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Optimization of power and efficiency of a vortex water turbine through blade–outlet distance and transmission ratio analysis

Florensius Kitaro Asagi, Danar Susilo Wijayanto*, Taufik Wisnu Saputra
Department of Mechanical Engineering Education, Sebelas Maret University, Surakarta 57126, Indonesia
*Corresponding author: danarsw@staff.uns.ac.id

Abstract

As fossil fuel resources decline, vortex water turbines offer a promising renewable energy alternative by utilizing river flow. This experimental research aims to analyze the effect of blade distance from the outlet and transmission ratio on the electrical power and efficiency produced by vortex water turbines as a renewable energy solution. Three variations of blade distance from the outlet (20 mm, 40 mm, and 60 mm) and three variations of transmission ratio (1:3, 1:4, and 1:5) were tested under seven water flow rate variations of 27.8 l/min, 33.68 l/min, 34.11 l/min, 34.54 l/min, 34.97 l/min, 35.4 l/min, and 35.83 l/min. Data were collected for 5 minutes, with a 10-second interval for each parameter. Test results show that the highest electrical power of 4.88 watts was achieved at a blade distance of 20 mm from the outlet, a transmission ratio of 1:5, and a water flow rate of 35.83 l/min. Meanwhile, the highest turbine efficiency of 11.25% was obtained at a blade distance of 20 mm from the outlet, a transmission ratio of 1:3, and a water flow rate of 35.83 l/min. Increasing blade–outlet distance reduced both power and efficiency, while higher transmission ratios increased power but decreased efficiency due to torque–speed trade-offs. These results confirm that the distance between the blade and the outlet, and the transmission ratio, are critical parameters for optimizing performance of vortex turbines. A blade distance closer to the outlet provides the best performance and a larger transmission ratio will also improve performance, although transmission loading must also be considered.

Keywords:
Vortex water turbine, blade to outlet distance, transmission, electrical power, turbine efficiency.

1 Introduction

Earth's energy resources are expected to decrease over time [1]. Fossil fuels, such as coal and petroleum, are expected to experience a significant decline in supply due to their continuous use, in line with population growth and increasing electricity consumption [2]. The demand for fossil fuels remains dominant in the industrial sector, with natural gas accounting for 83% of consumption and coal accounting for 9%. Based on the results from the transportation sector, 96% of fuel consumption is dominated by biodiesel and natural gas. However, electricity remains a significant factor in the household sector, which accounts for approximately 67% of energy source needs [3]. To meet the needs of various sectors, it is necessary to use renewable energy to provide future electricity to replace dwindling energy sources [4].

Water is a natural energy source that can be utilized as an alternative to non-renewable energy [5]. Indonesia's water supply is classified as abundant, and the potential of this water energy source can be utilized to generate electricity through hydroelectric power plants [6]. A small-scale HPP model is called a Picohydro Power Plant (PHPP), which has a capacity ranging from tens of watts to 5 kW [7]. The PLTPH mechanism uses flowing water channels to drive turbines, which in turn rotate generators to produce electrical power [8].

A vortex water turbine utilizes the central working system of a water vortex to drive the turbine blades into rotation [9]. The fluid used in this case is water [10]. This turbine operates using centrifugal force generated by water rotating in the basin [11]. The water flow is converted into kinetic energy to drive the generator rotor via a transmission system comprising a pulley and belt, thereby generating electrical energy [12].

The blade height in a vortex water turbine is the distance between the turbine blades and the turbine outlet [13]. The rotational energy of the vortex water turbine shaft is generated by utilizing the water vortex, which is then channelled to the discharge channel or outlet [14]. The role of transmission also affects the performance of vortex water turbines, where the type of transmission used must be efficient to improve the conversion of water kinetic energy into electrical energy, thereby increasing the power generated by the turbines [15]. Research conducted by Caturputra et al on the use of gearbox ratios in undershot picohydro turbines with ratio variations of 1:16, 1:32, and 1:48 produced the highest electrical energy and efficiency at a ratio of 1:48, with 1.4033 Watts of electrical energy and 0.1729% efficiency, while the lowest results were at a ratio of 1:16, with 0.2333 Watts of electrical energy and 0.1163% efficiency [16]. This research demonstrates that transmission in vortex water turbines can enhance the electrical energy and efficiency produced by these turbines.

