International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I12P105

Volume 72 Issue 12, 55-63, December 2024

Original Article

Improving Turbine Performance by Optimizing Nozzle Design

Mafruddin[1], Sulis Dri Handono[2], Dwi Irawan[3], Kemas Ridhuan[4]

[1,2,3,4]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Muhammadiyah Metro, Indonesia.*

[1]*Corresponding Author : mafruddinmn@gmail.com*

Received: 03 September 2024 Revised: 06 November 2024 Accepted: 22 November 2024 Published: 25 December 2024

Abstract *- Microhydropower plants are a solution to overcome the energy crisis, and they are efficient and environmentally friendly renewable energy sources. The choice of cross-flow turbine in micro hydro was based on a simple design but could produce excellent performance in various workload variations. The turbine performance assessment was based on the power and efficiency produced by the turbine, and nozzle design played an important role. An optimal design ensures the water flow enters at the precision angle and speed, producing maximum impulse force on the turbine blades. The research aims to optimize the nozzle design and observe the flow characteristics in the turbine to improve the performance of the Cross-flow turbine. An experimental tested the turbine using a base nozzle design and optimizing the nozzle entry arc and nozzle throat width designs at 225, 200 and 175 L/min water flows. The research results concluded that the flow characteristics in the turbine could be a reference for developing nozzle design to improve turbine performance. The findings from the research show that the suitability of the nozzle entry arc affects the angle of attack so that it can increase turbine efficiency by 9.3%, and optimizing the narrower nozzle throat width design increases momentum so that turbine efficiency increases by 35.6% from the base design of the turbine nozzle. The increment in turbine performance shows the success of research in maximizing Cross-flow turbines' role in overcoming the environmental energy crisis.*

Keywords *- Nozzle entry arc, Nozzle throat width, Flow character, Cross-flow turbine performance, Optimizing Nozzle.*

1. Introduction

Hydropower is one of the most commonly used renewable sources and the most efficient electricity generator [1],[2]. Hydropower accounts for 17-17.3% of the world's electricity and 68.7% of total renewable electricity production, positioning it as an up-and-coming solution to electricity shortages [3],[4],[5]. Hydroelectric power plants generally use Cross-flow turbines to convert water energy into mechanical energy [6]. The Cross-flow turbine is a type of turbine that is not only easy to design and manufacture but also has an efficiency of 66-90% [7],[8],[9],[10]. Cross-flow turbines are a highly efficient and economical option, allowing an excellent energy production cost-benefit ratio [11]. Cross-flow turbines have simple construction and good efficiency under various load conditions [7]. The main components of a Cross-flow turbine are the nozzle and runner [12]. The nozzle shape, the runner blades angle and the number of runner blades influence the performance and internal flow of the turbine [13]. The inlet nozzle's relatively narrow shape positively influences turbine performance [14]. Apart from that, the nozzle angle affects the performance of the Cross-flow turbine [15]. Computational Fluid Dynamics simulation indicated that there are parameters that can increase the performance of the Cross-flow turbine, such as number of blades, nozzle angle, diameter ratio, nozzle profile, blade profile and nozzle width [16]. Other numerical research with variations in nozzle design, guide vane angle and number of blades shows that nozzle design affects turbine performance [7]. The nozzle inlet arc angle design also affects the Cross-flow turbine performance [17]. An optimal alignment between the inlet and outlet angle of the flow entry blade can significantly improve the Cross-flow turbine performance [18]. Experimental research can be carried out to determine the electrical power generated by the turbine and its rotational speed. However, numerical method simulation research makes it easier to observe the appropriate pressure field and water velocity [19]. Several previous studies have shown that nozzle design improves turbine performance. Under real conditions, water discharge often changes, so observations need to be made regarding discharge variations in turbine performance. Discharge variation is important to ensure that nozzle design optimization can adjust to flow fluctuations and other conditions. This study analysed the dimensional parameters of the Cross-flow turbine to assess flow characteristics along with rotational speed, torque, power, and turbine efficiency using an experimental method with variations in water discharge: 225, 200, and 175 liters per minute. The study aimed to improve Cross-flow turbine performance by optimizing parameters such as the nozzle's entry arc and throat width. The turbine was constructed from transparent material to facilitate observation of the flow characteristics. The results obtained from observations of the water flow characteristics in the turbine served as the basis for analyzing the factors that affect turbine performance and provided new insights into the optimal nozzle design for Cross-flow turbines, contributing significantly to the development of renewable energy technology. Therefore, optimizing the nozzle design (entry arc and throat width of the nozzle) plays an important role in developing micro-hydro power plants as a solution for environmentally friendly and sustainable renewable energy sources.

2. Review of Related Literature

The water resources used will affect the dimensions of the turbine. The following equation is used to design the LD_1 runner [12].

$$LD_1 = \frac{2.63\ Q}{\sqrt{H}} \tag{1}$$

where, L is the width of the runner (m), Q is water discharge (m^3/s), and H is head (m). Comparison of inner diameter of runner D_2 (m) and outer diameter of runner D_1 (m) [4],[20].

$$D_2 = 0.68\ D_1 \tag{2}$$

The following equation determines the nozzle throat width (So) [16].

$$So = 0.2.\ D_1 \tag{3}$$

The following equation determines the distance between the blades (t_1) [12].

$$t_1 = 0.175.\ D_1 \tag{4}$$

The blade radius (r) can be determined from the equation [12].

$$r = 0.163.\ D_1 \tag{5}$$

The following equation determines the number of runner blades (nb) [12].

$$nb = \frac{\pi\ .\ D_1}{t_1} \tag{6}$$

Turbine efficiency is theoretically determined using the following equation [4],[12],[16],[21];

$$\eta_t = 0.5.\ C^2\ .\ (1+\psi)\ cos^2\ \alpha \tag{7}$$

where, α is the angle of attack, ψ is the coefficient of the roughness of the blade (0.98), C is the roughness parameter of the nozzle (0.95–0.99). Assessment of turbine performance was based on its power and efficiency. Turbine efficiency is the ratio of the power delivered by water to mechanical power [3]. Cross-flow turbine power is determined using equation [22]:

$$P_t = \omega\ .T \tag{8}$$

where, P_t is the turbine power (watt), T is the torque on the turbine shaft (N.m), and ω is the angular velocity (rad/s) [23].

