Mekanika: Majalah Ilmiah Mekanika

Performance of Vortex Turbines with Two-Stage Radial-Offset Runners

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Abstract

Gravitational water vortex turbines are environmentally friendly power generation systems that convert the energy of vortex water flow into mechanical energy using turbine runners. This study aims to analyze the effect of a two-stage configuration with varied radial runner positions and water discharge on turbine performance. Experiments were conducted using a low-speed water channel with a conical basin to generate vortex flow. Savonius-type runners were installed vertically in two stages with radial positions of 0.5, 0.6, and 0.7 relative to the basin radius. Each configuration was tested at several water discharge rates. The primary parameter measured was mechanical power output, which was obtained using torque sensors and rotational speed meters to provide precise data. Results showed that the radial position 0.5 produced the best performance, generating 12.28 watts in the first and 16.68 watts in the second. Runner position and water discharge directly influenced vortex stability and energy conversion efficiency. The two-stage configuration with optimal runner placement significantly improved system efficiency. These findings suggest that the two-stage vortex turbine design is promising for small-scale power generation in remote areas.

1 Introduction

Hydropower offers significant potential as a low-cost, sustainable, and environmentally friendly source of electricity [1]. In Indonesia, water resources such as rivers and lakes flow year-round and can be developed for hydropower generation [2,3]. Globally, hydropower accounted for only 6.7% of electricity production in 2021, while fossil fuels remained the dominant source at 82%. Among hydropower technologies, micro and pico-mini hydropower systems represent approximately 10 percent of global electricity demand and cover 91 percent of suitable locations worldwide [3,4].

Although Gravitational Water Vortex Turbines (GWVTs) have great potential, their practical application remains limited. This is mainly because turbine runner designs and overall system configurations have not been fully optimized to maximize energy conversion efficiency [5]. Addressing these design challenges is crucial to realizing the full capabilities of GWVT technology.

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GWVT is a promising micro-hydro technology that generates power below 100 kilowatts and operates efficiently under low head conditions ranging from 0.7 to 3 meters [6,7]. The turbine uses water flowing tangentially into a cone-shaped basin to form a strong vortex, with the outlet located at the basin's bottom [8]. Previous studies have explored various design and performance aspects of GWVTs. Dhakal et al. employed Computational Fluid Dynamics (CFD)simulations with ANSYS Fluent to demonstrate that conical basins achieve higher efficiency and power output than cylindrical basins under the same inlet conditions. Their findings indicated an optimal runner position between 65% and 75% of the basin height [8,9]. Srihari et al. experimentally investigated vortex intensification using different nozzle configurations in conical basins and showed that a vortex nozzle height of 200 millimeters significantly improved torque and turbine efficiency [10]. While these studies have advanced the understanding of single-stage turbines, the combined effects of runner position and blade spacing in multi-stage GWVT arrangements have not been thoroughly examined, primarily due to a lack of experimental validation.

Runner size also plays a vital role in turbine performance. Amanuel et al. found that increasing the runner diameter ratio enhances torque output and efficiency [11]. Cheema et al. reported that flow rate and vortex height influence turbine performance and that two-stage turbines outperform single-stage configurations [7]. Blade spacing is another critical parameter impacting vortex turbine efficiency, particularly in two-stage designs. Research by Amanuel et al. demonstrated that appropriate blade spacing reduces turbulence and stabilizes the vortex, increasing torque and power output [11]. Similarly, Cheema et al. demonstrated that blade spacing affects the pressure distribution and flow velocity across runner stages, thereby influencing the overall turbine efficiency [7]. Although individual studies have addressed basin shape, runner size, and vortex intensification, the combined effects of blade spacing and radial runner positioning in two-stage gravitational water vortex turbine configurations remain underexplored. Moreover, most research relies on numerical simulations or single-stage experiments, creating a significant gap in the experimental validation of multi-stage turbine designs. This lack of comprehensive experimental data limits the understanding of how these parameters interact to influence turbine performance. Therefore, an in-depth experimental study on the synergistic effects of blade spacing and runner position in two-stage GWVTs is crucial for optimizing design and enhancing energy conversion efficiency.

