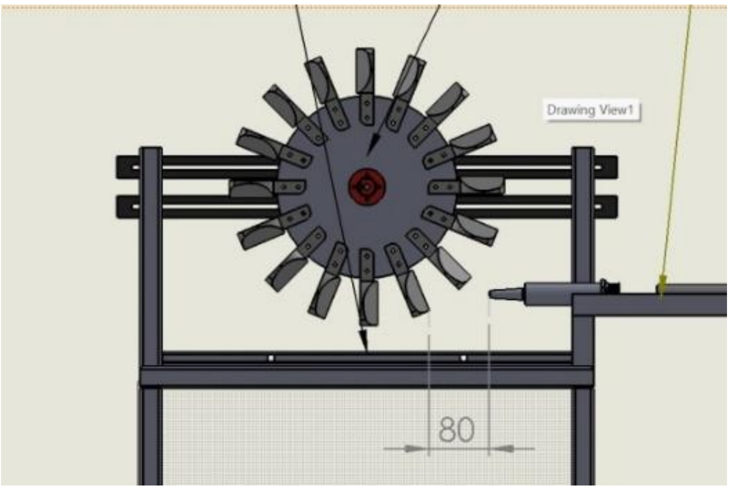

Fig. 4. Nozzle spray distance design 80 mm.

Theoretically, [19-20] the effect of nozzle spacing on Pelton turbine performance can be explained using velocity triangle analysis. The velocity of the water jet exiting the nozzle is expressed as Eq. (1):

$$V = \sqrt{2gH} \tag{1}$$

The kinetic energy transferred to the blade is influenced by the quality of the jet and the position of the nozzle relative to the blade. Optimal nozzle spacing maintains the jet at the appropriate speed and direction, allowing for maximum momentum transfer. Suboptimal spacing can result in energy loss due to jet dispersion before it reaches the blade.

The tangential velocity of the runner is expressed as Eq. (2), where V is runner tangential velocity (m/s), D is runner diameter (m), and N is runner rotation (rpm).

$$V = \frac{\pi \times D \times N}{60} \tag{2}$$

The relationship between jet velocity and runner speed can be analyzed using a velocity triangle. Maximum energy transfer occurs when the ratio of runner velocity to jet velocity is at its optimum. The nozzle distance affects the quality of the jet striking the blade, thus affecting the effective velocity and energy transfer.

Measurement uncertainty in this study was calculated based on the specifications of the measuring instruments. The tachometer has an uncertainty of ±1%, the multimeter ±0.5%, and the flowmeter ±2%. The electrical power uncertainty was calculated using the error propagation method (Eq. (3)).

$$\Delta P = P\sqrt{\left(\frac{\Delta V}{\mathrm{V}}\right)^2 + \left(\frac{\Delta I}{\mathrm{I}}\right)^2} \tag{3}$$

2.2 Research procedure

2.2.1 Testing process

The testing process in this study began by ensuring that all components of the Pelton turbine system were properly installed and functioning, including the pump, nozzle, runner, valve, and measuring instruments. The nozzle-to-runner distances were set at 60 mm, 70 mm, and 80 mm, while the valve openings were set at 30°, 60°, and 90°.

The nozzle distance variation was conducted to analyze its effect on the characteristics of the water jet impacting the runner blades, specifically on changes in the absolute and relative fluid velocity components based on the velocity triangle analysis of the impulse turbine. Changing the nozzle distance can affect jet quality, impact direction, and energy loss before impacting the blades, ultimately affecting momentum transfer and turbine power.

The valve opening variation was used to regulate the flow rate and water pressure entering the nozzle. However, in this study, the analysis focused not only on increasing the flow rate but also on its effect on energy conversion efficiency, as increasing the flow rate does not always result in increased efficiency due to potential disturbances in jet quality and inconsistencies with the turbine's optimum operating conditions.

During testing, the pump was operated to generate pressurized water flow through a nozzle. The water jet exiting the nozzle struck the runner blades, generating rotation. The runner rotational speed was measured using a tachometer, while the generator’s voltage and current were measured with a multimeter.

