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Experimental Study of the Blade Geometry Effect of Two-Stage Gravitational Water Vortex Turbine

Daniel Aderson Sinaga[1], Zainal Arifin[1], Singgih Dwi Prasetyo[1,2], Solikin Andriyanto[1], Muhamad Dwi Septiyanto[1], Syamsul Hadi[1*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia
[2] Department of Power Plant Engineering Technology, Faculty of Vocational Studies, State University of Malang, Malang 65145, Indonesia

Corresponding Author Email: syamsulhadi@ft.uns.ac.id

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ABSTRACT

This study investigates blades of varying geometries in the context of a two-stage Gravitational Water Vortex Turbine (GVWT). The objective was to identify the optimal blade shape and radius yielding the best rotational speed, mechanical power, and efficiency for a two-stage vortex turbine. Specifically, the study examined parameters such as the Savonius shape and curvature, utilizing different blade ratios on two separate shafts. The turbines were configured with a telescopic system positioned at a distance of 10 cm apart. Each variation was subjected to loads ranging from 0.5 kg to 2 kg. Various performance metrics—rotational speed, torque, and water height—were assessed following load adjustments. Turbine Stage 1, employing the Savonius blade, achieved an optimal mechanical power output of 12.4 W, while Turbine Stage 2, utilizing a curved blade, reached a maximum mechanical power of 11.1 W. The Savonius blade demonstrated higher torque, operating more efficiently under greater loads. Notably, the water vortex with a larger air core experienced distortion caused by the turbine, leading to unstable flow. In contrast, implementing curved blades with a ratio of 0.5 provided the water vortex ample space to flow, resulting in a more stable vortex formation. Thus, carefully considering the optimal contact area and blade geometry is essential to minimize water vortex distortion in each turbine.

1. INTRODUCTION

Recently, the energy issue has become a topic of discussion that has shaken the world, especially in the energy sector. The post-pandemic conflict has caused fossil-based energy sources to become more expensive [1]. As a result, this crisis has caused a spike in world prices, which has led to demands for a shift from fossil fuels to alternative energy. Subsidies amounting to 131 trillion rupiah in 2022 indicate a significant energy crisis in Indonesia [2]. Energy has become a primary human need and is in line with the increasing population. Non-renewable energy sources such as oil, gas, and coal are still the primary needs [3]. Due to this energy dependence, alternative energy sources are needed to address the need for energy resources, which are increasingly limited in both quantity and reserves [4]. One of the types of energy that is most needed today is electrical energy. Electricity production 2018 reached 283 TWh, generated from power plants using 20 % gas fuel and only 6.3% BBM, while 17.1% came from new renewable energy sources. The minimal utilization of renewable energy resources is caused by the high production price of renewable energy-based power plants, making it difficult to compete with fossil-based power plants, especially coal [5]. One of the uses of renewable energy is hydroelectric power plants. Hydroelectric power plants are an energy source that can be optimized significantly to minimize the global energy crisis [6]. Energy needs will continue to increase, especially in developing countries. Renewable energy, such as hydropower, is one of the most needed energy sources. It is necessary to build irrigation systems that can be connected to small-scale turbines to produce electricity in some remote regions [7]. Low-head hydroelectric power plants are needed in areas with inadequate geographical conditions [8].

The Gravitational Water Vortex Power Plant (GWVPP) is a renewable energy plant that harnesses water vortex flow within a basin as its driving fluid, operating at low head and classified with mini-micro hydrokinetic-scale turbines [9]. The smaller outlet hole geometry than the entrance basin generated in water core velocity distribution, which can be harnessed by the turbine rotor. According to the reference, this turbine operates at relatively low heat, with a range of 0.7-3 m and an average discharge of 50 L/s [10, 11]. The advantages of this generator are that it can generate electricity from low hydraulic pressure and is environmentally friendly. With a low hydraulic head height of 1 m, vortex turbines can be installed in rivers or streams to generate electricity for several homes [12]. Vortex is the phenomenon of the formation of a whirlpool when entering a container or basin; the flowing water will move tangentially at the inlet and outlet at the center of the vortex to rotate the turbine blades [13]. Water gradually flows due to gravity, causing the rotational speed of the water to increase and descend downwards. The pressure drops below atmospheric pressure and causes air to enter and form an air core. After that, the water will flow through the hole at the bottom of the container. The turbine blades rotate in the vortex and generate electricity when the shaft is coupled to the generator [14]. Micro-hydropower plants are a new renewable energy source of particular concern. This is because the capacity to generate electrical energy ranges from several Watts to hundreds of kilowatts [15]. Micro-hydro power generation is gaining attention to be applied in tropical areas with relatively low-velocity river flow. The other intriguing aspects of this technology include its relatively small investments, low manufacturing costs, and ease of construction compared to other methods. These benefits can meet electricity demand in rural areas or areas without the electricity grid channel [16].