Another study, conducted by Faizal et al., designed a vortex water turbine with a water discharge of 6.34 l/s and a pulley ratio of 8:25. The blades used were made of fiberglass, and the study employed 2, 3, and 4 blades [17]. The distances between the blades and the outlet used were 4 cm, 6 cm, 8 cm, and 10 cm. This study revealed that the highest turbine efficiency was 65.77% with four blades and a blade spacing of 6 cm from the outlet. The maximum turbine power generated with four blades and a blade spacing of 6 cm from the outlet was 9.72 Watts. On the other hand, research conducted by Kurniawan examined vortex water turbines with blade-to-outlet distances of 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm. The maximum electrical power was measured at a blade distance of 5 cm from the outlet, amounting to 9.7 W with a water flow rate of 2.11 L/s. The smallest electrical power was generated at a blade-to-outlet distance of 1 cm, yielding 1.7 W at a water flow rate of 1.26 L/s 18].

This study examines the impact of blade distance from the outlet and transmission ratio on the power and efficiency generated by vortex water turbines. The results of this study are also expected to provide valuable insights for developing a more efficient, high-performance small-scale vortex water turbine design.

2 Research method

The vortex water turbine is a research tool used in this study. The specifications of the vortex water turbine frame use hollow iron measuring 1410 mm × 1554 mm × 700 mm. The bed or base of the vortex water turbine uses a 1 mm thick aluminium plate, and the water passage wall uses a 0.35 mm thick aluminium plate. The vortex water turbine blades are made of Polylactic Acid (PLA) material produced using a 3D printer to achieve high precision in size. The blade specifications include an upper diameter of 270 mm, a lower diameter of 62.5 mm, and a height of 200 mm. 4 blades will be tested to assess their effect on the power produced by the vortex water turbine. This study also uses variations in the distance between the blades and the outlet of 20 mm, 40 mm, and 60 mm, as well as transmission ratios of 1:3, 1:4, and 1:5. The pulley uses PLA material made using a 3D printer, which can reduce the weight of the pulley when rotating [19]. This study also used a water pump to supply water flow into the turbine track from the reservoir. The pump used in this study was a centrifugal pump to increase the water discharge. The generator also functions as a device that produces electrical energy through mechanical energy generated by the vortex water turbine. The generator specifications used are model GRK1100K-Z, with a maximum power of 100 Watts and a maximum speed of 2000 rpm. An Arduino-based flow-meter measures flow rate in the pipe using a flow sensor connected between the connecting pipes. A digital multimeter is also needed to measure the generator's voltage and current. Therefore, this study utilizes two digital multimeters, each designed to measure electric current and voltage. An Arduino-based tachometer is also used to measure the rotational speed of the vortex water turbine shaft using an infrared sensor connected to an 8-hole encoder. A digital hanging scale measures the torque load the vortex water turbine produces on the shaft. A degree arc is used to adjust the degree of bypass valve opening, where this study also includes variations in water discharge. Fig. 1 shows the test setup for the vortex water turbine.