The angular velocity ω is calculated using the equation [7]:

$$\omega = \frac{2\ .\ \pi\ .\ n}{60} \tag{9}$$

where, n is the turbine rotation speed (rpm)

Water power is determined using the following equation [24].

$$P_{in} = \rho\ .g\ .H_{nett}.Q \tag{10}$$

where, P_{in} is water power (watt), g is gravity (m/s^2), ρ is the water density (kg/m^3), and H_{nett} is an effective head (m).

Turbine efficiency is determined using the following equation [25].

$$\eta = \frac{P_t}{P_{in}}\ x\ 100\% \tag{11}$$

3. Materials and Methods

3.1. Turbine Specifications

The potential of water resources used for the basic dimension planning of the Cross-flow turbine includes a head of 3 m and a discharge of 375 L/min. A laboratory scale was selected to facilitate the manufacturing and testing process. Figure 1. shows the Cross-flow turbine design. Nozzle optimisation was based on the design, as shown in Figures 2 and 3. The turbine is made from a transparent synthetic polymer material (*Polymethyl methacrylate*). The base dimensional specifications of the Cross-flow turbine are shown in Table 1.

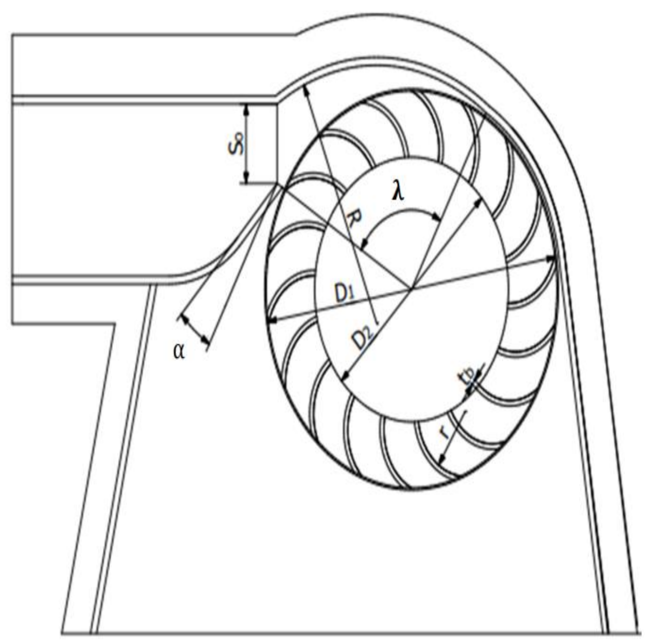


Fig. 1 Cross-flow turbine design

Table 1. Cross-flow turbine geometric parameter values

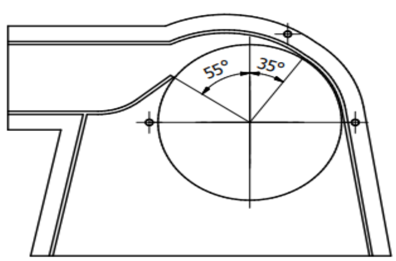
Variables	Value
Outer Diameter (D_1)	150 mm
Inner Diameter (D_2)	102 mm
Nozzle Entry Arc (λ)	90º
Nozzle Throat Width (So)	30 mm
Angle of attack(α)	15º
Rear-wall nozzle (R)	97.5 mm
Blade Radius (r)	24 mm
Number of Blade (nb)	18
Blade Thickness (tb)	2 mm
Shaft Dia	10 mm

3.2. Research Methods

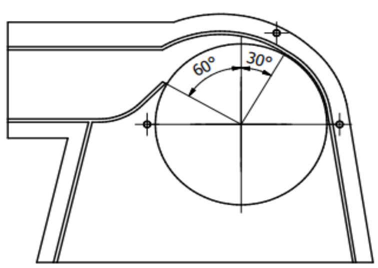
The research utilized experimental methods by designing and manufacturing a Cross-flow turbine and then testing its performance, including rotation, torque, and turbine power. The turbine was manufactured based on the base and optimized nozzle designs. It was tested with water discharge variations of 225, 200, and 175 liters per minute (L/min) and an effective head of 0.5 m.

3.3. Turbine Nozzle Design Optimization

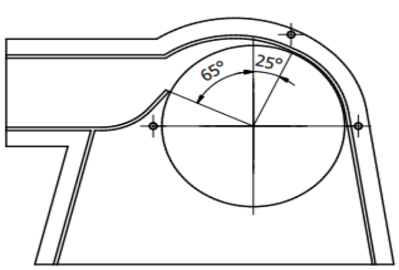
3.3.1. Nozzle Entry Arc (λ)



λ1 = 55º & 35º



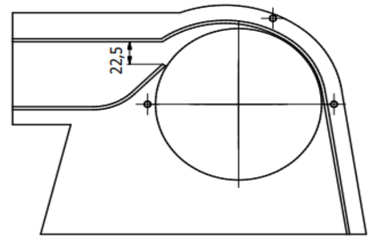
λ_2 = 60º & 30º (Base)



