Analysis of the Effect of Bucket Width and Valve Opening on the Performance of a Microhydro Pelton Turbine

Satrya Dirga Agung Prasetyo[a], Alfian Stieven Khetie Errangga[b], Supardi[c]
[a,b,c]*Department of Mechanical Engineering, Universitas 17 Agustus 1945 Surabaya, Indonesia*

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ABSTRACT

The increasing demand for energy has encouraged the development of environmentally friendly renewable energy sources, one of which is hydropower through microhydro systems. This study aims to analyze the effect of bucket width and valve opening variations on the performance of a microhydro Pelton turbine in terms of turbine power, hydraulic power, and turbine efficiency. The research was conducted experimentally using a Pelton turbine with 25 buckets and a 9 mm nozzle diameter. The bucket width variations used were 44 mm, 48 mm, and 52 mm, while the valve opening variations consisted of 3 turns, 5 turns, and fully open conditions. The collected data included flow rate and turbine rotational speed, which were then used to calculate turbine power, hydraulic power, and turbine efficiency. The results showed that increasing the bucket width and valve opening had a positive effect on turbine performance. The highest turbine power was obtained at a bucket width of 52 mm under the fully open valve condition, reaching 4.964 W, while the lowest turbine power was recorded at a bucket width of 44 mm with 3 valve turns, amounting to 3.884 W. The highest hydraulic power was achieved under the fully open valve condition at 5.093 W, while the lowest hydraulic power occurred at 3 valve turns at 4.956 W. The highest turbine efficiency was obtained at a bucket width of 52 mm with the valve fully open, reaching 97.47%, whereas the lowest efficiency was recorded at a bucket width of 44 mm with 3 valve turns, amounting to 78.37%. Based on these results, it can be concluded that the combination of a 52 mm bucket width and a fully open valve represents the optimum operating condition, producing the best performance of the microhydro Pelton turbine.

1 Introduction

The availability of non-renewable energy resources has become a global concern due to the increasing demand that continues to deplete fossil fuel reserves. Therefore, numerous studies have focused on the development of renewable energy sources. Among the various types of renewable energy, hydropower has significant potential because of its sustainability and widespread availability. The conversion of water into renewable energy can be achieved through the use of hydraulic turbines, including the Pelton turbine, which harnesses the kinetic energy of flowing water.

One type of water turbine commonly utilized is the Pelton turbine. The Pelton turbine is a type of impulse turbine that utilizes high water head conditions, even with relatively low water discharge. This type of turbine operates by using a nozzle to produce a water jet, which is directed onto the turbine buckets, causing the turbine to rotate and subsequently drive the turbine shaft. The buckets are shaped like two cups and serve as the initial receiver of the water jet discharged from the nozzle. The application of a Pelton turbine can generate substantial power output while employing a relatively simple construction [1].

The Pelton turbine is a development of the impulse turbine, which was first introduced by S.N. Knight in 1872 and N.J. Colena in 1873. Its development was achieved by adding buckets to the turbine wheel. The turbine buckets are symmetrically designed and divided into two parts. This bucket design ensures that the water jet strikes the center of the bucket and is then deflected to both sides. As a result, the water flow can be redirected effectively while minimizing lateral forces acting on the bucket [2].

Pelton turbines are commonly applied in Microhydro Power Plants (MHPPs), where a nozzle is used to regulate the water jet that drives the turbine buckets. The rotational speed of the turbine is influenced by several critical parameters, including the distance and position of the nozzle, the nozzle diameter, the number of nozzles employed, and the design and geometric configuration of the turbine buckets [3].

This study aims to determine the bucket width that produces the highest efficiency in a Pelton turbine. The research was conducted by varying the bucket width and valve opening. Accordingly, three Pelton turbine bucket designs were prepared with bucket widths of 44 mm, 48 mm, and 52 mm, while the valve opening variations were set at 3 turns, 5 turns, and fully open. Through these variations, the study analyzes the bucket width and valve opening that produce the highest output characteristics, which in turn will affect the efficiency of the microhydro power plant (MHPP) prototype system.