Testing was repeated for each combination of nozzle spacing and valve-opening variations to obtain accurate and representative data. The test data were then used to calculate the hydraulic, mechanical, and electrical power, and the efficiency of the Pelton turbine.

2.2.2 Data collection process

The data collection process was carried out systematically to ensure the accuracy and reliability of the test results. Prior to testing, all measuring instruments, such as the tachometer, flowmeter, pressure gauge, and multimeter, were checked to ensure proper functioning.

Each nozzle distance and valve opening variation was adjusted according to the specified test conditions. Flow rate was measured using a flowmeter, while water pressure was measured using a pressure gauge to determine available hydraulic energy.

The runner rotational speed was measured using a tachometer to determine the angular velocity of the shaft, which was then used to calculate mechanical power. The voltage and current generated by the generator were measured using a multimeter to calculate the electrical power generated by the turbine.

In addition, discharge measurements were confirmed using the V-notch method to improve data accuracy. The water level at the V-notch was recorded and used to calculate discharge based on the applicable empirical equation.

Each test was repeated three times for each variation to minimize random error and increase data reliability. The average value of the measurement results was used as the final data in the analysis.

The obtained data were then used in a data reduction process to calculate turbine performance parameters, including hydraulic power, shaft power, electrical power, and turbine efficiency.

The experimental data were used to calculate hydraulic power, electrical power, and turbine efficiency. Hydraulic power was calculated using Eq. (4), where P_h is hydraulic power (W), ρ is water density (kg/m³), Q is flow rate (m³/s), and H is head (m).

$$P_h = \rho g Q H \tag{4}$$

Electrical power was calculated using Eq. (5), where P_e is electrical power (W), V is voltage (Volt), I is current (Ampere).

$$P_e = VI \tag{5}$$

Turbine efficiency was calculated using Eq. (6). This equation was used to evaluate turbine performance.

$$\eta = \frac{P_e}{P_h} \times 100\% \tag{6}$$

3 Results and discussion

This research was conducted to analyze the effects of variations in nozzle distance and valve opening on the performance of the Pelton turbine, particularly on turbine rotation, hydraulic power, and electrical power generated, so that optimum operating conditions can be determined.

3.1 Turbine rotation results in relation to nozzle spray distance and valve opening

Turbine rotation is the primary parameter indicating the turbine's response to the kinetic energy of the water jet impacting the blades. Theoretically, turbine rotation is influenced by jet velocity and the tangential force generated by changes in fluid momentum. Jet velocity is determined by flow conditions influenced by valve opening, while nozzle spacing affects the quality of the jet before it hits the blades, as explained by an analysis of the velocity triangle in an impulse turbine. To analyze the influence of these two parameters, tests were conducted with varying nozzle spacings of 60 mm, 70 mm, and 80 mm and valve openings of 30°, 60°, and 90°. The results of the turbine rotation measurements are presented in Table 1.

Table 1. Turbine rotation in relation to nozzle spray distance and valve opening

Nozzle spray distance (mm)	Valve opening (%)	Turbine rotation result (rpm)
60	30°	450
	60°	490
	90°	500
70	30°	440
	60°	480
	90°	491
80	30°	431
	60°	464
	90°	477

Based on Table 1, it can be seen that turbine rotation is affected by variations in nozzle distance and valve opening. At a nozzle distance of 60 mm, rotation increases from 450 rpm to 500 rpm when the valve opening increases from 30° to 90°. This indicates that increasing the valve opening increases the flow rate, thereby increasing the jet momentum received by the blade. However, at longer nozzle distances, namely 70 mm and 80 mm, turbine rotation tends to decrease compared to the 60 mm distance. This condition indicates that nozzle distance affects jet quality. At too long a distance, the jet spreads and loses kinetic energy due to friction with the air before hitting the blade. This is in accordance with the Pelton turbine theory, where the resulting tangential force depends on changes in the tangential velocity component of the fluid in the velocity triangle. As jet quality decreases, the effective velocity component that produces rotation decreases as well. To clarify the relationships among nozzle distance, valve opening, and turbine rotation, the data in Table 1 is presented graphically in Fig. 5.