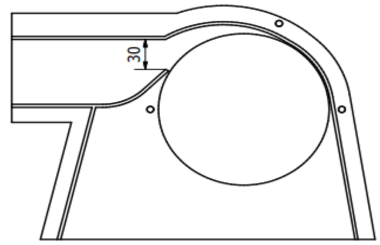
λ_3 = 65º & 25º

Fig. 2 Optimization of nozzle entry arc (λ) design

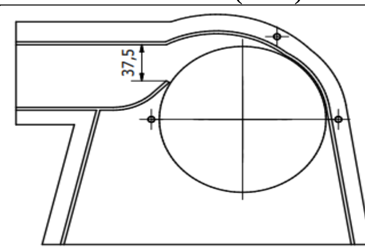
3.3.2. Nozzle Throat Width (S_o)



So1= 22.5 mm



So2 = 30 mm (Base)



So3 = 37.5 mm

Fig. 3 Optimization of nozzle throat width (S_o) design

3.4. Turbine Test Scheme

The turbine installation scheme is shown in Figure 4. Turbine testing was made by making water resources by delivering water from the reservoir to the forebay tank. Before entering the turbine, the water discharge from the forebay tank was measured by a flowmeter. The turbine's water will enter the reservoir and then be delivered to the forebay tank. This cycle will continue throughout the turbine testing process.

3.5. Turbine Testing Procedures

The turbine was tested using the braking method with a dynamometer to determine the turbine's torque. Braking was applied to the turbine shaft connected to the dynamometer. This braking created a load on the turbine up to a specific rotation, and torque was recorded by a force meter on the dynamometer. The torque and angular speed of the turbine were calculated to determine its power and efficiency. The water power was calculated based on discharge and effective head. Testing of turbine flow characteristics involved capturing images with a camera with specifications of 64 MP, 26mm (wide), 0.8µm, f/1.9, 1/1.72", and phase detection autofocus (PDAF). The resulting images were analyzed to observe the turbine flow characteristics, which provided insights for further development of turbine design.

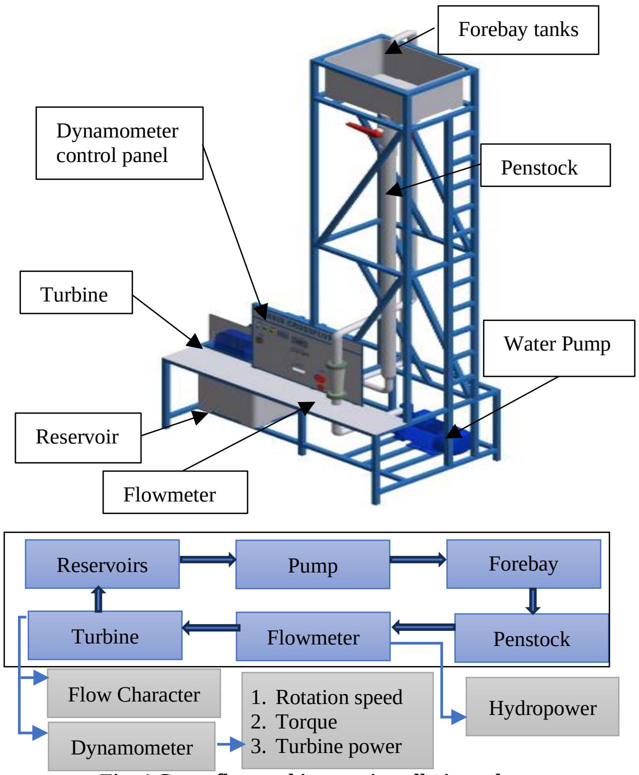


Fig. 4 Cross-flow turbine test installation scheme

4. Results and Discussion

4.1. Turbine Rotation

Results of the test of turbine maximum rotation by discharge variations are shown in Figure 5. Figure 5 shows that nozzle design affects the turbine's maximum rotation. Maximum rotation occurs without a braking load on the dynamometer. An optimum rotation of 418 rpm was obtained with the S_{o1} nozzle design at a water discharge of 225 L/min, making it the best nozzle design. Figure 5 also shows that water discharge affects turbine rotation: the smaller the water discharge, the lower the turbine rotation.

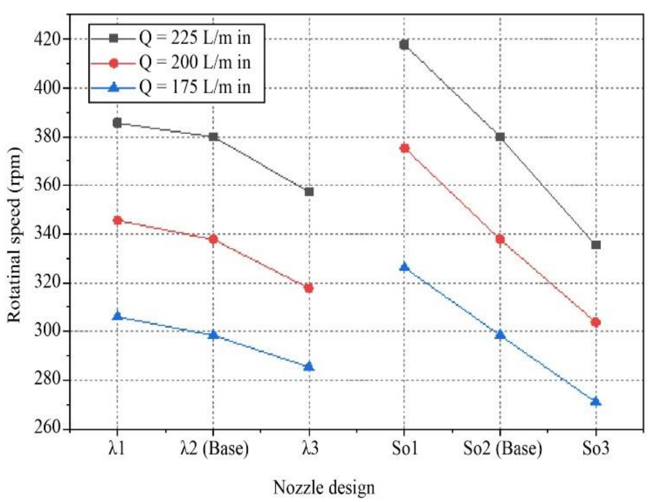
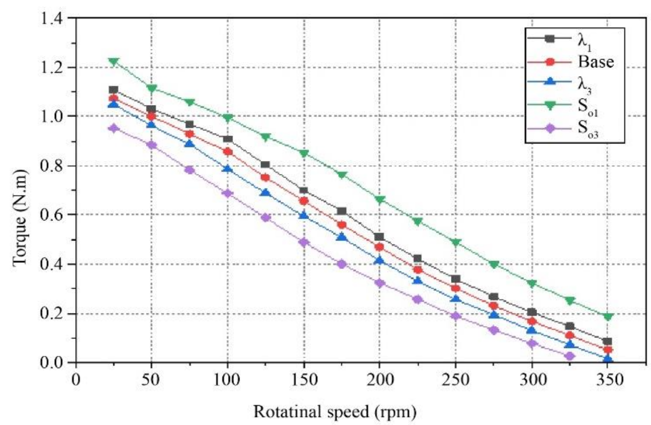