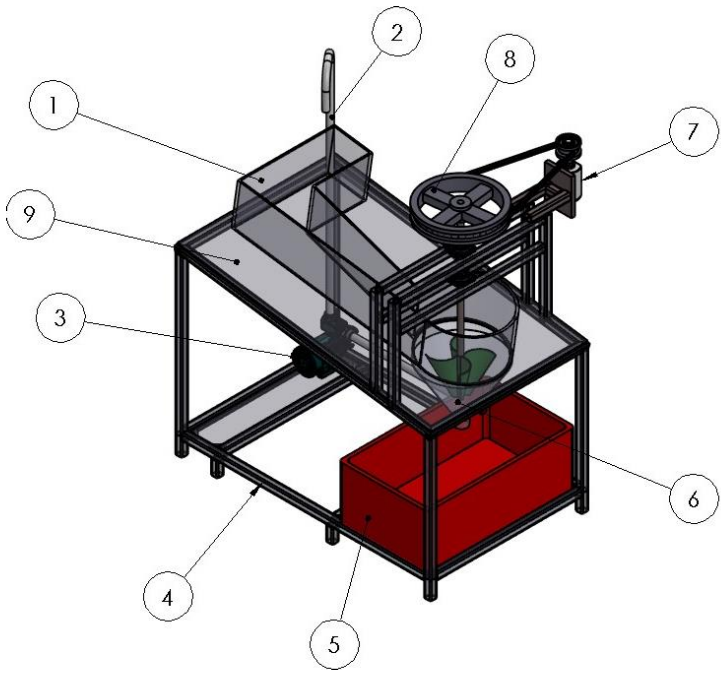

Fig. 1. Set up a test of a vortex water turbine.

1. Fluid track	6. Basin
2. Incoming fluid pipe	7. Generator
3. Centrifugal pump	8. Pulley
4. Turbine frame	9. Bed
5. Tank	

This vortex water turbine research employs an experimental method with several stages carried out continuously to achieve its objectives. The data analysis technique used is a quantitative descriptive approach. In the first stage, namely the preparation stage, all research tools are prepared and connected to the vortex water turbine, and tables are prepared to record the test results. The second stage was testing for variations in blade distance with outlets of 20 mm, 40 mm, and 60 mm, which were carried out alternately. Testing of the blade distance relative to the outlet was also conducted with transmission ratios of 1:3, 1:4, and 1:5, each alternated. Variations in water discharge of 27.8 l/min, 33.68 l/min, 34.11 l/min, 34.54 l/min, 34.97 l/min, 35.4 l/min, and 35.83 l/min were also tested in stages, along with variations in blade distance from the outlet and variations in the transmission ratio. The test results were recorded in a table, including voltage, current, and turbine shaft speed. The next stage was to process the test data from the vortex water turbine and analyze it. The data will be visualized in graphs to identify the relationships among the variations used in this study.

3 Results and discussion

3.1 Results

After testing the vortex water turbine, the results of the vortex water turbine testing in the form of electrical power are shown in Fig. 2 to Fig. 7.

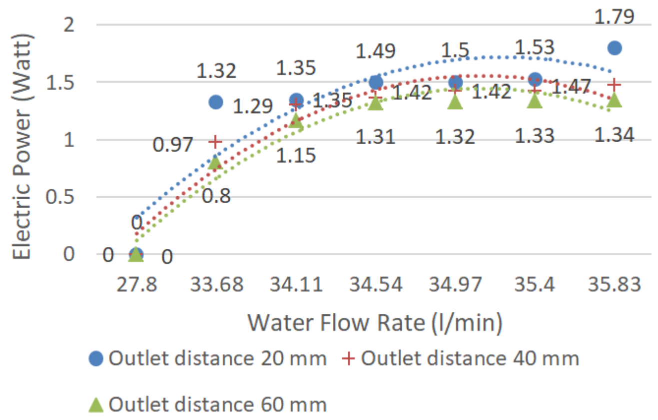

Fig. 2. Electrical power at transmission ratio variation of 1:3 relative to the blade distance from the outlet.