Conducting efforts to modify the shape and manner of the vortex turbine's design is essential to harness the maximum energy and efficiency, as long as we can achieve cheaper investment costs. Chattha et al. conducted an insightful numerical analysis using the basin geometry and vortex profile as their independent and dependent variables, respectively. Several basin designs in their research were tested with CFD software. The results indicate a linear increase in the vortex profile between the applied discharge and the water level, with this high vortex exhibiting a relatively high maximum tangential velocity [17]. Additionally, optimizing the vortex flow behavior, particularly its velocity, can be achieved with a relatively small notch inlet at an angle [18]. Understanding parameters such as hub diameter, blade inclination angle, blade installation position, and curvature angle is crucial for achieving the highest optimum power output [18]. The smaller notch angle results in a higher rotational speed and profile flow. The installation position can yield a more optimal rotational turbine with the highest brake power, approximately 3 cm from the outlet basin. The vortex profile has radial and axial velocities, which must be considered in the presence of an inclined blade to get optimum torque [14]. Due to the higher load, ω decreased naturally as the SB was changed to increase the resistance to the turbine movement, lowering the tank's water level. However, it appears that significant force was used to achieve the maximum power outputs and efficiencies whenever the power output depends more than on ω but also on the torque caused by the resistance force. The ideal SB setting for all blade designs seems to be halfway between the highest force measurement, which indicates no turbine rotation, and a zero force reading, which indicates turbine free flow [19, 20].

Ullah et al. have conducted experimental research on the performance of multi-stage vortex turbines on a cone-shaped basin. The study was conducted using the intra-staging, inter-staging, and rotor ratio variation methods, using a combination of distance between stages. With a flow rate of 4 L/s, a valve installed on the inlet channel regulates the vortex's height. Based on this research, it was concluded that the distance between stages also influences the efficiency of a multi-stage turbine. By varying the distance, the overall performance of the turbine will increase [21]. Research conducted by Cheema et al. shows the influence of flow rate and vortex height. The flow rate is obtained to determine the minimum value of the instantaneous vortex height touching the runner at stage 2. The results of the study showed that using a two-stage turbine design provides better performance than a one-stage turbine [22]. The influence of these parameter variations shows that the flow rate and vortex height greatly influence the performance of each stage in the turbine. The difference in flow in the water vortex causes differences in the turbine rotation speed. With a lower blade diameter, the turbine blade can achieve maximum rotation speed with relatively low torque. Conversely, a higher blade diameter provides maximum torque results with low rotation speed [23].

Based on the previous research, several earlier experiments were used to choose different blade shapes and rotor-basin ratios. When the water flow tends to travel axially, the curved shape can improve loading performance and better utilize angular momentum [24]. The Savonius shape prefers to use tangential flow and has greater torsional resistance. In earlier research, the rotor-basin ratio was determined both experimentally and numerically. Using values that are too high or too low can result in decreased performance and a failure to generate the maximum amount of mechanical power. An efficiency of 42.9% can be attained by numerical simulation [25] for a turbine with a rotor-basin ratio of 0.27. Experimentally, rotor-basin ratios of 0.6 and 0.79 yield the best mechanical power; nevertheless, the two turbines' diameter sizes differ in shape [21]. Additionally, the size is taken into account while choosing rotor-basin ratio variations so that they can be employed experimentally.

This study will test a two-stage vortex turbine with different blade shapes and rotor-basin ratios, while the two-stage turbine will use the same shape and ratio. The study involves two distinct blade types—flat Savonius blades and curved blades—and three rotor-to-basin ratios: 0.5, 0.6, and 0.7. The testing process focuses on analyzing the influence of these variations on the turbine's rotational speed, power output, and overall efficiency.