This experiment investigates the effect of varying runner diameters (90, 135, and 180 mm) while maintaining a constant basin diameter. Numerical analysis was conducted using CFD to simulate the flow behavior in a single-stage GWVT system. The results indicate that the 180 mm runner generates high torque at a rotational speed of 45 rpm, while the 135 mm runner achieves the highest power output of 2.12 W at 137.4 rpm. The maximum efficiencies recorded for the 90, 135, and 180 mm runners are 25.8%, 42.9%, and 41.2%, respectively. Based on these findings, the 135 mm runner demonstrates optimal power output and system efficiency performance compared to the other configurations [11]. The primary objective of this study is to assess the double-stage GWVT with varying runner positions in terms of turbine rotational speed, power output, and efficiency at different flow rates.

2 Methods

A basin is a water container with a cylindrical or conical shape used to create a water vortex [8]. Based on previous research, using a conical basin can provide better performance results than a cylindrical basin [9]. A conical basin can perform best using an orifice basin diameter ratio of 14% - 18%. The vortex gravity turbine consists of a cylindrical profile with different speeds. The flow velocity in the vortex is dominated by the tangential velocity, which the turbine blades can maximize. Turbines with curved shapes affect the efficiency produced by the turbine [3]. Research on multi-stage turbines was carried out by installing 2 or 3 turbines arranged in tiers [12]. A conical basin was chosen for data collection in this study. The method used to obtain turbine performance is the intrastaging method, which compares the turbine's performance in the same position with different stage configurations. In this research, this method compares the performance produced by the turbine with 2-level and 3-level configurations [13]. Based on this study, the selection of the ratio of increasing the different position runner ratios affects the efficiency produced by the turbine. This study will focus on the impact of the radial distance of the blade placement on the performance of the two-stage vortex turbine.

The conducted research was a laboratory-scale experimental assessment using a low-speed water tunnel, as shown in Figure 1. The low-speed water tunnel has two chambers, containing water in the bottom tunnel. The water is pumped into the top tunnel and then flows to the conical basin, creating vortex flow. Experimental design by adjusting the vortex head (*Hv*) to approximately 1.1 meters, a range encompassing most small rivers in Indonesia. The modification of the installation position of the two blades aims to determine the optimum performance achieved during the testing process.

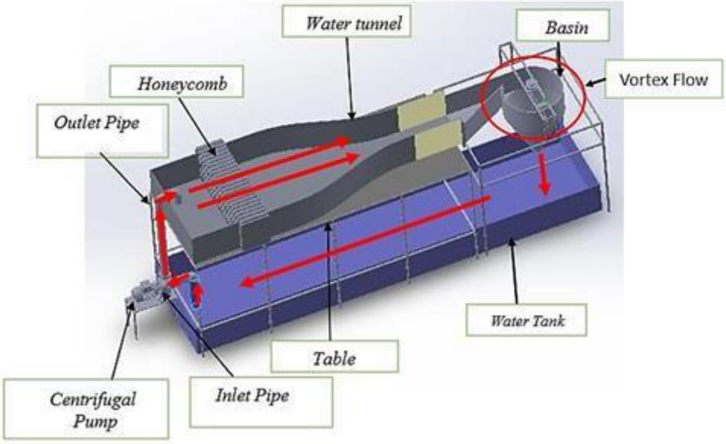
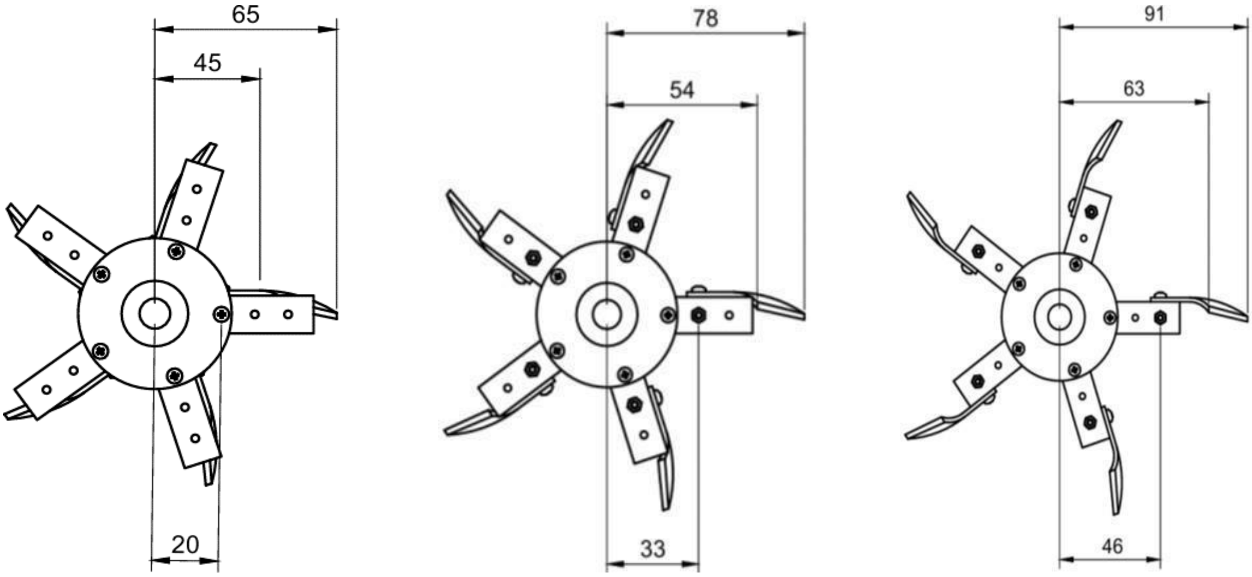