Fig. 5 Turbine rotation

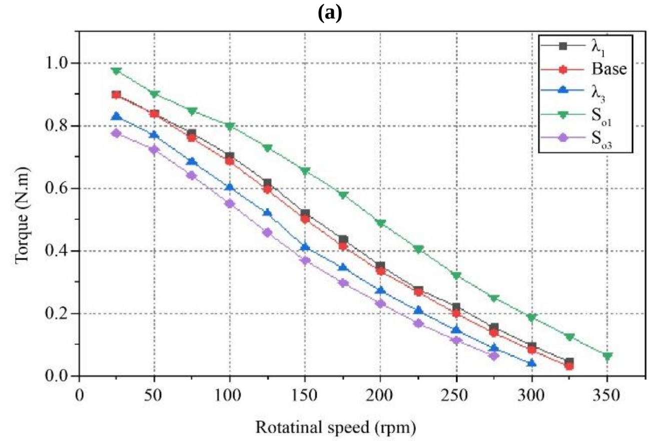
The lowest turbine rotation, 271 rpm, was observed with the S_{o3} nozzle design at a discharge of 175 L/min. The S_{o1} nozzle design has a smaller cross-sectional area than other nozzle designs. According to the law of continuity, with the same discharge, a narrower cross-sectional area of the nozzle results in increased velocity. Assuming no losses in the runner blades, the linear velocity of the turbine runner will match the water velocity, meaning the S_{o1} nozzle design will produce the optimum rotation. A smaller turbine flow cross-sectional area explains the factors influencing turbine rotation in the S_{o1} nozzle design, resulting in optimal rotation, as shown in Figure 10d (S_{o1}). Conversely, with the S_{o3} nozzle design, the increased cross-sectional area of the turbine flow decreases water velocity, which reduces turbine rotation, as shown in Figure 10e (S_{o3}).

4.2 Turbine Torque

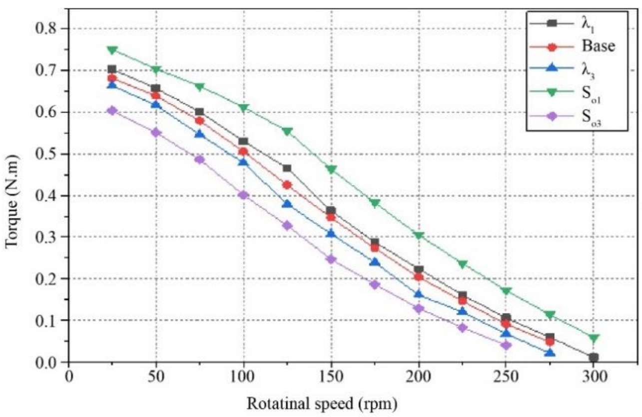
Figure 6 shows the turbine's torque with different discharge variations at each rotation. Discharge variations affect the torque produced by the turbine. The test results show that maximum torque was obtained under full load conditions. As turbine rotation decreases, turbine torque increases. These results are consistent with findings from previous researchers [23],[26]. Under full load conditions, the water flow in the turbine undergoes resistance that is affected by the decrease in runner rotation, resulting in a buildup of water in the turbine.



(a)



(b)



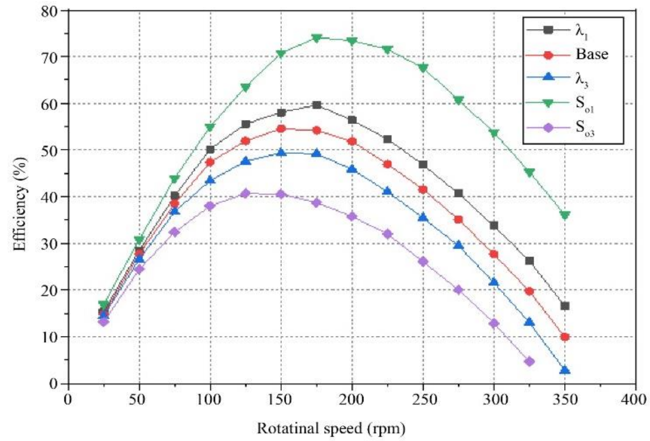
(c)

Fig. 6 Turbine torque (a) 225 L/min, (b) 200 L/min, (c) 175 L/min

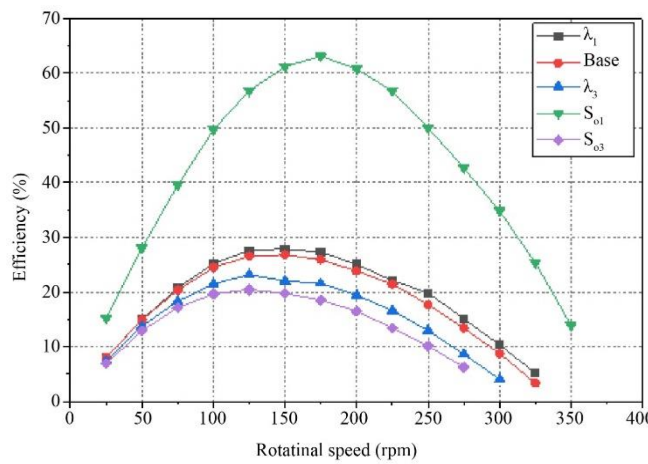
This condition causes a decreasing velocity of flow water out from the turbine runner. The turbine force is generated from changes in water momentum that hit the turbine runner blades, so the more decreasing velocity of the water flow increases the result of force [16]. Torque increases along with the increasing force produced by the turbine. This can describe the cause of the increasing torque produced by the turbine as the turbine rotation decreases. Figure 6. shows that the nozzle design affects the torque produced by the turbine. The highest torque is obtained with the S_{o1} nozzle design at a discharge of 225 L/min. While the lowest torque is obtained with the S_{o3} nozzle design at a discharge of 175 L/min.

