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Research Paper

Performance Evaluation of the Optimized Design Ratio Between the Diameters of the Basin and Curved Blade in the Gravitational Water Vortex Turbine

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The key role of the gravitational water vortex turbine (GWVT) is to generate electricity to support modern civilization in their essential daily needs by harnessing kinetic energy from flowing water. With this, the lack of access to electricity can be addressed by utilizing the potential of the Philippines' abundant bodies of water. This study evaluates the impact of low-density turbine blades on the GWVT with reference to the selected parameters: rotational speed and mechanical efficiency. The ANSYS simulation and laboratory test both found that the 0.55 ratio between the diameters of the nylon rod blade and the optimized basin with guide vanes achieved the highest rotational speed of 205.95 RPM and 120.1 RPM, respectively. Conversely, the design with a 0.60 ratio between the diameters of the steel blade and the normal basin provided optimum performance, achieving an average of 98.2 RPM and the highest mechanical efficiency of 43.75%, thereby preventing energy loss and maximizing output performance. Results also indicated a significant difference in the performance of the GWVT using the normal basin compared to the optimized basin with guide vanes. Lastly, there was a considerable difference in the performance of the GWVT for the design ratios of 0.55, 0.60, and 0.65 for the runner blade and basin, and further analysis showed that torque and rotational speed have a linear relationship. Thus, this study could serve as a benchmark for identifying alternative materials and optimizing the design of GWVT to help improve power generation using hydropower as a source of electricity.

Keywords: gravitational water vortex turbine; optimized basin; normal basin; steel turbine blade; nylon rod turbine blade.

1. Introduction

Electricity is an essential energy source that supports modern civilization and significantly influences nearly every aspect of human life. It is particularly crucial to daily lives of most Filipinos, as it enhances their quality of living by providing conveniences in daily tasks, helping to alleviate poverty, and fostering economic advancement [1]. However, 30% of the population in some areas in the Philippines still lacks access to this essential service because of increased electrical energy consumption and high demand. This situation has resulted in intentional power plant cutbacks to prevent widespread system blackouts [2]. In addition, most regions in the country continue to rely on traditional energy sources, particularly coal, for convenience, despite their environmental drawbacks. Fuel fossil such as oil, natural gas, and coal account for 80% of the country's energy sources [3].

In addressing these problems, there are alternative ways of collecting electrical energy sources, such as utilizing renewable energy (i.e., wind, sun, and water) aside from traditional ones. One of these is the utilization of hydroelectricity, a source of energy powered by water, which is a renewable energy source that contributes around 15% of global electricity generation [4]. By transforming the kinetic energy of water into electricity, it uses turbines to power generators. One of the most essential and sustainable renewable energy sources widely used in developing nations is the gravitational water vortex turbine (GWVT) system [5].

Considering the Philippine setting and its potential for using the GWVT system, the country's geographical area boasts vast quantities of free-surface bodies of water, including hundreds of rivers and lakes, as well as significant groundwater resources [6]. Given the high electricity demand, these abundant resources make the Philippines an ideal location for installing the GWVT system, providing a sustainable energy solution. Furthermore, the installation of the GWVT system is quite flexible, as the units can be scaled and cast to fit any mold depending on local conditions [7].

Numerous optimizations have been made to the GWVT system, focusing on both its blade and basin to maximize efficiency, particularly in the design of guide vanes. These vanes are primarily utilized in various hydro turbines, such as Francis and Savonius turbines, and have been adapted as direct replacements for runner blades in the GWVT system. To support this, the research of Bajracharya *et al.* [8] demonstrated that guide vanes significantly influence the tangential velocity of water. The authors tested various guide vane configurations, each producing different tangential velocity results, with a maximum value of 6.26 m/s compared to 5.84 m/s in normal (standard) basin. This resulted in a 7.63% increase in maximum efficiency for the leading guide vanes. Similarly, Mitra *et al.* [9] found that guide vanes contributed to the angular momentum of water flow, as these vanes converted pressure energy at the inlet into kinetic energy and directed the fluid toward the runner blades at an appropriate angle. Notably, these guide vanes also improved performance under less demanding operating conditions in a Francis turbine, as reported Joy *et al.* [10].