Figure 1. A low-speed water tunnel [14]

A certain amount of water mass is pumped into the upper water tunnel and flows into the conical basin, forming a vortex flow pattern, as shown in Figure 1. The testing was conducted using Savonius turbine profiles, with the geometric information shown in Table 1. The runner diameter is selected based on the fixed diameter of the output basin. Accordingly, the ratio represents the proportion between the turbine (runner) diameter and the basin diameter, as illustrated in Figure 2. The basin outlet size is 260 mm.

Table 1. Turbine geometry details

Runner Type	R (mm)	H_b (mm)	r-hub (mm)	r-axis (mm)
Savonius stage 1	115	150	25	6
Savonius stage 2	145	180	60	10.6



(a) (b) (c)

Figure 2. The runner ratio (a) 0.5, (b) 0.6, and (c) 0.7 mm

Stage 1 is the turbine installed at the bottom position near the exit basin hole, while Stage 2 is installed at the top near the inlet flow basin, as shown in Figure 3. The two-stage configuration utilises a telescopic shaft [13]. The performance of the turbines being compared includes torque, mechanical power, and turbine efficiency, which are measured using the measuring instrument displayed in Table 2. Data is obtained from readings taken by measuring instruments, including flow meters, tachometers, and a roll brake.

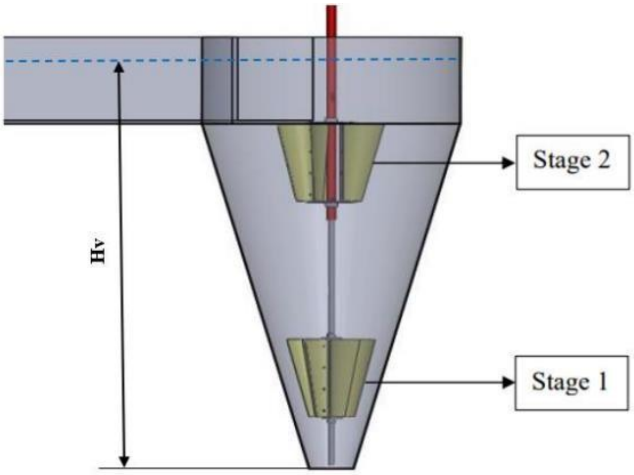


Figure 3. Turbine position [14]