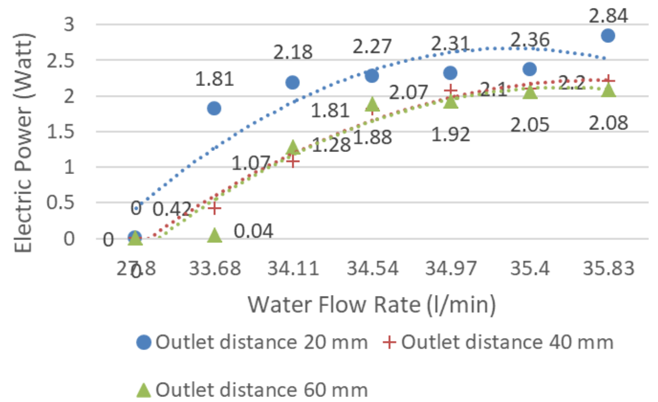

Fig. 3. Electrical power at transmission ratio variation of 1:4 relative to the blade distance from the outlet.

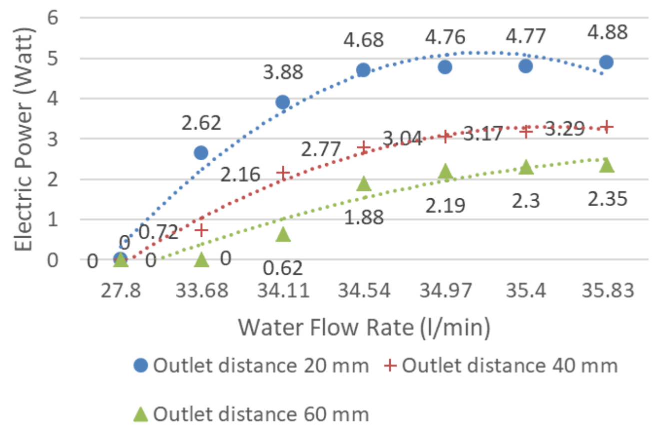

Fig. 4. Electrical power at transmission ratio variation of 1:5 relative to the blade distance from the outlet.

Based on the test results in Fig. 2-Fig. 4, the electrical power generated by the vortex water turbine increases with increasing water flow rate, where all variations failed to generate power at a minimum flow rate of 27.8 l/min and only began to operate at 33.68 l/min, because at a flow rate of 27.7 l/min it was not large enough to rotate the turbine shaft as the initial torque of the turbine, considering that the turbine shaft is directly integrated with the transmission in the form of a pulley and belt. Across all variations, peak electrical power was consistently achieved at a blade-to-outlet distance of 20 mm and a maximum flow rate of 35.83 l/min, with detailed results of 1.79 W, 2.84 W, and 4.88 W, respectively. Conversely, the lowest power output was generally recorded at the furthest blade distance from the outlet (60 mm) with a flow rate of 33.68 l/min, indicating that a combination of higher flow rates, a closer blade distance to the outlet, and a larger transmission ratio optimizes power generation.

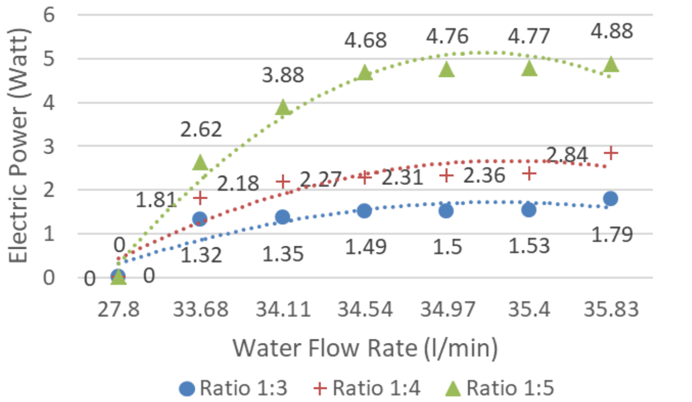

Fig. 5. Electrical power at varying blade distances with a 20 mm distance from the outlet relative to the transmission ratio.