Aside from performance enhancements, Abu-Thuraia [11] highlighted the role of guide vanes in controlling water flow within the turbine, underscoring their importance in optimizing turbine operation. Various cases of guide vanes were tested and both higher and lower power coefficient values compared to those without guide vanes were observed. The design with a higher power coefficient achieved a value of 0.398, surpassing 0.394 obtained without guide vanes. Further research by Tran *et al.* [12] identified that both the number and angle of guide vanes directly impact turbine performance, indicating that careful design and arrangement of these components is crucial for maximizing efficiency. Their study found that the optimal number of guide vanes was 8, resulting in a 6.3% increase in efficiency. Regarding angular position, guide vanes set at 30° yielded the best performance. Together, these findings emphasize the critical role of guide vanes in hydro turbine systems.

Moreover, the conventional design of the GWVT system uses a steel blade with a density of 7830 kg/m^3, which is relatively high compared to other materials that may be regarded as practical alternatives. This physical characteristic can affect the efficiency of the GWVT system, as demonstrated by Sritram *et al.* [13], where an aluminum blade with a lower density of only 2700 kg/m^3 performed better than steel. However, the search for the most efficient materials is ongoing, leading to the first gap identified in this study. Specifically, further research and exploration can be carried out using nylon rod material with a density of 1140 kg/m^3, as a potential substitute for stainless steel in the GWVT system. In addition to its low density, nylon is durable, capable of providing long-lasting performance, resistant to stress due to its flexibility, and composed of low-friction plastic material, making it suitable for manufacturing parts that can be utilized in high-friction industrial applications [14].

Conversely, the abovementioned studies by Bajracharya *et al.* [8], Mitra *et al.* [9], Joy *et al.* [10], and Tran *et al.* [12] used guide vanes in various hydro turbines and substituted them as runner blades. However, their studies did not emphasize the simultaneous use of guide vanes and blade designs in the GWVT system, which leads to the second gap identified in this study. On that account, one needs to test the performance of such a combined design through experimental evaluation to determine its effectiveness. This underscores the ongoing need for research and development in hydraulic engineering and renewable energy to further assess the effect of the optimized guide vanes on the efficiency of the GWVT system, particularly as it relates to the design ratio between the runner blade and its diameter. Thus, if optimizing the basin with guide vanes in the GWVT is proven to increase power output, it could improve the operability of the GWVT system as a sustainable electricity power supply.

The current study aims to evaluate the most efficient design ratio between the diameters of the basin and the curved blade in the performance of GWVT, using both a standard basin and an optimized basin with guide vanes. The study used three diameter ratios: 0.55 inch/inch, 0.60 inch/inch, and 0.65 inch/inch for test simulations and experimental setup evaluations to determine the most efficient design for the GWVT system. Additionally, both the standard steel blade and a low-density nylon rod blade were used to determine differences in efficiency between traditional and low-density materials. Furthermore, the study examined significant differences in results between standard and optimized basins, nylon and steel blade materials, and the ratios between the basin and curved blade diameters through statistical tests, including the independent-samples t-test and one-way analysis of variance (ANOVA). Lastly, the study also determined the significant difference and correlation of experimental results through the aforementioned statistical tests and a regression analysis.

2. Methodology

2.1. Design of the gravitational water vortex turbine

This study fabricated a prototype scale model of the GWVT with a basin diameter of 10 inches and an outlet diameter of 0.750 inches, as identified for achieving optimal efficiency by Ullah and Cheema [15]. This scale model adhered to the configuration of design ratio between the blade and basin diameters of 0.6, which also matched the dimensions of the hydraulic bench available in the Civil Engineering Department at Ateneo de Davao University, Philippines, as shown in Fig. 1a. This study employed a design ratio increment of 0.05, from

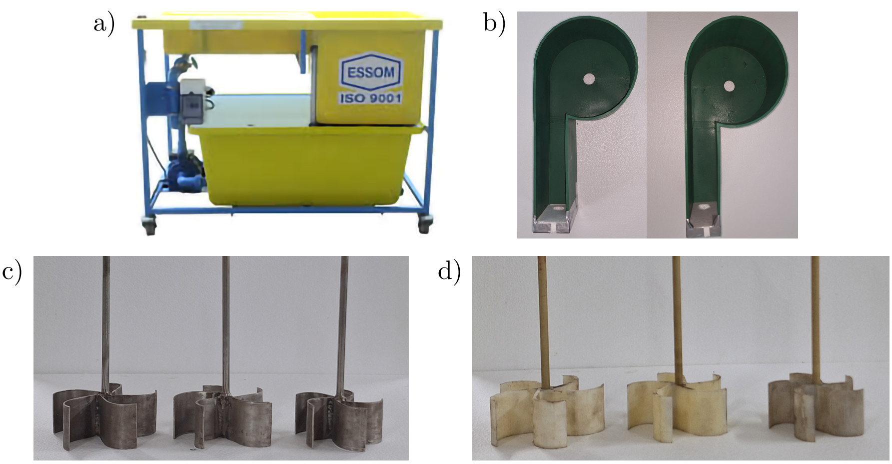

Fig. 1. GWVT system with: a) hydraulic bench, b) basin, c) stainless steel blades, d) nylon rod blades.