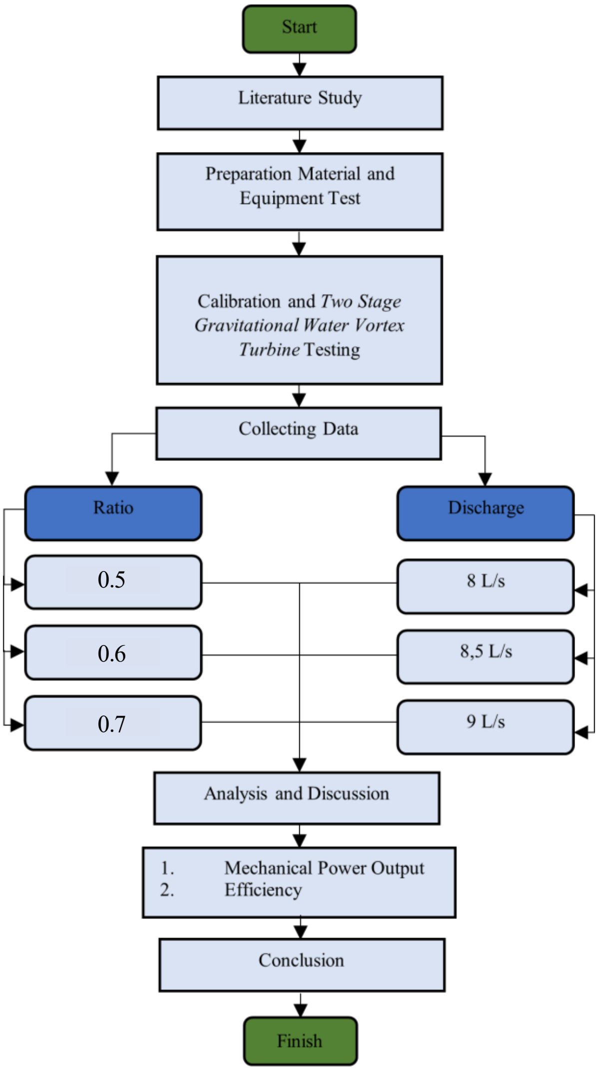


Figure 4. Research flowchart

In this study, the input flow rate that fills the upper tunnel also varied, using a valve opening mechanism adjusted according to the readings on the ultrasonic flow metre monitor, namely 8 L/s, 8.5 L/s, and 9 L/s. The Vortex turbine research utilizes a 2-stage Savonius turbine with five blades, featuring variations in blade placement distance. Each variation is tested with a different discharge. After obtaining the test results, namely rotational speed and power torque, the efficiency obtained is calculated based on the available equations. Meanwhile, a force loading mechanism is required to measure torque with a load cell read using Arduino. The load sensor will be installed on Stage 1 and 2 blades with varying loads and will be taken 3 times. The loading is carried out with the limitation of the water surface height in the basin, which can reach or exceed Stage 2 blade height. The experimental method and preparation are shown in Figure 4. This experimental study applied uniform loading at each stage to obtain the turbine performance in a 2 stage. Loading was conducted to evaluate the turbine performance with variations in the ratio and discharge.

3 General Equation

The fundamental data performance of the vortex turbine in this research was assessed using rpm, torque, mechanical power, and turbine efficiency results. The fluid flow rate in GWVT analysis can be calculated using Equation 1, where Hv represents the height of the vortex measured from the base of the conical basin outflow, ρ represents the density of water, and Q represents the water discharge in the tunnel [15].

$$P_{in} = \rho Q g H_v \tag{1}$$

The water vortex flow formed in the conical basin is hit by the runner blades and transformed into mechanical energy through rotation (N), which can be expressed as angular velocity ($\omega = 2\pi N / 60$). The torque from the turbine shaft (Tm) can then be calculated using Equation 2, and the mechanical power (Pm) can be calculated using Equation 3 [16].

$$T = F.r \tag{2}$$

$$P_m = T\omega \tag{3}$$

The roll brake system used to obtain the braking force result in Figure 7 is $F = m \cdot g$, where r is the radius of the pulley. The study aims to experimentally compare the performance of various runner profiles on two-stage runner gravitational systems under varying flow rate conditions. Whether a runner with a different position and ratio is suitable for installation in a two-stage system, and how it affects turbine performance.

4 Results and Discussion

The distance between the runner plate tip and the turbine axis influences the performance of a vortex turbine. Turbine rotation, mechanical power, and efficiency are parameters affected by variations in this ratio. The test data results are shown in Figures 5, 6, and 7. The first discussion concerns stage 1 of each position, with runner ratios of 0.5, 0.6, and 0.7 at different water discharge rates of 8 L/s, 8.5 L/s, and 9 L/s. Figure 5 shows stage 1 for each of the other position runner ratios (0.5, 0.6, and 0.7) and various water discharges of 8 L/s, 8.5 L/s, and 9 L/s. Figures 5a, 5b, and 5c show the results of mechanical power performance for each variation of turbine profiles in Stage 1 GWVT configuration. The highest mechanical power result in stage 2 is 12.18 W, with a ratio of 0.5, at a water discharge of 9 L/s. The results are 9.96 W at 8.5 L/s and 7.4 W at 8 L/s. A shorter position runner ratio impacts the value of mechanical power and torque, which is more optimal. This is caused by the energy from the water vortex converted by the turbine blade in the effective area of the water vortex flow.