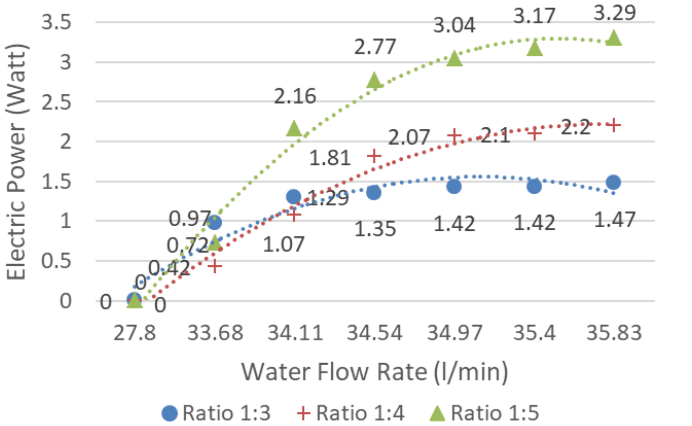

Fig. 6. Electrical power at varying blade distances with a 40 mm distance from the outlet relative to the transmission ratio.

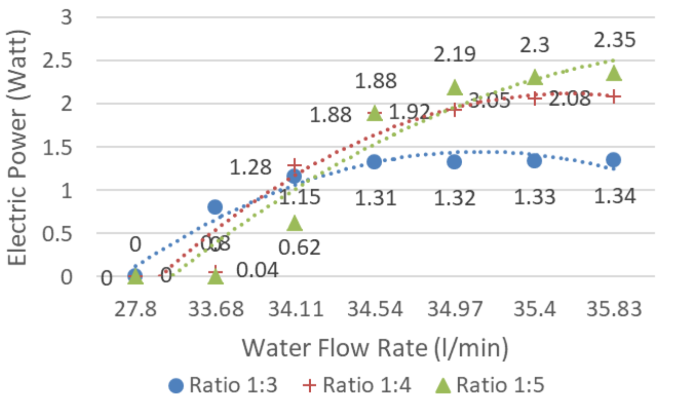

Fig. 7. Electrical power at varying blade distances with a 60 mm distance from the outlet relative to the transmission ratio.

Based on the test results in Fig. 5-Fig. 7, peak electrical power was consistently generated at a transmission ratio of 1:5 with a flow rate of 35.83 l/min, amounting to 4.88 W, 3.29 W, and 2.35 W, respectively. In general, electrical power increases with increasing water flow rate, where all variations fail to generate power at a flow rate of 27.8 l/min and only begin to operate at 33.68 l/min. The findings show an intersection in the trend lines between transmission ratios, such as 1:3, 1:4, and 1:5, caused by the transmission load, where the higher the transmission ratio, the greater the transmission load and the torque required to rotate the turbine shaft. The lowest recorded power ranged from 0.04 W to 1.32 W at a flow rate of 33.68 l/min, confirming that the interaction among water flow rate, blade distance from the outlet, and transmission ratio strongly determines the electrical power generated by vortex water turbines.

The results of the vortex water turbine testing in the form of turbine efficiency are shown in Fig. 8 to Fig. 13.

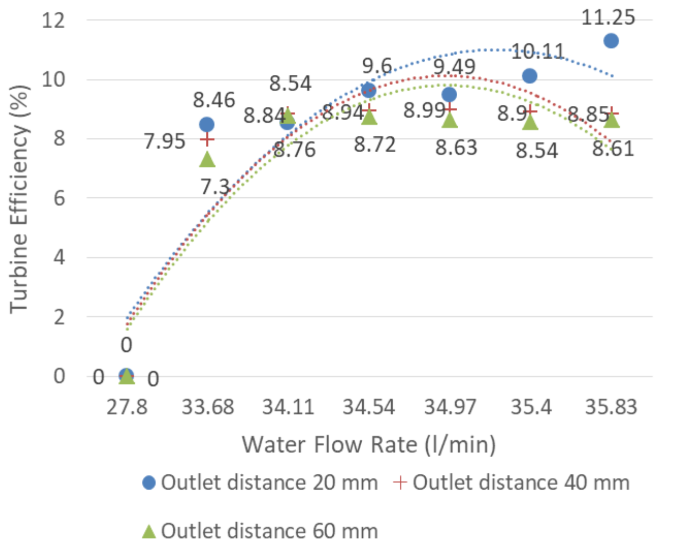

Fig. 8. Turbine efficiency at a transmission ratio variation of 1:3 relative to the blade distance from the outlet.