4.3. Turbine Efficiency

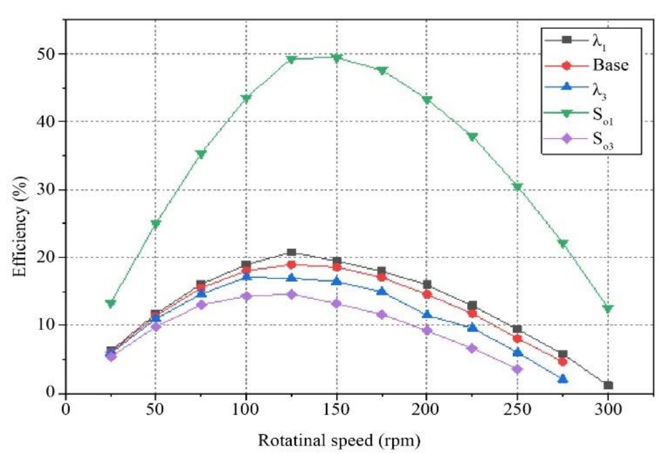
Figure 7 shows the efficiency generated by the Cross-flow turbine at each turbine rotation by variations in discharge and nozzle design. The turbine's optimum efficiency is obtained at a medium rotational speed around 150-200 rpm. The turbine efficiency decreases at higher rotational speed [3],[8],[14],[15],[17],[18],[19],[27]. The power generated by the turbine is obtained from the torque and speed of the turbine runner. In high rotation conditions, the turbine runner has no cross flow, and only a few blades are passed by the water. This impacts the irregular shape of the water flow (turbulent), and the utilization of water energy occurs only in the first stage. In addition, changes in the speed of water entering and leaving the turbine runner tend to be lower, so the momentum produced is lower, which impacts the torque generated by the turbine. The addition of braking load on the dynamometer causes the turbine rotation to decrease. However, the water flow in the turbine becomes more uniform (laminar), and cross flow occurs on the turbine runner. This condition impacts increasing the number of blades passed by the water to maximize the utilization of water energy and increase turbine performance. This factor causes the turbine to produce maximum efficiency at a certain rotation. The results obtained in this study are in line with previous studies [28]. The greater the braking load on the dynamometer will affect the increase in turbine torque but will cause hydraulic losses caused by the accumulation of water flow in the turbine runner, causing the rotation and efficiency of the turbine to decrease. The greater the water discharge used, the greater the impact on increasing turbine efficiency. Conversely, the smaller the water discharge used, the lower the turbine efficiency. In the design of the nozzle throat width S_{o1}, the decrease in water discharge does not significantly impact the decrease in turbine efficiency.



(a)



(b)



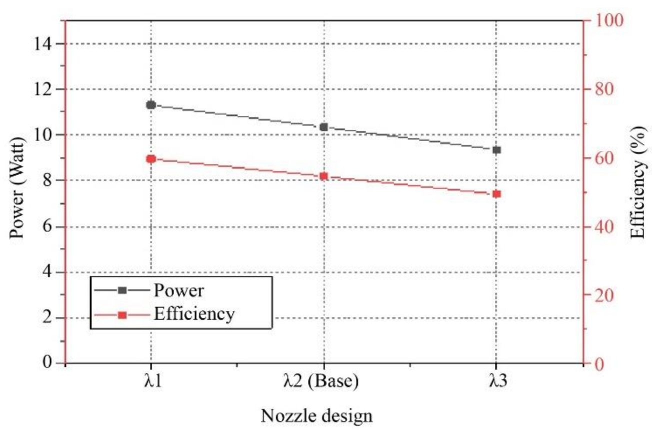
(c)

Fig. 7 Turbine efficiency (a) 225 L/min, (b) 200 L/min, (c) 175 L/min

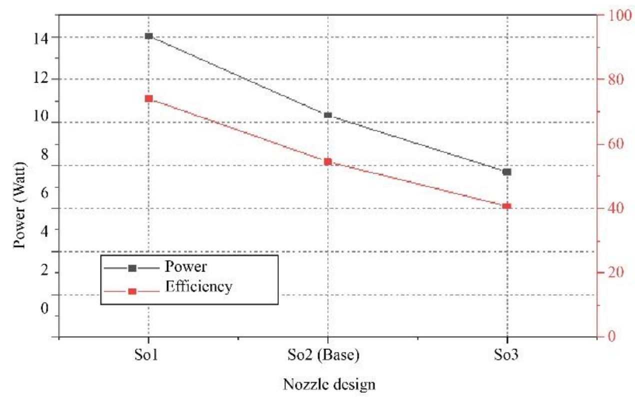
Unlike other nozzle design variations, the decrease in water discharge from 225 L/min to 200 L/min significantly decreases turbine efficiency. This describes that optimising the nozzle throat width S_{o1} design can adapt well to water discharge fluctuations. Figure 8a shows that the nozzle entry arc design affects the power and efficiency of the turbine with a discharge of 225 L/min. Nozzle design optimization λ_1 has succeeded in increasing the turbine power, while in the nozzle design λ_3, something unexpected happened: the turbine power decreased. Using nozzle design λ_1, turbine efficiency increases by 9.3 % from the turbine basic nozzle profile (λ_2). In another condition, using nozzle design λ_3, turbine efficiency decreases by 9.5 %. The nozzle entry arc can affect the water's angle of attack in the first and second stages.