Mechanical power is predominantly dominated by the turbine with a 0.5 ratio, compared to the turbines with 0.6 and 0.7 ratios. This is based on the theoretical torque equation (see Equation 3), as a 0.5 ratio has a shorter coverage position for the turbine to receive a certain amount of water momentum [13].

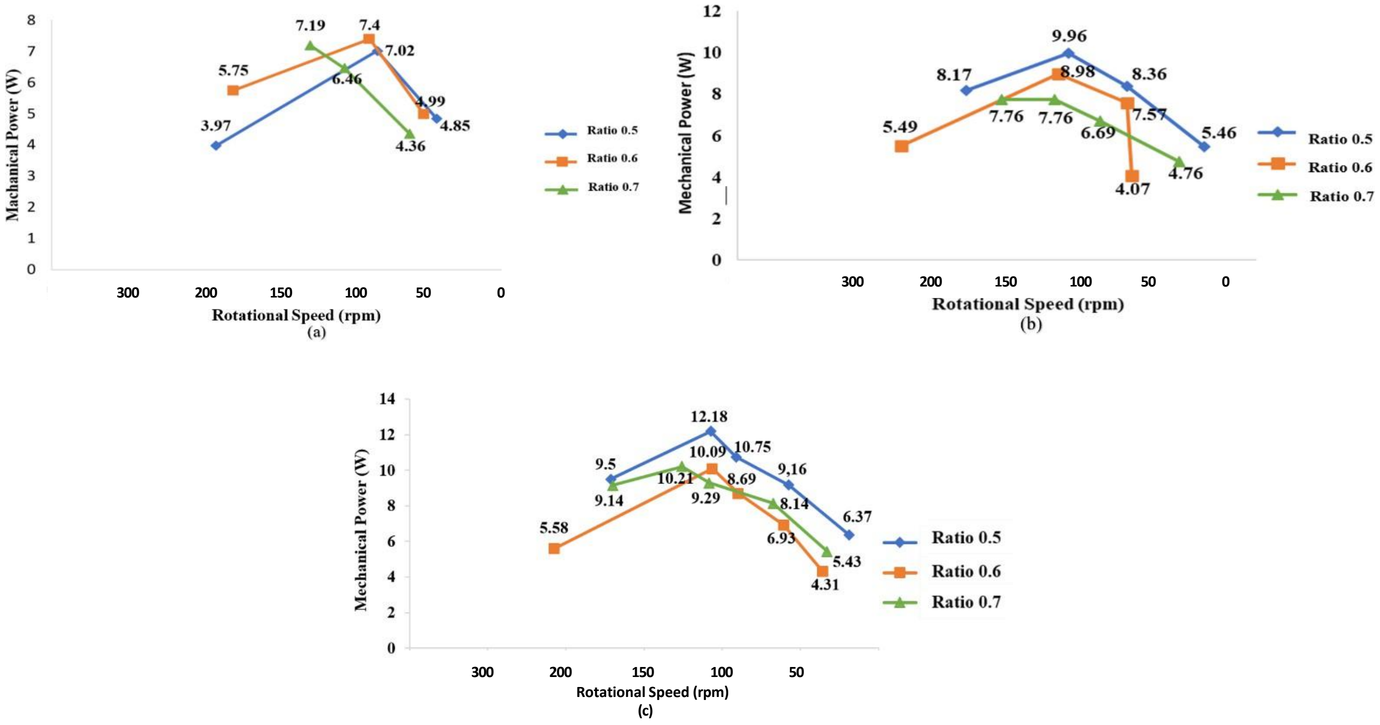


Figure 5. The plotted mechanical power comparison of stage 1 runners with different discharge: (a) 8 L/s, (b) 8.5 L/s, and (c) 9 L/s

However, there is an anomaly in Figure 5a, where the decrease in water discharge affects the mechanical power results. This is caused by the energy from the water vortex, as converted by the Savonius blade in the effective area, being less than optimal. It is indicated by a blade with a ratio of 0.5, producing less than optimal performance, with a mechanical power of 7.4 W.