Fig. 5 shows that turbine rotation speed increases with increasing valve opening for each nozzle spacing. This occurs because a larger valve opening produces a higher flow rate, thereby increasing the fluid momentum transferred to the blades. However, increasing the nozzle spacing does not always result in higher rotation speed. The maximum rotation speed occurs at 60 mm, while at 80 mm it tends to be lower. This indicates that there is an optimal distance at which the jet still has maximum kinetic energy when it hits the blades. From a velocity triangle perspective, this condition indicates that the relative velocity component that effectively generates tangential force decreases as the jet loses energy before hitting the blades. Consequently, the resulting torque and turbine rotation speed also decrease. Therefore, it can be concluded that valve opening increases rotation speed by increasing fluid flow rate and momentum, while nozzle spacing determines the effectiveness of the jet's kinetic energy transfer to the blades. The combination of these two parameters significantly determines the rotation performance of the Pelton turbine.

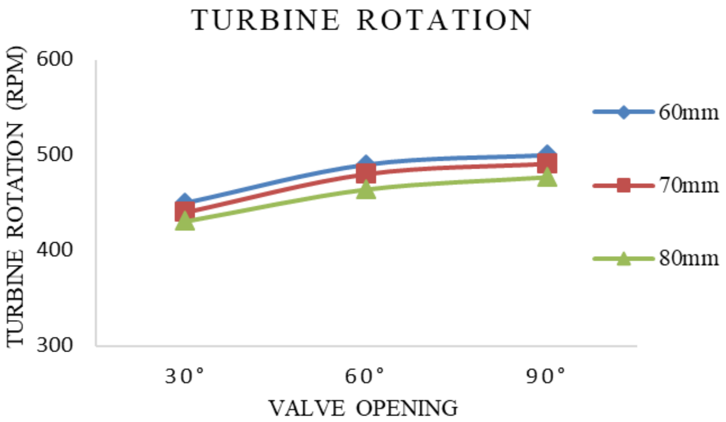

Fig. 5. Turbine rotation against nozzle spray distance and valve opening.

3.2 Hydraulic power results against nozzle spray distance and valve opening

Hydraulic power is the fluid energy available for conversion into mechanical energy in a turbine. Theoretically, hydraulic power is influenced by the flow rate and effective head, as expressed in Eq. (4).

In a Pelton turbine, hydraulic power is directly related to the kinetic energy of the jet exiting the nozzle. Valve opening affects the flow rate, while nozzle spacing affects jet quality and potential energy loss before the jet reaches the blades. The results of hydraulic power measurements for each variation are presented in Table 2.

Table 2. Hydraulic power results against nozzle spray distance and valve opening

Nozzle spray distance (mm)	Valve opening (°)	Hydraulic power (Watt)
60	30°	50.63
	60°	69.79
	90°	82.62
70	30°	45.63
	60°	58.79
	90°	75.62
80	30°	37.63
	60°	45.79
	90°	66.62

Based on Table 2, it can be seen that hydraulic power increases with increasing valve opening at each nozzle distance variation. For example, at a nozzle distance of 60 mm, hydraulic power increases from 50.63 Watts to 82.62 Watts when the valve opening increases from 30° to 90°. This occurs because a larger valve opening produces a higher flow rate, thereby increasing the fluid energy available to the turbine. However, at the same valve opening, hydraulic power decreases as the nozzle distance increases. For example, at a 90° opening, hydraulic power decreases from 82.62 Watts at a distance of 60 mm to 66.62 Watts at a distance of 80 mm. This shows that nozzle distance affects the effective head and jet quality. As the nozzle distance increases, the water jet spreads and experiences energy loss due to friction with the air, so the effective hydraulic energy available decreases. To clarify the relationships among nozzle distance, valve opening, and hydraulic power, the data in Table 2 are presented graphically in Fig. 6.