The angle of attack affects Cross-flow turbine efficiency [12]. This condition describes an optimal nozzle entry arc design that can increase turbine efficiency.Figure 8b shows the effects of the nozzle throat width design on the power and efficiency of the turbine by discharge of 225 L/min. Optimizing the S_{o1} nozzle design successfully increased turbine power. In another condition, the S_{o3} nozzle design decreases turbine power. The turbine's highest power is 14.04 watts, obtained with the S_{o1} nozzle design at a discharge of 225 L/min. While the lowest power of 7.7 watts is obtained with the S_{o3} nozzle design at a discharge of 175 L/min. The S_{o1} nozzle design increased turbine efficiency by 35.8 % from the base turbine nozzle (S_{o2}) design.

A narrower intake nozzle design generates more power. These results show that the optimal inlet nozzle design considerably affects turbine performance [14]. Turbine efficiency decreased by 25.4 % when using the S_{o3} nozzle design. This happens because the cross-sectional area of the water flow is greater, so the water flow velocity is low. This impacts the momentum generated, and energy transfer to the turbine decreases.Figure 9. Shows the effect of discharge variations on turbine efficiency using design nozzle S_{o1}. Turbine efficiency decreases as long as with a decrease in the water flow used.



(a)



(b)

Fig. 8 Optimization of nozzle design on turbine power and efficiency (a) Nozzle Entry Arc (b) Nozzle Throat Width

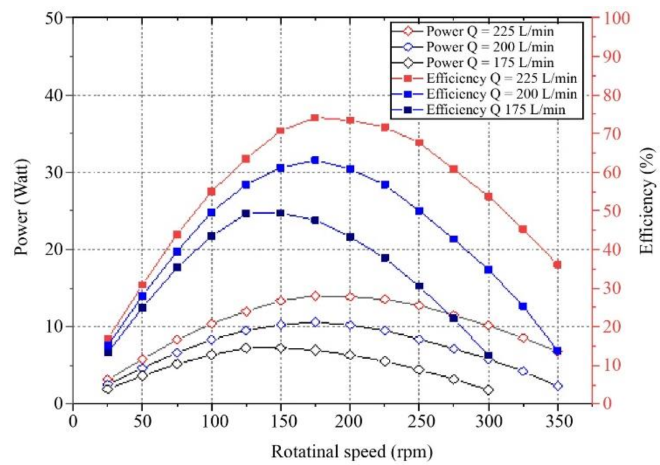


Fig. 9 Variation of discharge on turbine power and efficiency

A reduction of water discharge will have an impact on uneven flow distribution in the turbine and cause a reduction of turbine efficiency [3]. At water discharge of 225 and 200 L/min the turbine produces maximum efficiency at 175-200 rpm while at water discharge of 175 L/min the turbine produces maximum efficiency at 125-150 rpm. This provides insight that water discharge affects the specific rotation of the turbine. The turbine is designed with an angle of attack $\alpha = 15^o$ so that, theoretically, the turbine can produce maximum efficiency between 86-93%. However, the test results obtained optimum efficiency with the S_{o1} nozzle design at 74%. There is a difference between the experimental results and theoretical results. This occurs because friction factors, flow losses, and hydraulic losses are theoretically ignored. In addition, the design of the turbine dimension was based on water discharge and head, so when using the turbine, water discharge and head have to be suitable by design to optimize turbine performance. Overall, the optimization of the nozzle entry arc λ_1 and nozzle throat width S_{o1} design is the most optimal configuration to improve turbine performance compared to other designs. The increase in turbine performance is a significant achievement in maximizing the role of the Cross-flow turbine as an energy conversion machine in micro-hydro power plants.

4.4. Flow Characteristics

There are differences in each turbine's flow characteristics, as shown in Figure 10. The direction of water flow to the outlet from the first stage when using λ_1 and S_{o1} of the design nozzle is lower and hits the turbine shaft than other design nozzle. The more water flow that hits the turbine shaft, the more it will affect the direction of the water flow that enters the second stage and cause friction losses between the turbine shaft and the water flow. The directsion of the flow entering the second stage will affect the force generated by the turbine. This describes that the flow characteristics can be used to develop turbine designs. Nozzle design optimization S_{o1}, flow in the inlet of the first stage is narrower, resulting in a higher water flow velocity, and the outlet of the first stage, lower flow, hits the turbine shaft. The velocity of the water can be described as the head H is converted into kinetic energy, and the suitable nozzle entry arc design will increase the momentum that occurs in the turbine so that the energy transfer to the turbine also increases [8][17]. The turbine efficiency of nozzle design λ_3 is lower than the base nozzle design λ_2 because of the wrong direction of the inlet flow in the second stage. This condition describes several water flows in the turbine that hit behind the blade, shown in Figure 11c.