2 Literature Study

Hydropower plants are electricity generation facilities that utilize the kinetic energy of flowing water to produce electrical power. The electricity generated by this type of power plant is known as hydroelectric power. The operating principle involves converting the potential energy of water, stored in reservoirs or obtained from waterfalls, into mechanical energy through the use of hydraulic turbines. This mechanical energy is subsequently converted into electrical energy by a generator and then transmitted through the available power distribution network [4].

A hydraulic turbine is a type of turbine that uses water as its working fluid. Water flows from a higher elevation to a lower elevation, converting its potential energy into kinetic energy as it passes through a penstock or pipeline. Inside the turbine, the kinetic energy of the water is transformed into mechanical energy, causing the turbine runner to rotate. The rotational motion is then transmitted to a generator to produce electrical energy.

As stated in [5], among the various types of water turbines, the Pelton turbine also known as a constant-pressure turbine, is one of the most significant and widely applied types. The Pelton turbine was first invented by Lester Allan Pelton in 1879 and was successfully tested. This turbine is primarily installed in mountainous areas, where water sources such as lakes or

Corresponding author: satryadirga795@gmail.com

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reservoirs are located several hundred meters above the turbine unit.

The Pelton turbine is designed to operate under high-head conditions with relatively low water discharge. Its working principle involves the use of a nozzle to produce a water jet directed toward the turbine buckets. The interaction between the water jet and the buckets causes the turbine to rotate, thereby converting the kinetic energy of the water into mechanical energy to drive a generator and produce electrical power. The application of the Pelton turbine in power generation can produce significant power output with a relatively simple construction.

Figure 1. Pelton Turbine

According to the study conducted by Oktavianus [4], a Pelton turbine consists of a series of buckets driven by high-velocity water jets discharged through one or more nozzles. Each bucket has a symmetrical double-cup geometry separated by a central splitter. This design enables the water jet to strike the center of the bucket and then divide into two equal streams that flow in opposite directions. As a result, the water undergoes an efficient change in momentum while minimizing lateral forces acting on the buckets, thereby improving the turbine's operational stability and energy conversion efficiency.

The Pelton turbine converts the potential energy of water into mechanical energy through the impulse principle acting on the turbine runner. The turbine runner rotates when the water jet strikes its buckets. Water discharged from the nozzle impinges on the turbine buckets, causing the turbine runner to rotate. This rotational motion then drives the turbine pulley, which is connected to the generator pulley through a belt, enabling the generator to operate [1].

The increase in flow rate is influenced by the valve opening, which affects the resulting rotational speed. This phenomenon indicates a proportional relationship between fluid velocity and the rotational speed of the Pelton turbine. The use of a small-diameter nozzle with a fully open valve produces a high fluid velocity, which in turn increases the turbine rotational speed [6].

The bucket width in a Pelton turbine has a direct correlation with the rotational speed of the unit (RPM). This is because the bucket width determines the exposure area to the water jet flow as well as the amount of momentum transferred. Buckets with larger dimensions tend to capture a greater amount of the water's kinetic energy, resulting in an increase in tangential force and torque. This increase, in turn, contributes to a higher turbine rotational speed and the optimization of its efficiency [7].

Based on the study conducted by Saputra [1], an increase in the number of buckets on a Pelton turbine runner will enhance the momentum force received by the buckets. This leads to an increase in turbine rotational speed, which in turn improves the overall system efficiency.

Research reported in [8] also indicates that the number of buckets has an effect on electrical energy production. An increase in the number of buckets is positively correlated with an increase in the amount of electrical energy generated.

3 Methodology

This study employed an experimental research method, involving empirical testing to obtain the data required for analysis. The experiment focused on the development and testing of a microhydro Pelton turbine, with particular emphasis on variations in bucket width and valve opening to evaluate their effects on turbine performance and power output. The data collection process was carried out through a series of systematic experimental procedures.

The research procedure consisted of several essential stages, including the preparation of equipment and materials, turbine performance testing, data acquisition, and data processing and analysis. The theoretical framework underlying this study was established through an extensive review of relevant literature. After the experimental data had been collected and analyzed, the results were interpreted in relation to the research problem, the objectives of the study, and the theoretical framework that served as the basis for the analysis.