2. EXPERIMENTAL SETUP AND METHODOLOGY

2.1 Experimental methodology

Gravitational Water Vortex Turbine is a turbine that uses a vortex formed in the basin to generate power. The research will be conducted with a simple setup based on previous research to create a whirlpool formed from fluid moving at a certain speed. The tool is a Water Tunnel (refer to Figure 1). The water in the tub will be pumped through the inlet pipe to the outlet pipe.

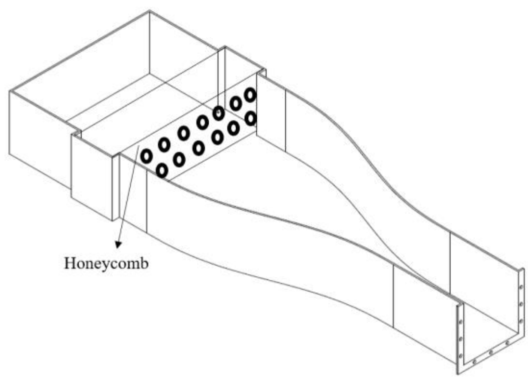
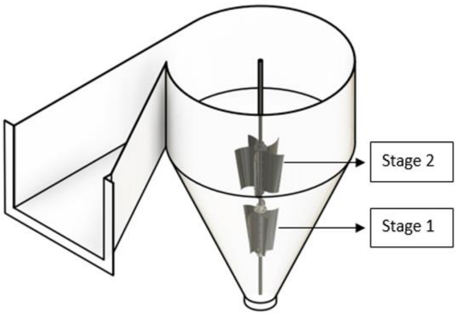


Figure 1. Water tunnel

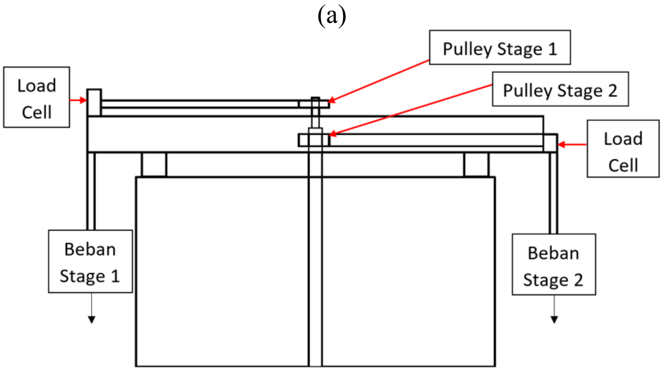
Honeycomb is used in the water tunnel to create a more laminar flow and less turbulence, which makes the flow more stable and creates a water vortex as it passes down the tunnel and into the basin. The turbine will then be propelled by the water vortex striking the blades.

Naturally, the water vortex that forms in the basin results from naturally occurring flow, and the presence of a turbine perturbs the vortex's shape. Increased axial and radial velocity and decreased tangential velocity result in a decrease in the vortex's height. A reduction in turbine speed results from this flow instability and the performance that can be attained is restricted to specific loads [26].

According to earlier research, conical basins perform better than cylindrical basins. The optimal vortex performance is achieved with conical basins, which have an orifice basin diameter ratio of 14% to 18% [18, 27]. In this study, a basin with a ratio of 17% was utilized to create a powerful vortex generation [28]. The turbine is placed on the different shafts with a telescopic schematic, as shown in Figure 2(a).



(a)



(b)

Figure 2. (a) Two-stage GWVT setup and (b) Prony-brake setup)