Figure 6 shows stage 2 for each of the different position runner ratios (0.5, 0.6, and 0.7) and various water discharges of 8 L/s, 8.5 L/s, and 9 L/s. Figures 6a, 6b, and 6c show the results of mechanical power performance for each variation of turbine profiles in Stage 2 GWVT configuration. The highest result of mechanical power in stage 2 is 16.69 W with a ratio of 0.5 in the 9 L/s water discharge, 10.79 W in the 8.5 L/s, and 7.67 W in the 8 L/s. A shorter position runner ratio impacts the value of mechanical power and torque, which is more optimal. This is caused by the energy from the water vortex converted by the turbine blade in the effective area of the water vortex flow.

Mechanical power is predominantly dominated by the turbine with a 0.5 ratio, compared to the turbines with 0.6 and 0.7 ratios. This is based on the theoretical torque equation (see Equation 3), as a 0.5 ratio has a shorter coverage position for the turbine to receive a certain amount of water momentum [13]. However, there is an anomaly in Figure 9a, where the decrease in water discharge affects the mechanical power results. This is caused by the energy from the water vortex, as converted by the Savonius blade in the effective area, being less than optimal. It is indicated by a blade with a ratio of 0.5, producing less than optimal performance, and the mechanical power is 7.67 W.

Based on Figure 7a, stage 1, with a discharge of 9 L/s and a ratio of 0.5, exhibits the highest efficiency among the other ratios. Stage 1 turbine achieves its maximum efficiency of 12.39%. This is caused by the energy from the water vortex converted by the turbine blade in the effective area of the water vortex flow. Utilizing a contact angle that flows the water velocity to create a more stable water vortex, a ratio of 0.5 keeps the water flowing tangentially. However, there is no discernible difference in the efficiency of the turbine. In particular, Stage 1 turbine, which is heavily impacted by the ratio and discharge, requires careful consideration when choosing the blade.