The experiment was conducted using a laboratory-scale Pelton turbine with the following specifications :

- Head (H) = 1.8 m
- Nozzle Diameter (d) = 9 mm
- Runner Diameter (D) = 20 cm
- Bucket Angle = 175°
- Bucket Height = 2.88 cm
- Bucket Splitter Width = 1.32 cm
- Number of Buckets = 25
- Bucket Width = 44, 48, 52 mm
- Bucket Depth = 9.7 mm
- Valve Opening = 3 turns, 5 turns, fully open
- Shaft Diameter = 12 mm

The procedure began by setting the desired blade width and valve opening on the prototype. The pump was then turned on to supply water to the upper reservoir so that a constant falling water flow could be maintained. After stable flow conditions were achieved, the flow rate and turbine rotational speed were measured simultaneously for one minute. The measurements were repeated three times for each parameter combination.

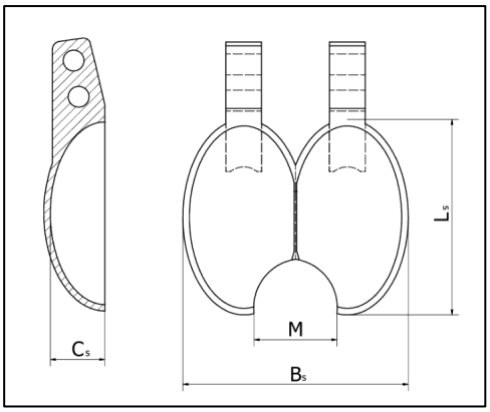

Figure 2. Desain Bucket Pelton Turbine

Corresponding author: satryadirga795@gmail.com
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Figure 4. Bucket Width 44 mm

Figure 5. Bucket Width 48 mm

Figure 6. Bucket Width 52 mm

Figure 7. Globe Valve For Opening Valve

Figure 8. Runner Pelton Turbine

Figure 3. Experimental Testing of the Pelton Turbine

3.1 Equations

1. Runner Rotational Speed (U_1)

To determine the runner diameter, the runner rotational speed is first calculated using the following equation:

$$U_1 = U_2 = \frac{\pi . D . n}{60} \quad (1)$$

Where:

$U_1 = Runner\ rotational\ speed\ (m/s)$
$D = Runner\ diameter\ (m)$
$n = Turbine\ rotational\ speed\ (rpm)$

2. Cross-Sectional Area of the Water Jet

The cross-sectional area of the water jet at the nozzle is calculated using the following equation:

$$A = \frac{1}{4} . \pi . d^2 \quad (2)$$

Where:

$A = Water\ jet\ area\ (m^2)$
$d = Nozzle\ diameter\ (m)$

3. Volumetric Flow Rate

According to Tarigan [9], the flow rate can be calculated using Equation (3).

$$Q = A . v \quad (3)$$

Where:

$Q = Water\ flow\ rate\ (\frac{m^3}{s})$
$v = Jet\ Velocity\ \left(\frac{m}{s}\right)$

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4. Velocity Triangle

Based on [10] the bucket dimensions of the turbine, a bucket rotation angle of 175° was obtained, resulting in an outlet bucket angle of 5°. Therefore, preliminary calculations were carried out, including the following:

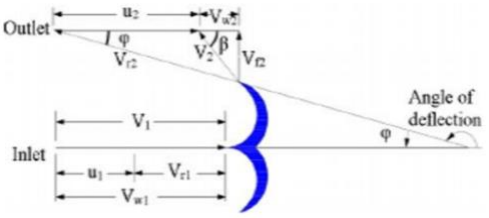

Figure 9. Velocity Triangle

$$V_1 = V_{w1} = \frac{Q}{A} \quad (4)$$

$$V_{r1} = V_{r2} = V_1 - U_1 \quad (5)$$

$$V_{w2} = V_{r2}\,.\,Cos\,\varphi - U_2 \quad (6)$$

Where :