Fig. 6 shows that hydraulic power increases significantly with increasing valve opening across all nozzle spacing's. This is consistent with fluid flow theory, which states that a larger flow rate produces higher hydraulic energy. However, Fig. 6 shows that hydraulic power decreases with increasing nozzle spacing. This phenomenon indicates energy loss before the jet hits the blade. From the perspective of impulse turbine theory, the effective jet energy depends on the jet's velocity at the point of impact. If the jet loses energy due to dispersion, the kinetic energy available for conversion to mechanical energy will decrease. This indicates that while valve opening increases hydraulic power, excessive nozzle spacing can reduce the jet's effective energy, thus affecting overall turbine performance. Therefore, it can be concluded that valve opening directly increases hydraulic power by increasing the flow rate, while nozzle spacing affects the jet's energy available to the turbine.

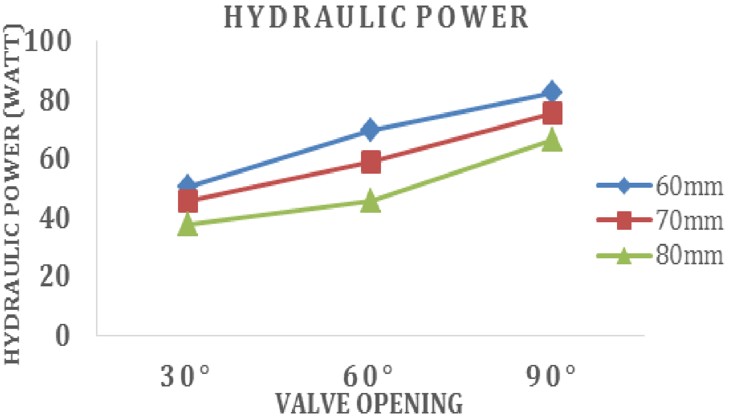

Fig. 6. Hydraulic power against nozzle spray distance and valve opening.

3.3 Electrical power results in relation to nozzle spray distance and valve opening

Electrical power is the end result of the energy conversion process in a Pelton turbine system: from hydraulic energy to mechanical energy, and then to electrical energy via a generator. Theoretically, electrical power depends on the mechanical power of the turbine and the efficiency of the generator, as stated Eq. (5).

The amount of electrical power is influenced by the kinetic energy of the jet received by the blades, which depends on jet quality, flow rate, and momentum transfer efficiency. Therefore, variations in nozzle spacing and valve opening will affect the electrical power generated. The results of the electrical power test are presented in Table 3.

Table 3. Results of electrical power against nozzle spray distance and valve opening

Nozzle spray distance (mm)	Valve opening (°)	Hydraulic power (Watt)
60	30°	8.34
	60°	8.46
	90°	9.14
70	30°	10.00
	60°	10.05
	90°	10.23
80	30°	10.43
	60°	10.50
	90°	10.58

Based on Table 3, it can be seen that electrical power increases with increasing valve opening and nozzle distance. The lowest value of 8.34 Watts was obtained at a nozzle distance of 60 mm and a valve opening of 30°, while the highest value of 10.58 Watts was obtained at a nozzle distance of 80 mm and a valve opening of 90°. The increase in electrical power due to increased valve opening occurs because the larger flow rate produces higher jet kinetic energy, thereby increasing the turbine's mechanical power and producing greater electrical power. In addition, increasing the nozzle distance to 80 mm increases electrical power, indicating that at that distance the jet has better quality when it hits the blade. A stable jet allows for more effective momentum transfer, thereby increasing the mechanical energy and electrical power produced. To clarify the relationships among nozzle distance, valve opening, and electrical power, the data are presented graphically in Fig. 7.