The research on the Vortex Two-Stage turbine will be conducted using a 2-stage turbine with five blades and variations in blade shape and rotor-basin ratio size. A turbine with five blades is the optimal number of blades in a vortex turbine. This occurs because the water vortex and blades' contact area are in ideal condition, increasing torque [29]. The shape variations used are flat and curved blades. Theoretically, a cylindrical profile with varying speeds makes up the vortex gravity turbine. The tangential velocity that the turbine blades can use dominates the flow velocity in the vortex. The Savonius design and curved shapes impact the vortex turbine's efficiency in making the most of the solid tangential flow [24, 30]. A test or testing of the blade position in the basin is carried out to determine the rotor-basin ratio. To maximize the tangential flow on the turbine [31], the position of the stage 1 turbine blade is placed 0.15 m above the orifice hole. Testing of each variation will be carried out at a constant fluid discharge. A tachometer is used to measure rotational speed. Data is gathered for each load to ascertain each turbine's maximum output in the two-stage system, and a 0.5 kg load increment is used to improve performance in each loading variation. Various load variations can be used with certain load constraints to maximize performance on other turbines. Its load consists of 0.5 kg, 1.0 kg, 1.5 kg, and 2.0 kg for each stage 1 and 2 variations. The installation position of the load cell is illustrated in Figure 2(b). After obtaining the rotational speed and torque values, the efficiency value will be calculated using the available equation. The data collection method is carried out using the Arduino application. The load sensor will be installed on the stage 1 and 2 blades with varying loads and taken 3 times. The loading is carried out with the limitation of the water surface height in the basin, which can reach or be higher than the stage 2 blade. The experimental method and preparation are shown in Figure 3.

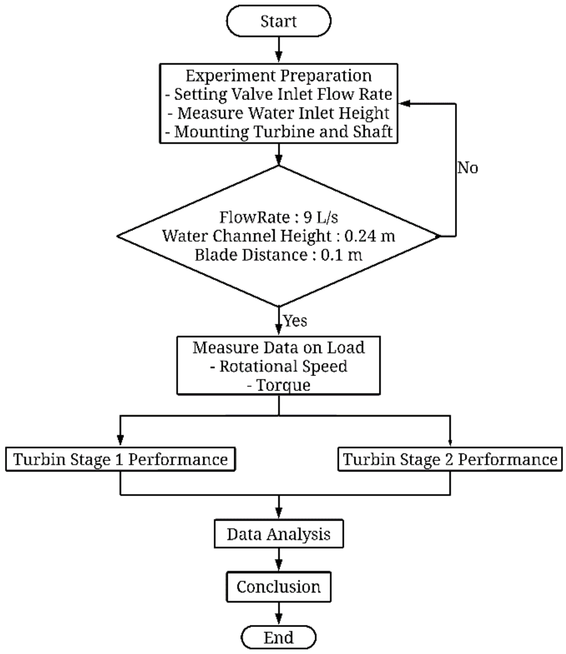
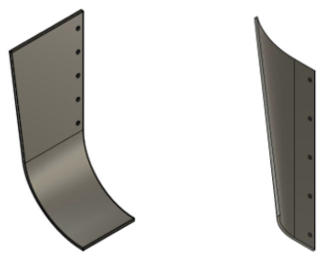


Figure 3. Experimental flowchart

This experimental study applied uniform loading at each stage to obtain the turbine performance in a double-stage whirlpool turbine arrangement. Loading was conducted to evaluate the turbine performance with variations in size and shape. Figure 4 shows the shape of the blade used in this experiment. The two-blade design experimented with three different ratios to determine the optimal geometries in a two-stage gravitational water vortex turbine. The difference in runner size was adjusted using the diameter ratio between the runner and the basin. This was done to change the blade geometry shape's effectiveness to the whirlpool's contact area with the turbine runner.



(a) (b)

Figure 4. (a) Curved blade, (b) Savonius blade

2.2 Governing equation

In the present study, a two-stage turbine was positioned at the same height along the shaft. Two locations for each turbine have been chosen at a distance of 0.15 m and 0.4 m from the bottom of the conical basin and designed as stages 1 and 2, respectively. The flow rate used is 9 L/s constant in all variations. They uniformly use the same design in each stage to examine the distortion caused by the turbine and find the best performance for each ratio rotor-basin and blade shape.

$$\omega = \frac{2\pi N}{60} \tag{1}$$

ω is the rotational speed of the turbine, measured by the tachometer to determine performance based on the load.

$$F = mg \tag{2}$$

The load value will work as a brake torque so that the loading value on the load cell can be used as the turbine's total mass (m).

$$T = Fr \tag{3}$$

The mass value is generated from the rope brake system, which will produce the total mass in the turbine and is measured using a load cell tool. The amount of force calculated comes from using a load cell so that the torque (T) on the turbine can be defined.