0.55 inch/inch to 0.65 inch/inch, which was near the ratio of 0.6. This increment was carefully selected, as lower values help minimize the effect of air core or friction loss generation, leading to more precise results [16].

Consequently, the material used for the basin prototype was polylactic acid (PLA) and it was molded through 3D printing, as shown in Fig. 1b. The blades were made from two different materials: stainless steel and nylon rod, as depicted in Figs. 1c and 1d, respectively. These components were sourced and fabricated by a local shop in Davao City, Philippines. The two materials differ in density, with nylon rods having a lower density than steel. As previously mentioned, Sritram *et al.* [13] found that high-density materials can reduce the blade's revolutions per minute (RPM). On the contrary, low-density materials may improve the performance of the GWVT.

2.2. Basin and blade design, software simulation, laboratory test, and data gathering

This section outlines the basin and blade design, software simulation, laboratory experimental tests, and data gathering, which are all key processes for the GWVT prototype development. Detailed designs and step-by-step methods for data gathering in both simulation and field experiments are discussed below.

2.2.1. Basin and blade design. The installation of guide vanes is a critical parameter in designing an efficient GWVT system [16]. In this study, two types of basins were used in the laboratory experiments: (1) an optimized basin equipped with different components that affected the performance of the GWVT, and (2) a standard (normal) basin. Table 1 presents dimensions of the basin components used in this study. Note that the symbol (–) indicates the absence of guide vanes in the basin.

Table 1. Basin design parameters.

Component	Normal basin	Optimized basin
Outside diameter of guide vanes	–	7 inches
Inside diameter of the basin	10 inches	10 inches
Height of the basin	7 inches	7 inches
Area of the orifice	0.442 in^2	0.442 in^2

In the table above, the normal basin did not have guide vanes, while the optimized basin had guide vanes with an outer diameter (Ø1) of 7 inches. Likewise, both basins had the same inside diameter (Ø2) of 10 inches. Similar to the inside diameters, both the basin heights (H) and their orifice areas (A_o)

had the same measurements of 7.5 inches and 0.442 in^2, respectively. Figures 2a and 2b illustrate the details of the normal and optimized basins.

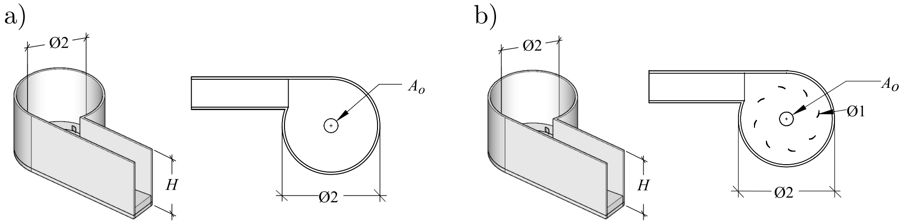

Fig. 2. Details of the basin using: a) the normal design, and b) the optimized design.

Moreover, we referred to the studies conducted by Obozov *et al.* [17] and Ullah and Cheema [15] for the design and dimensional parameters of the GWVT. As such, the fundamental blade design details were consistent, whereas the dimensions were varied to optimize performance. As shown in Fig. 3, the design parameters included the total blade height (H), blade diameter (Ø3), shaft diameter positioned between the blades, and the blade angle (β) relative to the tangential line of the circular blade. This blade angle was carefully set to achieve optimal rotational speed and efficiency. Additionally, the blade thickness (b_t) and the total number of blades were considered critical factors for to the performance of the turbine's propellers.

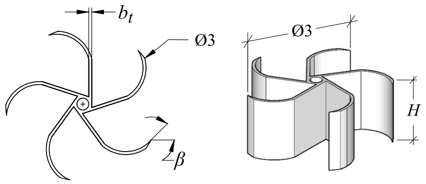

Fig. 3. Dimension and outline of the blade.

Furthermore, Table 2 provides dimensions of the three different blades, as referenced in Fig. 3. In the table, all blades shared identical measurements for

Table 2. Dimension of blades.