$V_1 = Absolute\ water\ inlet\ velocity\ \left(\frac{m}{s}\right)$

$V_{r1} = Relative\ nozzle\ velocity\ to\ bucket\ at\ inlet\ side\ \left(\frac{m}{s}\right)$

$V_{w1} = Inlet\ whirl\ velocity\ \left(\frac{m}{s}\right)$

$V_2 = Absolute\ water\ inlet\ velocity\ \left(\frac{m}{s}\right)$

$V_{r2} = Relative\ nozzle\ velocity\ to\ bucket\ at\ outlet\ side\ \left(\frac{m}{s}\right)$

$V_{w2} = Inlet\ whirl\ velocity\ \left(\frac{m}{s}\right)$

$V_{f2} = Relative\ nozzle\ velocity\ to\ bucket\ at\ oulet\ side\ \left(\frac{m}{s}\right)$

$\varphi =$: Bucket angle(°)

5. Force Acting on the Turbine Buckets

The force acting on the turbine can be calculated using Equation (7).

$$F = \rho.Q.V_{w1} - V_{w2} \quad (7)$$

Where:

$F = The\ force\ acting\ on\ the\ turbine\ buckets\ (N)$

$\rho =$ Density of water $(1000\ \frac{kg}{m^3})$

$V_{w1} = Inlet\ whirl\ velocity\ \left(\frac{m}{s}\right)$

$V_{w2} = Inlet\ whirl\ velocity\ \left(\frac{m}{s}\right)$

6. Turbine Torque

The turbine torque can be calculated using Equation (8).

$$T = F.r \quad (8)$$

Where:

$T = Turbine\ torque\ (Nm)$

$r = Runner\ radius\ (m)$

7. Angular Velocity

The angular velocity can be calculated using Equation (9).

$$\omega = \frac{2.\pi.n}{60} \quad (9)$$

Where:

$\omega = Angular\ velocity\ \left(\frac{rad}{s}\right)$

$n = Turbine\ rotational\ speed\ (rpm)$

8. Turbine Power

According to Mafrudin [11], the turbine power can be calculated using Equation (10).

$$P_t = T.\omega \quad (10)$$

Where:

$P_t = Turbine\ power\ (Watt)$

$T = Turbine\ torque\ (Nm)$

$\omega = Angular\ velocity\ \left(\frac{rad}{s}\right)$

9. Hydraulic Power

The hydraulic power can be calculated using Equation (11).

$$P_h = \rho.g.Q.H \quad (11)$$

Where:

$P_h = Hydraulic\ power\ (Watt)$

$Q = Water\ flow\ rate\ \left(\frac{m^3}{s}\right)$

$\rho =$ Density of water $(1000\ \frac{kg}{m^3})$

$g = Gravitational\ acceleration (9{,}81 \frac{m}{s^2})$

$H = Head\ (m)$

10. Turbine Efficiency

The turbine efficiency can be calculated using Equation (12).

$$\eta_s = \frac{P_t}{P_h} x100\% \quad (12)$$

Dimana:

$\eta_s = Turbine\ efficiency\ (\%)$

$P_t = Turbine\ power\ (Watt)$

$P_h = Hydraulic\ power\ (Watt)$

3.2 Table

Tabel 1. Experimental Results for the 44 mm Bucket Width

Variation				Testing	Value	
Number of Buckets	Nozzle Diameter (mm)	Bucket Width (mm)	Valve		Debit (Q)	Turbine Rpm
25	9	44	3	Test 1	16,8	252
				Test 2	16,8	249
				Test 3	16,8	252
				Average	16,8	251
			5	Test 1	17,1	260
				Test 2	17,1	257
				Test 3	17,1	260
				Average	17,1	259
			Full	Test 1	17,3	266
				Test 2	17,3	263
				Test 3	17,3	266
				Average	17,3	265

Corresponding author: satryadirga795@gmail.com
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Tabel 2. Experimental Results for the 48 mm Bucket Width