$$P_{in} = \rho g Q H \tag{4}$$

Hydraulic power (P_{in}) comes from the flow of fluid that flows with a specific discharge towards the basin and moves rotationally so that a vortex is formed with a certain height. ρ is the fluid density, g is the gravitational acceleration with a value of 9.8 m/s^2, Q is the fluid discharge, and H is the vortex head.

$$P_m = T\omega \tag{5}$$

Turbine mechanical power (P_m) is the power generated from the rotation of the shaft with a specific torque and speed value. T is torque (N/m), and ω is the angular velocity (rad/s).

$$\eta = \frac{P_m}{P_{inn}} \times 100\% \tag{6}$$

The efficiency (η) is the percentage of cumulative turbine power produced (P_m) on the available power in the basin (P_{in}).

2.3 ANOVA two-factor

In the present study, ANOVA was conducted to analyze the influence of factors on the research results. Three variables affect the turbine's performance: load, blade shape, and rotor-basin ratio. Two primary variation data were selected for analysis as the primary components due to the highly diverse data. The factors examined in this study were the turbine's design and ratio, which impact its mechanical power. The parameters used for this investigation were the design and rotor-basin ratio of the turbine to its mechanical power. The data taken was the highest value of all variations of the blade ratio and design to the mechanical power value. Several hypotheses will be determined for each factor.

-Hypothesis on design factors:

Ho: there is no difference in mechanical power in all design variations

Ha: there is a difference in mechanical power in all design variations

-Hypothesis on the Blade Ratio factor:

Ho: there is no difference in mechanical power in all blade ratios

Ha: there is a difference in mechanical power in all blade ratios

-Hypothesis for the interaction between design and blade ratio:

Ho: there is no interaction between design and ratio in influencing mechanical power

Ha: there is an interaction between design and blade ratio in influencing mechanical power

The level of significance used is 0.05 so that the decision of the hypothesis for each factor is

If the p-value > 0.05, then the null hypothesis is accepted, meaning that there is no significant influence of the factor or interaction on mechanical power

If the p-value < 0.05, the null hypothesis is rejected, meaning that the factor or interaction significantly influences mechanical power.

3. RESULTS

3.1 Turbine stage 1 performance

The diameter ratio between the runner and the basin is used to identify the difference in runner size. This increases the blade's geometric shape efficacy about the water vortex's contact area with the turbine runner. The size and shape of the rotor compared with the contact area of the water vortex flow affects each turbine's rotational speed, which generates different amounts of mechanical power.

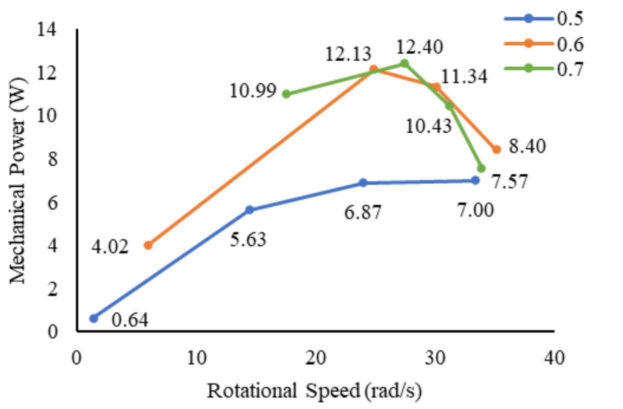


Figure 5. Savonius blade performance

Figure 5 shows the experimental data for turbine stage 1; it was obtained that the ratio of 0.7 had the best performance in all load variations. Savonius blades, with a ratio of 0.7, produced a mechanical power of 12.4 W with a loading of 1.5 kg. The mechanical energy of both variations of the blade shape gave quite significant results at ratios of 0.6 and 0.7. The blade's geometry at each loading has a different effect on the structure of the water vortex flow. A larger rotor-basin 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. The effective water vortex area is obtained when the runner basin ratio is at a specific value. The lower water vortex radius position produces unstable fluid tangential velocity. It is indicated by a blade with a ratio of 0.5 producing less than optimal performance.