Component	Blade 1	Blade 2	Blade 3
Total height of the blade	2.5 inches	2.5 inches	2.5 inches
Diameter of the shaft between the blade	6.5 inches	6 inches	5.5 inches
Diameter of the blade	0.5 inch	0.5 inch	0.5 inch
Angle of the blade	30 degrees	30 degrees	30 degrees
Thickness of the blade	0.125 inch	0.125 inch	0.125 inch
Number of blades	5	5	5

total height, blade diameter, blade angle, blade thickness, and number of blade propellers. In contrast, the shaft diameter between the blades varies.

2.2.2. ANSYS simulation of the GWVT. For the evaluation of the design of the GWVT, this study utilized ANSYS® Engineering Simulation Software [18] as a preparatory step to assess the performance of turbine materials. This simulation enabled a thorough examination of the materials' capacity when installed on the hydraulic bench. In addition, it helped ensure that the design was efficient and confirmed the effectiveness of the turbine during laboratory experimental tests. This approach is supported by the research conducted by Li [19], which confirmed that ANSYS provides precise point values for any variable at any location within the simulated domain thereby enhancing the reliability of the findings.

2.2.3. GWVT setup and series of tests. Determining the performance of a turbine is essential for evaluating its efficiency, reliability, and overall functionality in various applications. Performance testing typically involves measuring parameters such as rotational speed (RPM), torque, power input, power output, and mechanical efficiency. In this study, the prototype turbine was installed on a hydraulic bench, which served as the source of water inflow. It continuously provided a constant and steady flow rate into the GWVT prototype. The experimental setup adopted conditions similar to those of an actual river, envisioning applications for the study in real-life situations. Similarly, Betancour *et al.* [20] conducted an investigation of the parameters of the GWVT. Figure 4 shows the experimental setup based on the design of the GWVT prototype, featuring (1) adjusted flow rate and (2) recycled water. An HB 100 Hydraulic Bench was used as the source of the water supply, and the water discharge was adjusted to 0.823 L/s for all tests performed.

Fig. 4. Experimental setup of the GWVT and hydraulic bench.

This experiment utilized two measuring tools: a tachometer and a Prony brake, to record data for the performance evaluation of the GWVT. Figure 5a features the Prony brake, where a pulley was attached to the rotating vessel shaft and the prototype stand's edge. A rope was hooked to the stand and looped around the pulley, which allowed varying weights to be suspended. Weights were gradually added until the blade stopped rotating. The torque was then calculated by multiplying the suspended weight by the radius of the pulley. The suspended weights utilized in the Prony brake were measured on a weighing scale to verify their exact mass. Figure 5b shows the tachometer, a device used to measure the minimum, maximum, and average shaft rotation speed. The readings from the tachometer were compared to the manual counting of blade revolutions per minute to verify the device's accuracy, and revealing an error margin of 1%–2%. Finally, brake power was calculated by multiplying the measured torque by the rotational speed in [RPM].

a) b)

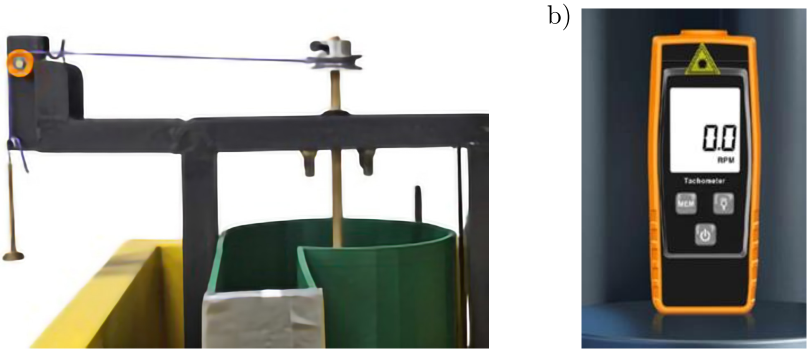

FIG. 5. Devices used to measure: a) brake power, and b) RPM.

Thereafter, different variables were recorded during the experiment to evaluate the performance of the steel and nylon rod turbines, as shown in Tables 3 and 4. These variables were crucial in determining the overall efficiency of the GWVT prototype. Three trials were conducted for each combination of blade type, basin type, and blade-to-basin diameter ratio, measuring their corresponding dependent variables, such as RPM, torque, brake power, power input, and mechanical efficiency. The experiment was conducted at the Civil Engineering Department laboratory of Ateneo de Davao University.

2.3. Computation of power and mechanical efficiency

The power output and mechanical efficiency were computed based on established hydraulic principles to assess the performance of the GWVT. The study by SALEEM *et al.* [21] presented a series of performance parameters using

TABLE 3. Experimental data for stainless steel turbine.