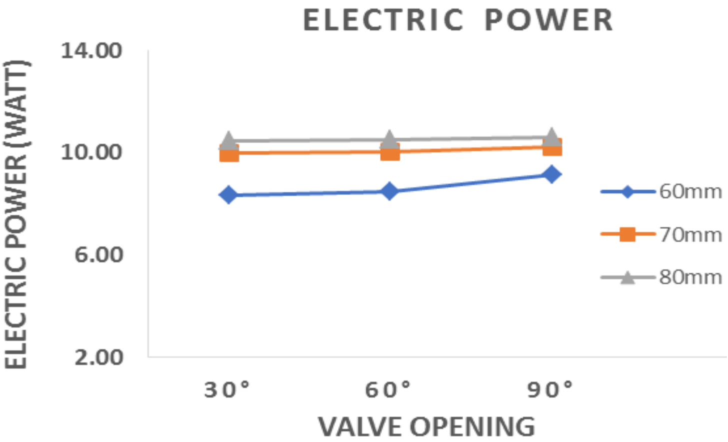

Fig. 7. Results of electrical power against nozzle spray distance and valve opening.

Fig. 7 shows that electrical power increases gradually with increasing valve opening and nozzle spacing. This indicates that increasing jet flow and quality increases the kinetic energy transferred to the blades. According to impulse turbine theory, the power generated depends on the change in the fluid’s momentum. When the jet hits the blades under optimal conditions, kinetic energy can be maximally converted into mechanical energy, which is then converted into electrical energy. This indicates that optimal nozzle spacing allows the jet to fully expand before hitting the blades, thereby increasing energy transfer efficiency.

3.4 Turbine power results against nozzle spray distance and valve opening

Turbine power is the mechanical energy generated by the runner due to the impact of the water jet. Theoretically, turbine power depends on the tangential force generated by changes in fluid momentum and blade velocity, as explained in the impulse turbine theory. The greater the jet's kinetic energy and the more effective the momentum transfer, the greater the turbine power generated. The results of the turbine power test are presented in Table 4.

Table 4. Turbine power results against nozzle spray distance and valve opening

Nozzle spray distance (mm)	Valve opening (°)	Hydraulic power (Watt)
60	30°	5.49
	60°	6.75
	90°	7.38
70	30°	9.15
	60°	9.88
	90°	10.36
80	30°	10.28
	60°	10.28
	90°	10.52

Based on Table 4, turbine power increases with increasing nozzle distance and valve opening. The lowest value of 5.49 Watts occurs at a nozzle distance of 60 mm and a valve opening of 30°, while the highest value of 10.52 Watts occurs at a nozzle distance of 80 mm and a valve opening of 90°. The increase in turbine power with increased valve opening occurs because the larger flow rate produces a greater impulse force on the blade. In addition, the increase in turbine power at a nozzle distance of 80 mm indicates that this distance allows the jet to reach optimal conditions before impinging on the blade, so that momentum transfer becomes more effective. To clarify the relationship between the variables, the data are presented graphically in Fig. 8.

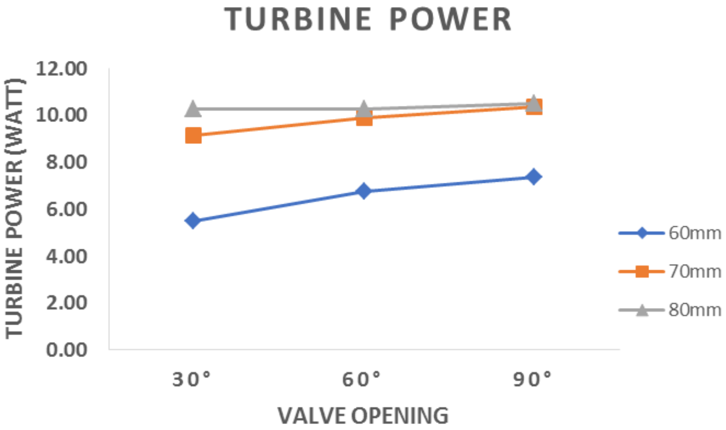

Fig. 8. Turbine power results against nozzle spray distance and valve opening.