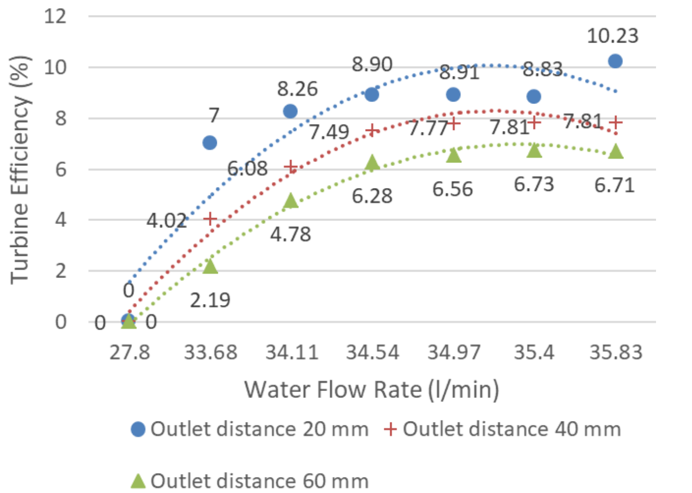

Fig. 9. Turbine efficiency at a transmission ratio of 1:4 versus blade distance from the outlet.

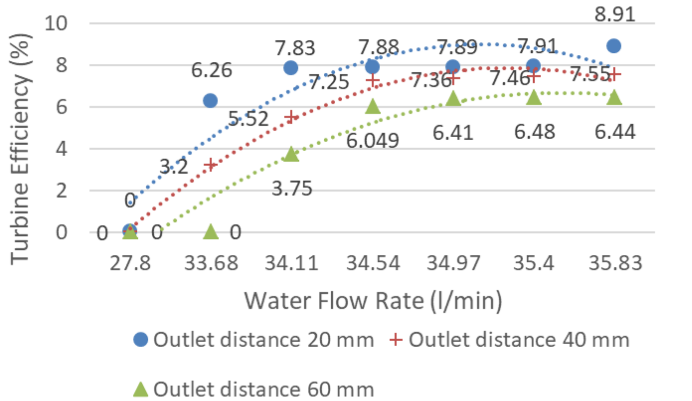

Fig. 10. Turbine efficiency at a transmission ratio of 1:5 versus blade distance from the outlet.

Based on the test results in Fig. 8-Fig. 10, the vortex water turbine achieved the highest efficiency at a blade distance of 20 mm from the outlet with a flow rate of 35.83 l/min, producing 11.25%, 10.23%, and 8.91%, respectively. No variations in blade distance from the outlet were observed; efficiency was first detected at 27.8 l/min. Conversely, the lowest efficiency was generally recorded at a blade distance of 40 mm or 60 mm from the outlet at a flow rate of 33.68 l/min, with values ranging from undetectable to 7.3%. Overall, the turbine efficiency shows that the closer the distance between the blade and the outlet, the greater the turbine efficiency, and that it is inversely proportional to the transmission ratio: the greater the transmission ratio, the lower the turbine efficiency.