Variation				Testing	Value	
Number of Buckets	Nozzle Diameter (mm)	Bucket Width (mm)	Valve		Debit (Q)	Turbine Rpm
25	9	48	3	Test 1	16,8	258
				Test 2	16,8	261
				Test 3	16,8	261
				Average	16,8	260
			5	Test 1	17,1	266
				Test 2	17,1	268
				Test 3	17,1	270
				Average	17,1	268
			Full	Test 1	17,3	272
				Test 2	17,3	271
				Test 3	17,3	273
				Average	17,3	272

Tabel 3. Experimental Results for the 52 mm Bucket Width

Variation				Testing	Value	
Number of Buckets	Nozzle Diameter (mm)	Bucket Width (mm)	Valve		Debit (Q)	Turbine Rpm
25	9	52	3	Test 1	16,8	268
				Test 2	16,8	265
				Test 3	16,8	268
				Average	16,8	267
			5	Test 1	17,1	277
				Test 2	17,1	274
				Test 3	17,1	277
				Average	17,1	276
			Full	Test 1	17,3	281
				Test 2	17,3	278
				Test 3	17,3	281
				Average	17,3	280

Tabel 4. Calculated Results of Pelton Turbine Efficiency

Variation				Value		
Number of Buckets	Nozzle Diameter (mm)	Bucket Width (mm)	Valve Opening	Turbine Power (Watt)	Hydraulic Power (Watt)	Turbine Efficiency (%)
25	9	44	3	3,884	4,956	78,37
			5	4,204	5,038	83,44
			full	4,449	5,093	87,35
		48	3	4,166	4,956	84,06
			5	4,499	5,038	89,3
			full	4,688	5,093	92,04
		52	3	4,392	4,956	88,62
			5	4,771	5,038	94,7
			full	4,964	5,093	97,47

4 Discussion

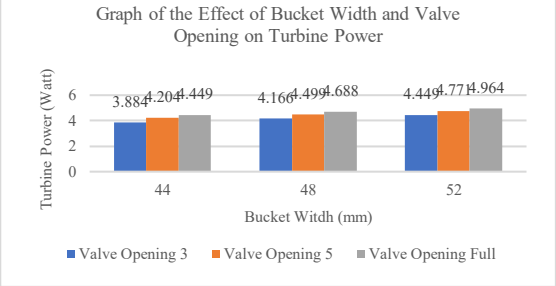

Figure 10. Graph of the Effect of Bucket Width and Valve Opening on Turbine Power

Based on the graph showing the effect of bucket width and valve opening on turbine power, turbine power increases as both bucket width and valve opening increase. For every valve opening, the 52 mm bucket width produced higher turbine power than the 48 mm and 44 mm bucket widths. This indicates that a wider bucket can capture the water jet more effectively, resulting in greater turbine power.

At the 3-turn valve opening, the turbine power was relatively low because the water flow rate entering the nozzle had not reached its maximum value. When the valve opening was increased to 5 turns, turbine power increased for all bucket width variations due to the higher water flow rate and the greater energy received by the buckets.

The highest turbine power was obtained with a 52 mm bucket width and the valve fully open, reaching 4.964 W. Meanwhile, the lowest turbine power was recorded with a 44 mm bucket width and a 3-turn valve opening, amounting to 3.884 W. These results indicate that a wider bucket combined with a larger valve opening provides better energy transfer, thereby increasing the power output of the microhydro Pelton turbine.

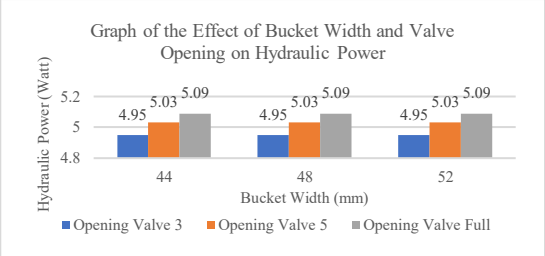

Figure 11. Graph of the Effect Bucket Width and Valve Opening on Hydraulic Power

Based on the graph showing the effect of bucket width and valve opening on hydraulic power, hydraulic power increases as the valve opening becomes larger, while bucket width has no significant effect. This is because hydraulic power mainly depends on the water flow rate and head. Therefore, the hydraulic power values for bucket widths of 44 mm, 48 mm, and 52 mm at the same valve opening are nearly identical.