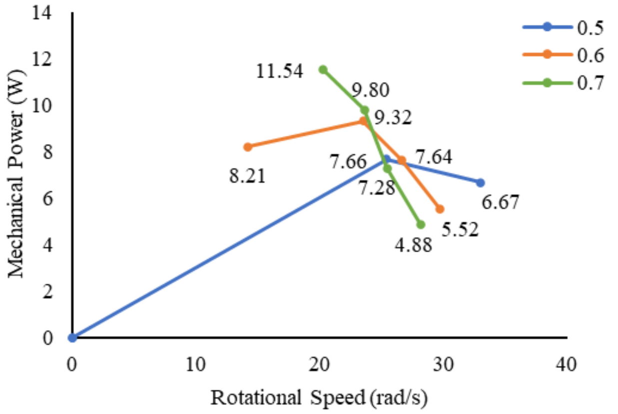


Figure 6. Curved blade stage 1 performance

According to Figure 6, curved blades with a ratio of 0.7 produce an optimal power of 11.54 W with a load of 2 kg. The curved blade shape with a ratio of 0.7 can achieve this power because the torque of the turbine can withstand high loads, resulting in more optimal power. This occurs based on the theory of water vortex, which states that water vortexes have two different areas: rotational and irrotational. The rotational area is an area that is unstable at a particular position. The rotational flow is dominant in the position around the water core, with the maximum fluid velocity obtained. However, the torque resistance force that results is decreasing to the point where it is insufficient to propel the turbine with a smaller radius. It impacts the turbine with a blade ratio 0.5, producing low power and rotational speed. The formation of a flow in a whirlpool that occurs in the basin must also be considered because a higher ratio between the turbine blades and the basin can disrupt the formation of a whirlpool. This disturbance can cause the structure of the whirlpool flow challenging to form and cause the turbine to rotate incorrectly.

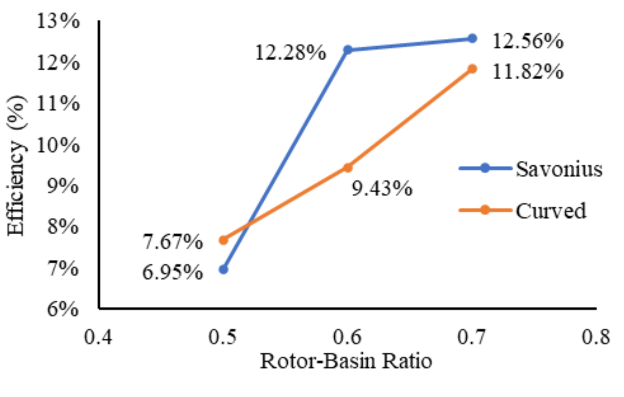


Figure 7. Efficiency turbine stage 1

At stage 1, there was no discernible variation in the optimal mechanical power produced by the two blades' different shapes; the percentage difference between them was only 7.18%. The rise in the ratio between 0.5 and 0.6, where the value obtained was 53.63%, and between 0.6 and 0.7, where the value obtained was 2.2%, differed significantly with the Savonius blade. Furthermore, using a curved blade, the percentage difference between the ratios of 0.5 and 0.6 and 0.6 and 0.7 was found to be 19.55% and 21.28%, respectively. The Savonius blade achieves the maximum efficiency for a single-stage turbine, with 12.56%, as shown in Figure 7. This is caused throughout an ideal contact area in the Savonius blade's radius of curvature. Furthermore, the Savonius shape tends to make the water flow more uniform and does not alter the basin's water vortex's shape.

3.2 Stage 2 turbine performance

The first and second stage blades are 0.1 m apart to maximize water eddies' formation. This is done to optimize the vortex flow structure and the height of the water vortex formation between the two turbines. In addition, the turbine's efficiency is also influenced by the immersion of the water vortex against the turbine blades.