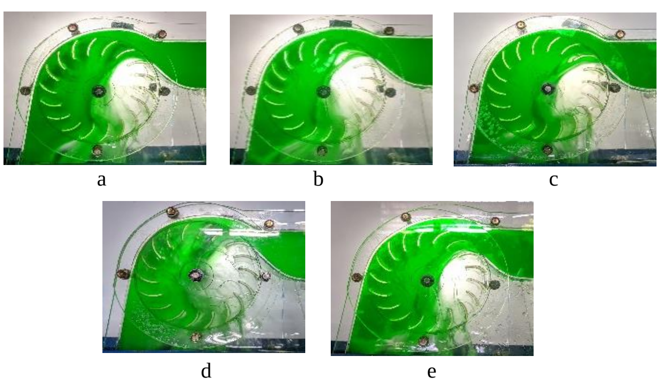


Fig. 10 Flow characteristics with a discharge of 225 L/min
(a) Base, (b) λ_1, (c) λ_3, (d) So_1 , (e) So_3

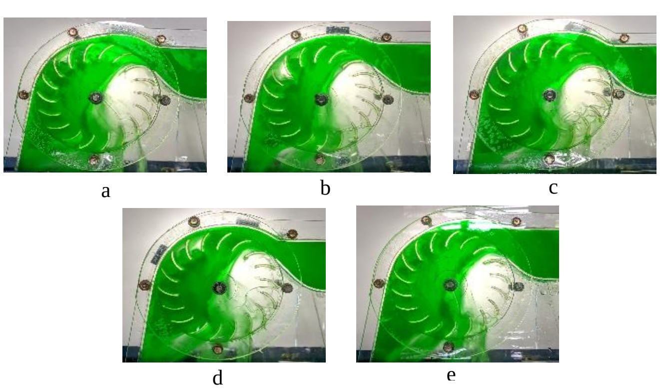


Fig. 11 Flow characteristics with a discharge of 200 L/min
(a) Base, (b) λ_1, (c) $\lambda 3$, (d) So_1, (e) So_3

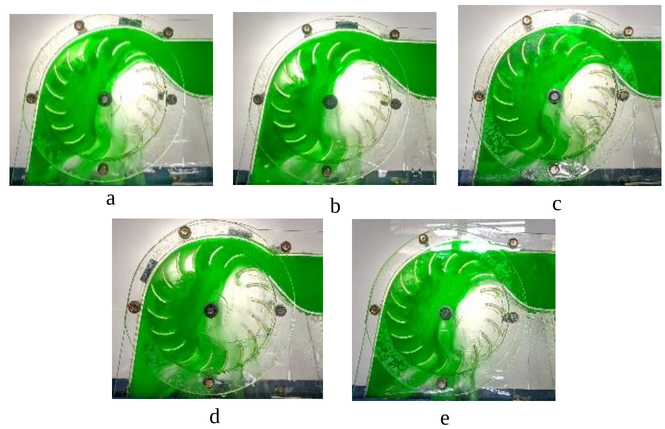


Fig. 12 Flow characteristics with a discharge of 175 L/min
(a) Base, (b) λ_1, (c) λ_3, (d) S_{o1} , (e) S_{o3}.

The water flow in the first stage will change direction after hitting the runner blades, as shown in Figure 12. (b and d). These conditions describe a change in water velocity after it hits the runner blades. Changing the water flow velocity will produce more incredible momentum and optimize energy absorption from the water flow by the turbine. This describes one of the factors that cause the nozzle entry arc design λ_1 and nozzle throat width S_{o1} to increase turbine performance. The results align with previous studies, stating that nozzle design affects flow distribution and velocity profile [7]. The nozzle design affects the direction of the outlet flow in the first stage, where the wrong flow direction will hit the turbine shaft in more significant capacities, which causes a changing inlet direction of the flow in the second stage, as shown in Figure 12(c and e).

These conditions affect frictional losses between the turbine shaft and water, and the direction of inlet flow in the second stage can be wrong. The wrong flow direction does not produce a thrust force on the turbine runner blades but will cause losses and reduce turbine efficiency.The research results show that optimization of the nozzle inlet arc design and nozzle throat width can increase turbine efficiency. The results of flow character observations provide new insights into the real factors that affect turbine performance, making a real contribution to the development of renewable energy technology. The results obtained illustrate the successful achievement of the research objectives.

5. Conclusion

Optimal nozzle entry arc design can ensure that the water flow enters at the right angle and speed, thereby producing maximum impulse force on the turbine runner blades and increasing the turbine efficiency from 54.57% (base nozzle design) to 59.63% using the λ_1 arc entry nozzle at a flow rate of 225 L/min. The narrower nozzle throat width design increases momentum. It optimizes the energy absorption from the water flow by the turbine, thereby increasing the turbine efficiency from 54.57% (base nozzle design) to 74% with nozzle throat width S_{o3} at 225 L/min discharge. The flow characteristics within the turbine affect turbine performance and can be used as a basis for developing nozzle designs in further research. Optimizing the nozzle entry arc and throat width design successfully optimises turbine performance. Research shows that increasing power and efficiency can maximize the performance of Cross-flow turbines as hydroelectric power plants.

Funding Statement

This research is fundamental (national competitive research) funded by the Indonesian Ministry of Education, Culture, Research and Technology with grant number 104/E5/PG.02.00.PL/2024.

Acknowledgments

The authors thank the Indonesian Ministry of Education, Culture, Research and Technology for funding research and scientific publications. The authors also would like to thank those who had helped in the manufacturing and testing of the turbine and the preparation of scientific articles.