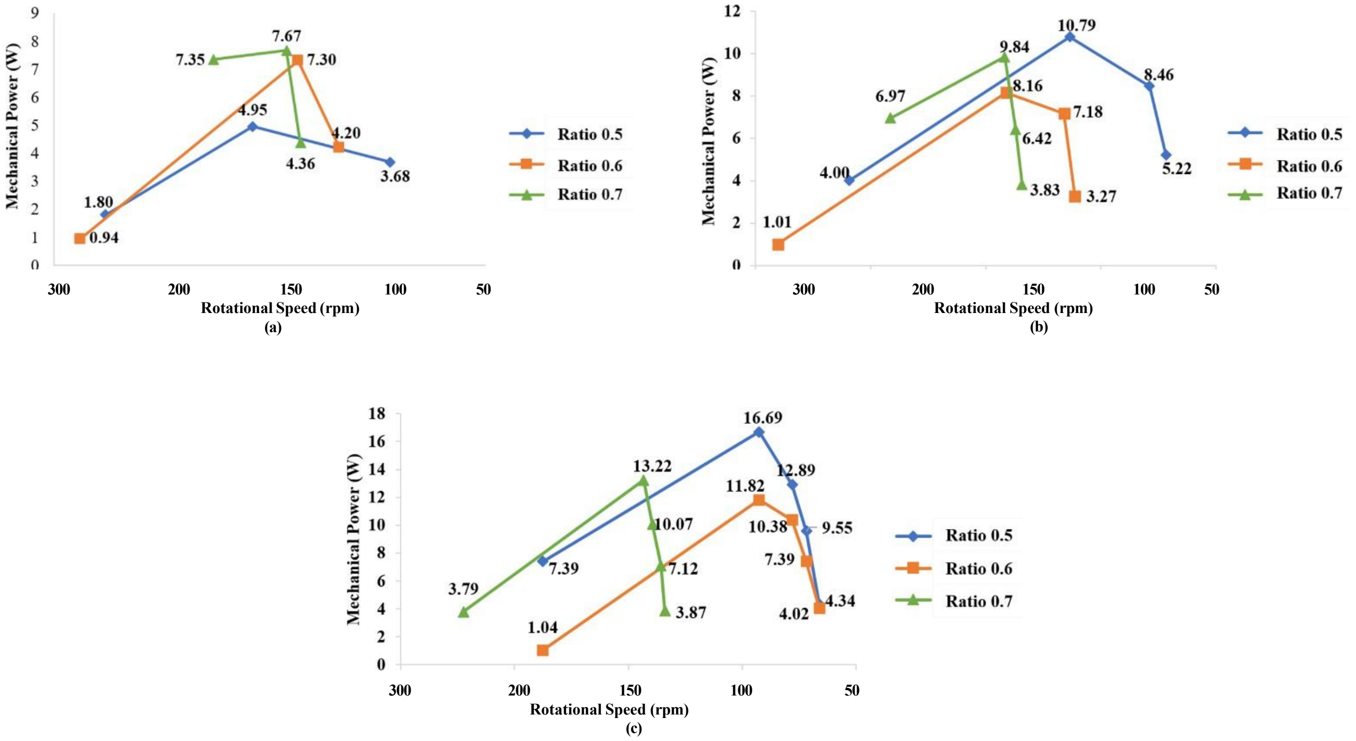


Figure 6. The plotted mechanical power comparison of stage two runners with different discharge: (a) 8 L/s, (b) 8.5 L/s, and (c) 9 L/s

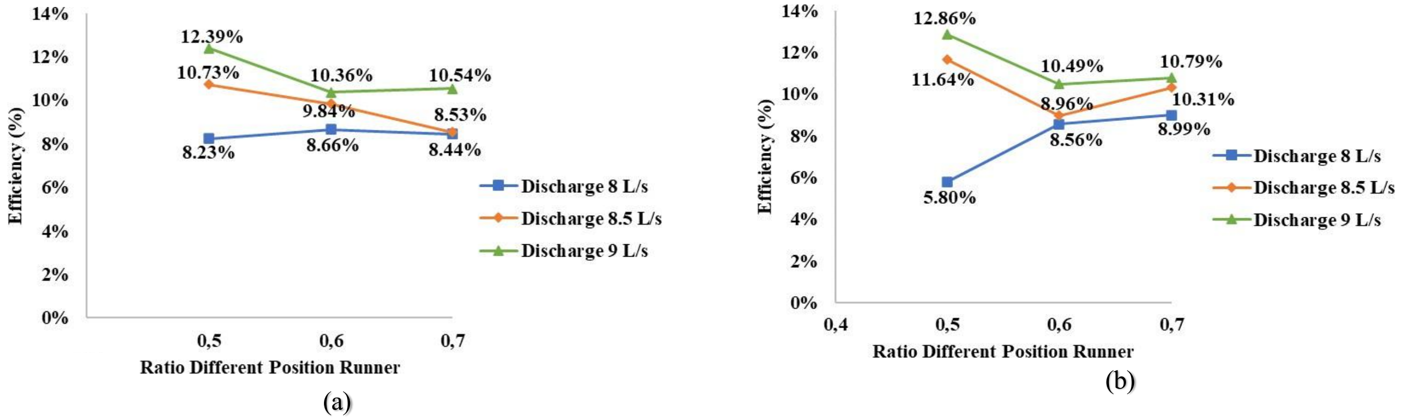


Figure 7. The plotted efficiency comparison of different discharges with positions: (a) Stage 1 and (b) Stage 2

Figure 7b shows that at stage 2, with a discharge of 9 L/s and a ratio of 0.5, it achieves greater efficiency than other ratios. The stage 2 turbine achieves its maximum efficiency of 12.86%. This is caused by the energy from the water vortex converted by the turbine blade in the effective area of the water vortex flow. Utilizing a contact angle that flows the water velocity to create a more stable water vortex, a ratio of 0.5 keeps the water flowing tangentially. However, there is no discernible difference in the efficiency of the two design types. In particular, Stage 2 turbine, which is heavily impacted by the ratio and discharge, requires careful consideration when choosing the blade.

5 Conclusions

The study shows that the mechanical power of the GWVT turbine increases with higher water discharge and runner position ratios. At discharges of 8.5 L/s and 9 L/s, the 0.5 ratio consistently produces the highest mechanical power, reaching 10.79 W and 16.68 W, respectively. Stage 2 configuration performs better than stage 1, with a maximum output of 16.69 W. In contrast, stage 1 reaches only 12.28 W.

These results indicate that the right combination of water discharge and runner ratio significantly enhances turbine power and efficiency. For future research, CFD simulations will be conducted to analyze the vortex interactions between Stage 1 and Stage 2 runners. Test turbine performance under variable flow rates to assess stability and dynamic response. Both methods provide critical data with minimal changes to the turbine hardware.

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