Fig. 8 shows that turbine power increases with increasing valve opening and nozzle pitch. This indicates that jet quality and flow rate play a significant role in determining turbine power. In the Pelton turbine velocity triangle theory, maximum power occurs when the fluid’s momentum transfer is optimal. If the jet hits the blades at the appropriate direction and speed, kinetic energy can be maximally converted into mechanical energy. Therefore, nozzle pitch and valve opening are important parameters in determining turbine power performance.

3.5 Turbine efficiency results against nozzle spray distance and valve opening

Turbine efficiency indicates the turbine's ability to convert hydraulic energy into mechanical energy, mathematically as Eq. (6). Efficiency is influenced by jet quality, energy loss, and the effectiveness of momentum transfer. The results of the efficiency tests are presented in Table 5.

Table 5. Turbine efficiency results against nozzle spray distance and valve opening

Nozzle spray distance (mm)	Valve opening (°)	Turbine efficiency (%)
60	30°	50.63
	60°	69.79
	90°	82.62
70	30°	45.63
	60°	58.79
	90°	75.62
80	30°	37.63
	60°	45.79
	90°	66.62

Table 5 shows that turbine efficiency does not always increase with increasing valve opening. The highest efficiency occurs at a nozzle distance of 80 mm and a valve opening of 30%. However, when the valve opening is enlarged to 90%, efficiency tends to decrease. This indicates that increasing the flow rate does not always improve efficiency, as some energy can be lost due to turbulence and suboptimal jet distribution. To clarify the efficiency trend, the data are presented in Fig. 9.

Fig. 9 shows that efficiency has non-linear characteristics. Maximum efficiency occurs when the jet hits the blades optimally. If the flow rate is too high, some energy is lost to turbulence and kinetic energy. According to Pelton turbine theory, maximum efficiency occurs at a certain speed ratio between the jet and the blades. If this condition is not met, efficiency will decrease. This shows that the optimum condition does not always occur at maximum flow rate, but rather at the point where energy transfer is most effective.

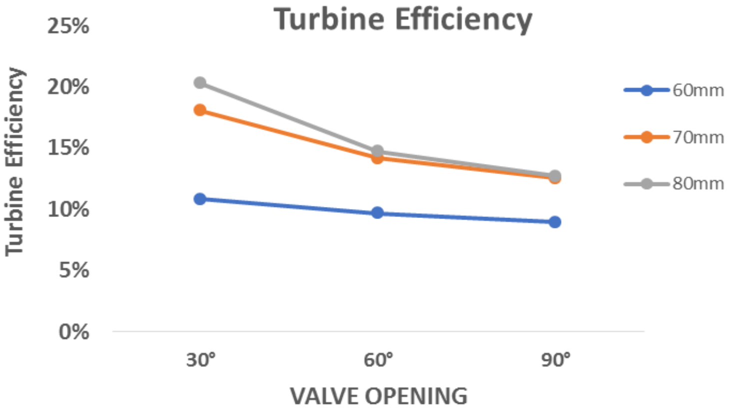

Fig. 9. Turbine efficiency results against nozzle spray distance and valve opening.

4 Conclusions

Based on the research results, it can be concluded that variations in nozzle spray distance and valve opening significantly affect the performance of the Pelton turbine. Increasing the valve opening tends to increase the flow rate, resulting in greater hydraulic, turbine, and electrical power. The optimum power condition is achieved at a spray distance of 80 mm with a valve opening of 90°, resulting in a turbine power of 10.52 Watts and an electrical power of 10.58 Watts. Meanwhile, turbine efficiency does not always increase with increasing valve opening; instead, it shows a non-linear pattern. The highest efficiency is obtained at a spray distance of 80 mm with a valve opening of 30°, which indicates that excessive flow can cause energy losses due to turbulence. Overall, the combination of a spray distance of 80 mm and a valve opening of 90° is recommended to obtain maximum power. In comparison, the best efficiency is obtained at a spray distance of 80 mm and a valve opening of 30°, making the results of this study a reference for the design and development of laboratory-scale Pelton turbines for micro-hydro power plant applications.

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