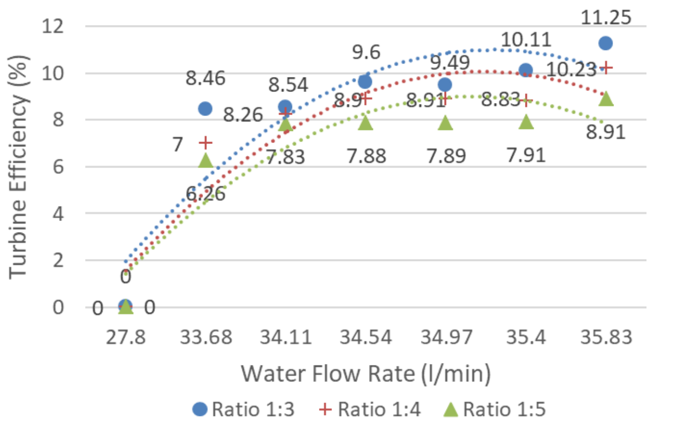

Fig. 11. Turbine efficiency at a blade to outlet distance of 20 mm versus transmission ratio.

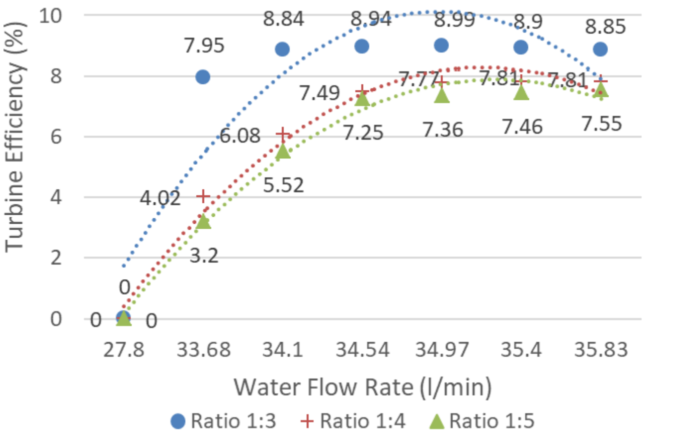

Fig. 12. Turbine efficiency at a blade distance to outlet distance of 40 mm versus transmission ratio.

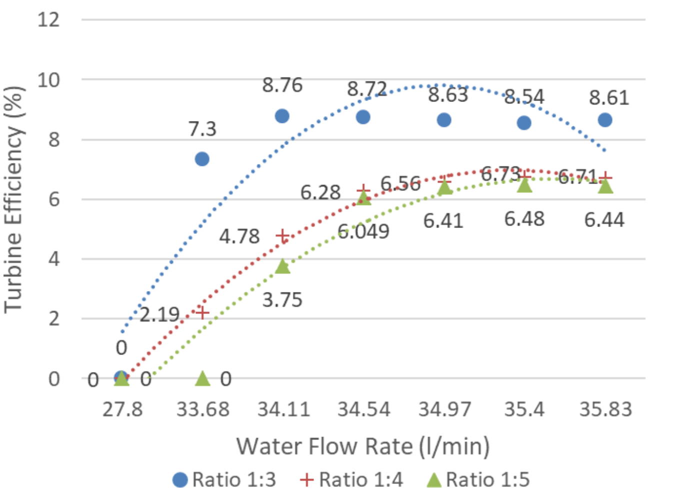

Fig. 13. Turbine efficiency at a blade to outlet distance of 60 mm versus transmission ratio.

Based on the test results in Fig. 11 to Fig. 13, the vortex water turbine achieved the highest efficiency at a transmission ratio of 1:3 and a flow rate of 35.83 l/min, with efficiencies of 11.25%, 8.85%, and 8.61%, respectively. None of the transmission ratio variations produced efficiency at a water flow rate of 27.8 l/min; efficiency first appeared at 33.68 l/min. At this low flow rate of 33.68 l/min, the 1:5 transmission ratio showed the worst performance, failing to produce any efficiency, with the lowest recorded efficiency ranging from 2.19% to 6.26%. Overall, the data show that the 1:3 transmission ratio provides superior efficiency compared to higher ratios under various water flow conditions.