At the 3-turn valve opening, the hydraulic power was the lowest at approximately 4.956 W. When the valve opening was increased to 5 turns, the hydraulic power increased to about 5.038 W, and reached its highest value of 5.093 W when the valve was fully open. This shows that a larger valve opening allows more water to flow through the nozzle, resulting in greater hydraulic energy available to drive the turbine.

These results indicate that valve opening is the main factor affecting hydraulic power because it controls the water flow rate entering the turbine. In contrast, bucket width mainly affects how efficiently the available hydraulic energy is converted

Corresponding author: satryadirga795@gmail.com

Doi : 10.30996/elsains.v8i1.133679

into mechanical turbine power, rather than changing the hydraulic power itself.

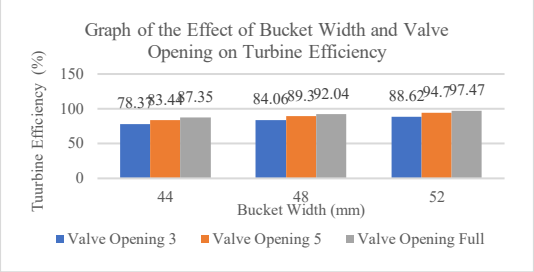

Figure 12. Graph of the Effect of Bucket Width and Valve Opening on Turbine Efficiency

Based on the graph showing the effect of bucket width and valve opening on turbine efficiency, turbine efficiency increases as both bucket width and valve opening increase. Under all test conditions, the 52 mm bucket width produced the highest efficiency, followed by the 48 mm and 44 mm bucket widths. This indicates that a wider bucket can utilize the water jet more effectively, resulting in higher turbine efficiency.

At the 3-turn valve opening, turbine efficiency was at its lowest because the water flow rate entering the turbine was not yet optimal. When the valve opening was increased to 5 turns, efficiency increased for all bucket width variations. This shows that a higher water flow rate improved the energy transfer from the water jet to the buckets.

The highest efficiency was obtained with a 52 mm bucket width and the valve fully open, reaching 97.47%, while the lowest efficiency was recorded with a 44 mm bucket width and a 3-turn valve opening, amounting to 78.37%. These results indicate that a larger bucket width combined with a fully open valve provides the optimum operating condition for the microhydro Pelton turbine and improves its ability to convert hydraulic energy into mechanical energy.

5 Conclusion

This study shows that bucket width and valve opening are important parameters affecting the performance of a microhydro Pelton turbine, particularly turbine power, hydraulic power, and efficiency. The experimental results indicate that a wider bucket captures the water jet more effectively, while a larger valve opening provides a higher water flow rate and greater hydraulic energy. The combination of these two parameters determines the effectiveness of converting hydraulic energy into mechanical energy.

A key contribution of this study is demonstrating that improving Pelton turbine performance depends not only on controlling the water flow rate but also on selecting an appropriate bucket width. A properly designed bucket can receive and utilize the water jet more effectively, leading to better energy transfer. This shows that both geometric and operating parameters should be considered together to achieve better turbine performance.

Based on the experimental results, a **52 mm** bucket width with the valve fully open provided the optimum operating condition under the present test configuration. Therefore, the design and development of laboratory-scale and small-scale microhydro Pelton turbines should optimize bucket width and valve opening simultaneously. The findings of this study can serve as a useful reference for the design, development, and optimization of simple, low-cost, and efficient microhydro Pelton turbine systems.

Author Contributions

The first and second authors were involved in all stages of the research, including conceptualization, methodology, instrument development and validation, data collection, data processing, formal analysis, and manuscript preparation. The third author served as the academic supervisor, providing strategic guidance, constructive feedback, supervision, and continuous evaluation throughout the research process. This role included optimizing the methodological approach, interpreting the research findings, and critically reviewing and substantially revising the manuscript.

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Corresponding author: satryadirga795@gmail.com
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