References

[1] Oliver Paish, "Small Hydro Power: Technology and Current Status," *Renewable and Sustainable Energy Reviews*, vol. 6, no. 6, pp. 537-556, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[2] A. H. Elbatran et al., "Operation, Performance and Economic Analysis of Low Head Micro-Hydropower Turbines for Rural and Remote Areas: A Review," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 40-50, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[3] Mujahid Naseem, Arslan Saleem, and Muhammad Shoaib Naseem, "Investigation of Blade Design Parameters for Performance Improvement of Hydraulic Cross Flow Turbine," *Ocean Engineering*, vol. 257, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[4] Goodarz Mehr et al., "A Novel Design and Performance Optimization Methodology for Hydraulic Cross-Flow Turbines Using Successive Numerical Simulations," *Renewable Energy*, vol. 169, pp. 1402-1421, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[5] Re-Ann Cristine O. Calimpusan, Lydelle P. Arcite, and James Michael A. Yula, "Design and Enhancement of Pico Hydro and Monitoring System for Generation of Electricity," *International Journal of Engineering Trends and Technology*, vol. 72, no. 3, pp. 49-54, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Audrius Židonis, and George A. Aggidis, "State of The Art in Numerical Modelling of Pelton Turbines," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 135-144, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[7] Nirmal Acharya et al., "Numerical Analysis and Performance Enhancement of a Cross-Flow Hydro Turbine," Renewable Energy, vol. 80, pp. 819-826, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[8] R. C. Adhikari, and D. H. Wood, "A New Nozzle Design Methodology for High Efficiency Crossflow Hydro Turbines," *Energy for Sustainable Development*, vol. 41, pp. 139-148, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[9] Ram Adhikari, and David Wood, "Computational Analysis of a Double-Nozzle Crossflow Hydroturbine," *Energies*, vol. 11, no. 12, pp. 1-15, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[10] Ram Adhikari, and David Wood, "The Design of High Efficiency Crossflow Hydro Turbines: A Review and Extension," *Energies*, vol. 11, no. 2, pp. 1-18, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[11] Marco Sinagra et al., "Cross-Flow Turbine Design for Variable Operating Conditions," *Procedia Engineering*, vol. 70, pp. 1539-1548, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[12] C.A. Mockmore, and Fred Merryfield, "*The Banki Water Turbine*," Engineering Experiment Station, Oregon State System of Higher Education, Oregon State College, Bulletin Series no. 25, pp. 1-27, 1949. [Google Scholar] [Publisher Link]

[13] Young-Do CHOI et al., "Performance and Internal Flow Characteristics of a Cross-Flow Hydro Turbine by the Shapes of Nozzle and Runner Blade," *Journal of Fluid Science and Technology*, vol. 3, no. 3, pp. 398-409, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[14] Young-Do Choi, and Sung-Woo Son, "Shape Effect of Inlet Nozzle and Draft Tube on the Performance and Internal Flow of Cross-Flow Hydro Turbine," *The Korean Society of Marine Engineering*, vol. 36, no. 3, pp. 351-357, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[15] Venkappayya R. Desai, and Nadim M. Aziz, "An Experimental Investigation of Cross-Flow Turbine Efficiency," *Journal of Fluids Engineering*, vol. 116, no. 3, pp. 545-550, 1994. [CrossRef] [Google Scholar] [Publisher Link]

[16] Saeed Rajab Yassen, "*Optimization of the Performance of Micro Hydro-Turbines for Electricity Generation Optimization of the Performance of Micro Hydro-Turbines for Electricity Generation*," University of Hertfordshire, PhD Theses Collection, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[17] Rajeev Kumar Ranjan et al., "Performance Investigations of Cross Flow Hydro Turbine with The Variation of Blade and Nozzle Entry Arc Angle," *Energy Conversion and Management*, vol. 182, pp. 41-50, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[18] Jiyun Du, Zhicheng Shen, and Hongxing Yang, "Study on The Effects of Runner Geometries on The Performance of Inline Cross-Flow Turbine Used in Water Pipelines," *Sustainable Energy Technologies and Assessments*, vol. 40, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[19] Rodolfo Espina-Valdés et al., “Small Cross-Flow Turbine:Design And Testing In High Blockage Conditions,” *Energy Conversion and Management*, vol. 213, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[20] Mrudang Patel, and Nirav Oza, “Design and Analysis of High Efficiency CrossFlow Turbine for Hydro-Power Plant,” *International Journal of Engineering and Advanced Technology (IJEAT)*, vol. 5, no. 4, pp. 187-193, 2016. [Google Scholar] [Publisher Link]
[21] R.S. Anand et al., “A Comprehensive Review on Crossflow Turbine for Hydropower Applications,” *Ocean Engineering*, vol. 240, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[22] A.H. Samitha Weerakoon et al., “Design Optimization of a Novel Vertical Augmentation Channel Housing A Cross-Flow Turbine and Performance Evaluation as A Wave Energy Converter,” *Renewable Energy*, vol. 180, pp. 1300-1314, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[23] Yasuyuki Nishi et al., “Effect of Flow Rate on Performance and Flow Field of An Undershot Cross-Flow Water Turbine,” *Renewable Energy*, vol. 149, pp. 409-423, 2020. [CrossRef] [Google Scholar] [Publisher Link]
[24] Bilal Abdullah Nasir, “Design Considerations of Micro-Hydro-Electric Power Plant,” *Energy Procedia*, vol. 50, pp. 19-29, 2014. [CrossRef] [Google Scholar] [Publisher Link]
[25] Hayati Olgun, “Investigation of The Performance of a Cross-Flow Turbine,” *International Journal of Energy Research*, vol. 22, no. 11, pp. 953-964, 1998. [CrossRef] [Google Scholar] [Publisher Link]
[26] Rudy Soenoko, “First Stage Cross Flow Turbine Performance,” *International Journal of Applied Engineering Research (IJAER)*, vol. 11, no. 2, pp. 938-943, 2016. [Google Scholar] [Publisher Link]
[27] Eiichi Satou et al., “Development of An Undershot Cross-Flow Hydraulic Turbine Resistant to Snow and Ice Masses Flowing in An Installation Canal,” *Renewable Energy*, vol. 200, pp. 146-153, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[28] Corvis L Rantererung et al., “A Double Nozzle Cross Flow Turbine Fluid Flow Dynamics,” *Journal of Southwest Jiaotong University*, vol. 55, no. 4, pp. 1-10, 2020. [CrossRef] [Google Scholar] [Publisher Link]