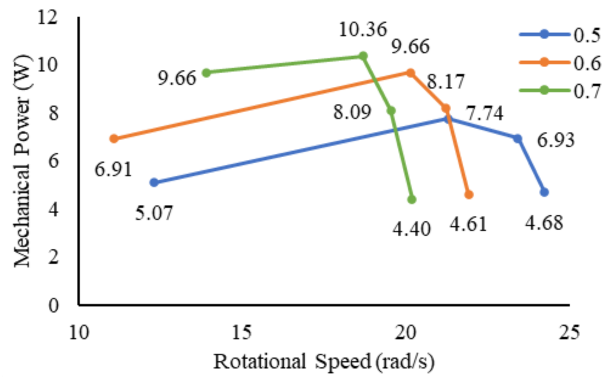


Figure 8. Savonius blade stage 2 performance

Based on Figure 8, the performance of the stage 2 Savonius blade turbine with a ratio of 0.7 produces the highest mechanical power of 10.36 W. Savonius blades with smaller radii have higher rotational speed. However, the mechanical energy generated is relatively low. This is caused by the less optimal contact area of the blade flow, which causes the torque obtained by the turbine to be low. Based on the Euler equation, tangential velocity and contact angle significantly affect the torque value generated by the turbine. The high turbine speed at initial loading is due to the turbine area being in an area with high tangential velocity. Disturbances in the flow structure are also experienced by the stage 2 turbine, which is also affected by the stage 1 turbine. However, with a fixed immersion height at each stage, the uniform loading does not cause a difference in the power available in the whirlpool.

Based on Figure 9, the performance of the stage 2 curved blade turbine, with a ratio of 0.5, produces the highest mechanical power at 11.1 W. The stage 1 turbine that stops rotating at a specific load causes the fluid moving around the stage 2 turbine to be more stable, forming a solid vortex flow. This is because the turbine with a smaller ratio has a lower resistance force. The low resistance force causes the turbine to tend to stop rotating. The energy stored in the vortex is concentrated to form a more stable flow and is used by the curved stage 2 blade. This is indicated by the 1.5 kg and 2 kg loading on the curved blade with a ratio of 0.5, producing higher mechanical power than other ratios. In addition, the mechanical power results of the stage 2 turbine produced between the Savonius and curved designs are obtained more optimally by the curved design with a ratio of 0.5. The Savonius shape has a curvature angle that can maximize the flow contact area, so the converted energy is higher at stage 1. On the other hand, the air core formed at stage 2 flow is quite large, so a contact area that is too large can interfere with the formation of a water vortex at stage 2.

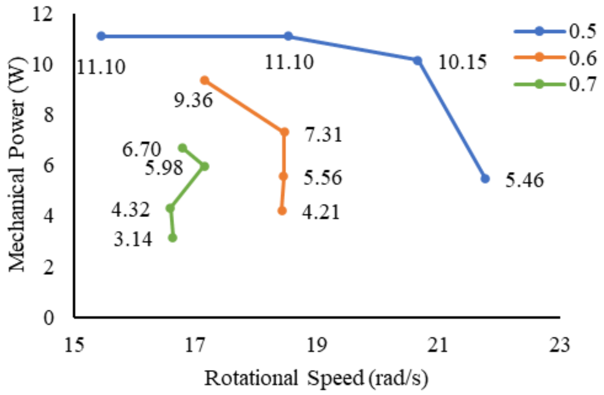


Figure 9. Curved blade stage 2 performance

At stage 2, there was no discernible variation in the optimal mechanical power produced by the two blades' different shapes; the percentage difference between them was only 6.89%. It was discovered that the Savonius blade caused a very large difference in the growth in the ratio between 0.5 and 0.6, where the value achieved was 22.07%, and the ratio between 0.6 and 0.7, where the value obtained was 7%. Employing a curved blade, it was discovered that the percentage difference between the ratios of 0.5 and 0.6 and 0.6 and 0.7 was 17% and 33.1%, respectively.

Based on Figure 10, the curved design with a ratio of 0.5 produces more efficiency at stage 2. The stage 2 turbine achieves its maximum efficiency of 11.37%. This results from an insufficient turbine-to-rotor ratio that does not alter the water vortex's form. Because of the torque resistance force, the Savonius blade offers a higher efficiency at a more excellent ratio. Utilizing a contact angle that flows the water velocity to create a more stable water vortex, the Savonius shape keeps the water flowing tangentially. However, there is no discernible difference in the efficiency of the two design types. In particular, the stage 2 turbine, which is heavily impacted by the ratio and design, requires careful consideration when choosing the blade geometry.