3.2 Discussion

Testing the vortex water turbine indicates that a blade-to-outlet distance variation of 20 mm is optimal for generating electrical power. A blade distance of 20 mm has the highest electrical power compared to 40 mm and 60 mm. Water flow variation can also affect the electrical power generated; the greater the variation, the more power is generated. The most significant electrical power generated was 4.88 watts, achieved with a blade-to-outlet distance variation of 20 mm, a transmission ratio variation of 1:5, and a water flow variation of 35.83 l/min. On the other hand, the smallest electrical power was generated at 0.04 watts with a blade distance of 60 mm from the outlet, a transmission ratio of 1:3, and a water flow of 33.68 l/min. At all water flow rates, variations of 27.8 l/min, it was unable to generate electrical power because the turbine shaft could not rotate properly. At a flow rate of 33.68 l/min, a blade-to-outlet distance of 60 mm, and a transmission ratio of 1:5, the turbine shaft also failed to rotate correctly. In the previous study on vortex water turbines conducted by Prasetyo et al, the highest electrical power generated by the generator was 2.89 watts. This study demonstrated that varying the distance between the blades and the outlet can significantly improve the performance of vortex water turbines [20].

This research on vortex water turbines aligns with the work of Faizal et al., who tested vortex water turbines and found that a blade distance of 6 cm from the outlet produced the highest electrical power, specifically 9.72 watts. In comparison, blade distances of 8 cm and 10 cm from the outlet produced lower electrical power values of 7.79 watts and 5.42 watts, respectively [17]. This shows that the greater the distance between the blade and the outlet, the smaller the electrical power generated by the vortex water turbine. In terms of electrical power for transmission ratio variations, this is also in line with research on vortex water turbines conducted by Abimanyu et al, whose research used pulley transmission ratio variations of 1:2, 1:4, and 1:6, where the highest electrical power was generated at a pulley transmission ratio variation of 1:6, amounting to 31.9 watts. In contrast, the other pulley transmission ratio variations experienced a decrease in electrical power [7]. This indicates that the larger the transmission ratio, the greater the electrical power generated; however, the transmission load will also increase.

Testing the vortex water turbine indicates that a blade-to-outlet distance of 20 mm maximizes turbine efficiency. A blade distance variation with an outlet of 20 mm yields the highest turbine efficiency compared to blades with an outlet of 40 mm and 60 mm. The use of water discharge variation can also affect turbine efficiency; the greater the variation, the higher the efficiency. The highest turbine efficiency was 11.25%, achieved with a blade-to-outlet distance of 20 mm, a transmission ratio of 1:3, and a water discharge of 35.83 l/min. On the other hand, the smallest turbine efficiency was 2.19%, with a blade-to-outlet distance of 60 mm, a transmission ratio of 1:4, and a water discharge of 33.68 l/min. At all water flow rates, the turbine was unable to generate efficiency because the turbine shaft could not rotate properly. The turbine shaft could also not rotate properly at a flow variation of 33.68 l/min with a blade distance variation of 60 mm from outlet and a transmission ratio 1:3. This study also proves that the efficiency produced in the variation of the distance blade to outlet and the transmission ratio tends to be higher when compared to previous research conducted by Kurniawan et al, where the highest efficiency was produced at 6.72% at a water flow of 2.11 l/s without using transmission [18].

4 Conclusions

This research demonstrates that blade–outlet distance and transmission ratio significantly influence the electrical power and efficiency of a vortex water turbine. The key findings are: (1) a shorter blade–outlet distance (20 mm) consistently produced the highest electrical power and efficiency across all flow variations; (2) the maximum electrical power (4.88 W) was obtained at a 20 mm blade distance, a 1:5 transmission ratio, and a flow rate of 35.83 L/min; (3) the highest turbine efficiency (11.25%) occurred at the same blade distance and flow rate but with a 1:3 transmission ratio; (4) increasing the transmission ratio enhances electrical power due to higher torque but reduces turbine efficiency as shaft speed decreases; (5) optimal configuration depends on the design objective: a 1:5 ratio for maximum power output or a 1:3 ratio for maximum efficiency. Future research should use a larger transmission ratio with wider water channel to achieve maximum results.

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