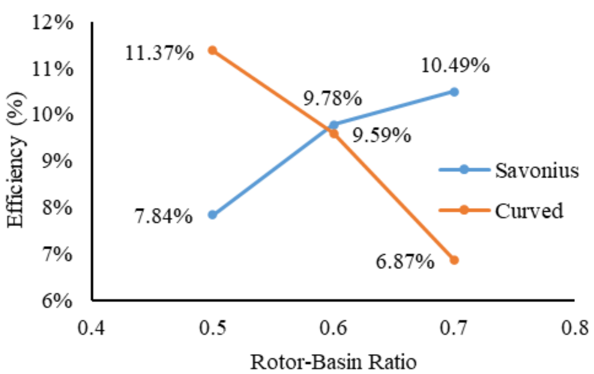


Figure 10. Efficiency turbine stage 2

3.3 ANOVA

ANOVA 2-factor analysis was performed on stages 1 and 2 to determine each factor's effect on the turbine's mechanical power.

Table 1. Analysis of varian turbine stage 1

Source	SS	df	MS	Fo	P-Value	F-Table
Ratio	69.12	2	34.5	30.67	1.92×10^{-5}	3.885
Design	4.53	1	4.53	4.02	0.068	4.747
AB	9.12	2	4.56	4.04	0.045	3.885
Error	13.52	12	1.127			
Total	96.3	17				

Based on Table 1, it is obtained that the ratio factor provides a p-value < 0.05 so that it can be concluded that the effect of the ratio on the mechanical power of stage 1 is significant, while for the p-value of the design factor, the design is > 0.05 which indicates that the design does not have a substantial effect on the mechanical power of stage 1. Table 1 also shows that the interaction between factors is not significant. In addition, the p-value < 0.05 indicates that the rotor-basin ratio has an independent effect on mechanical power and is not affected by design factors.

Table 2. Analysis of varian turbine stage 2

Source	SS	df	MS	Fo	P-Value	F-Table
Ratio	3.53	2	1.763	3.780	0.053	3.885
Design	0.17	1	0.172	0.369	0.554	4.747
AB	36.9	2	18.452	39.575	5.21×10^{-6}	3.885
Error	5.60	12	0.466			
Total	46.2	17				

Table 2 shows that the ratio and design factors provide a p-value > 0.05, so it can be concluded that the effect of the ratio and design on the mechanical power of stage 2 is not significant. In contrast, the interaction effect < 0.05 indicates that the interaction between factors significantly impacts the mechanical energy of stage 2. The indication of interaction between these factors shows that each factor does not independently have a significant effect on the mechanical energy of stage 2.

4. CONCLUSION

Experimental studies have been conducted to determine the performance of the 2-stage vortex turbine. The highest performance of the 2-stage vortex turbine is obtained by stage 1, with a Savonius ratio design of 0.7, producing a mechanical power of 12.4 W. Stage 2, with a curved ratio design of 0.5, produces a mechanical power of 11.1 W. The stage 2 vortex turbine with a Savonius ratio design of 0.7 and a curved ratio design of 0.5 produces optimal mechanical power. The performance of the 2-stage vortex turbine is greatly influenced by the rotor-basin ratio of stages 1 and 2.

The difference in the shape of the Savonius and curved designs does not significantly affect the mechanical power value of the stage 1 turbine. This shows that the air core does not dominate the vortex area in stage 1. On the other hand, in stage 2, there is an influence from the design and ratio, so it is essential to consider the geometric shape that can maximize the torque resistance force and the performance of the stage 2 turbine.

This experimental study used a laboratory scale, resulting in relatively low mechanical power or efficiency. However, the researcher posited that performance in real-world conditions could improve if optimized for locations with large-scale and consistent river discharge year-round. Implementing this double-stage vortex turbine offers extensive advantages in its application, particularly in regions with low-head rivers ranging from 0 to 1 m. The turbine demonstrates high efficiency regarding construction and maintenance expenditures. To achieve optimal results, it is recommended that the researcher utilize a higher conical basin geometry. This offers a distinct benefit in the optimization process of water energy conversion through the operation of stage 1 and stage 2 turbines.

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NOMENCLATURE

m	mass, kg
F	force, kg.m.s^{-2}
g	gravitational acceleration, m.s^{-2}
H	head, m
T	torque, kg.m^{2}.s^{-2}
P	power, kg.m^{2}.s^{-3}

Greek symbols

ρ	fluid density, kg.m^{-3}
ω	rotational speed, rpm

Subscripts

in	input hydraulic/available
m	mechanic