Normal basin					Optimized basin				
Trial	Rotational speed [RPM]			Torque [N · m]	Trial	Rotational speed [RPM]			Torque [N · m]
	max	min	avg			max	min	avg	
Blade-to-basin diameter ratio: 0.55									
1	120.6	108.9	114.7	0.021	1	121.3	97.5	109.3	0.021
2	114.8	74.9	108.6	0.021	2	109.5	103.5	106.5	0.021
3	112.2	105.4	108.8	0.021	3	111.7	100.1	105.9	0.021
Blade-to-basin diameter ratio: 0.60									
1	102.3	95.5	98.9	0.031	1	102.3	98.2	100.2	0.027
2	100.7	93.2	96.9	0.031	2	97.8	88.9	93.3	0.027
3	101.4	96.5	98.9	0.031	3	97.2	88.6	92.9	0.027
Blade-to-basin diameter ratio: 0.65									
1	96.9	88.7	92.7	0.033	1	92.5	86.2	89.3	0.030
2	96.9	91.0	93.7	0.033	2	94.3	87.4	90.8	0.030
3	97.2	89.2	93.2	0.033	3	95.0	85.4	90.2	0.030

TABLE 4. Experimental data for nylon rod turbine.

Normal basin					Optimized basin				
Trial	Rotational speed [RPM]			Torque [N · m]	Trial	Rotational speed [RPM]			Torque [N · m]
	max	min	avg			max	min	avg	
Blade-to-basin diameter ratio: 0.55									
1	126.7	120.0	123.3	0.012	1	123.6	119.1	121.3	0.018
2	125.2	111.3	118.2	0.012	2	128.3	115.0	121.6	0.018
3	124.3	112.6	118.4	0.012	3	119.5	115.6	117.5	0.018
Blade-to-basin diameter ratio: 0.60									
1	117.4	112.8	115.1	0.018	1	107.3	97.2	102.2	0.021
2	115.7	113.6	114.6	0.018	2	106.7	99.1	102.9	0.021
3	118.1	110.9	114.4	0.018	3	108.9	102.4	105.6	0.021
Blade-to-basin diameter ratio: 0.65									
1	106.9	102.3	104.6	0.024	1	104.5	99.5	102.0	0.024
2	108.4	100.6	104.5	0.024	2	94.1	84.3	89.2	0.024
3	106.9	102.0	104.4	0.024	3	92.4	85.8	89.1	0.024

mathematical expressions to evaluate rotational speed, torque, brake power, and mechanical efficiency of a single-stage GWVT under various flow and design conditions. Our study calculated the power output and mechanical efficiency using those mentioned mathematical expressions.

Subsequently, the flow rate was calculated using Eq. (2.1), employing the volumetric bucket method – a technique suitable for small channels and commonly used in past studies of open channel flow rates. This method was repeated five to seven times to ensure result accuracy [22]:

$$Q = \frac{V}{t}, \tag{2.1}$$

where V is the cross-sectional volume of the bucket, and t is the time taken to fill the bucket. In this experiment, the volumetric flow rate divided by the cross-sectional area of the hose in the hydraulic bench corresponds to the inlet velocity in meters per second [m/s].

Equation (2.2) refers to the rotational force generated by the water flow through the runner blades. This value was measured using the Prony brake method. In this method, varying weights suspended by a rope are pressed against a rotating wheel on a pulley, generating friction at the wheel's edges, which produces torque (T_{exp}) on a lever. This study measured torque using a scale that captures the resulting force. Thus, the equation can be expressed as:

$$T_{\text{exp}} = r \cdot F, \tag{2.2}$$

where r is the radius of the pulley [m], and F is the applied brake force [N]. In line with this, the force was calculated by multiplying the weights used in the pulley by gravity.

To determine the brake power ($P_{B\,\text{exp}}$), the torque value that was calculated in Eq. (2.2) was multiplied by the angular velocity (ω_{exp}) in revolutions per minute [RPM]. This represents the actual power output of the turbine, as shown in Eq. (2.3):

$$P_{B\,\text{exp}} = T_{\text{exp}} \cdot \omega_{\text{exp}}. \tag{2.3}$$

Equation (2.3) indicates that torque depends on the rotational velocity to determine the output power. The revolution speed of the blade is significant in calculating the angular velocity (ω_{exp}) in radians per second [rad/s]. This notion refers to the angular velocity of the blade rotating about the turbine's axis. In Eq. (2.4), the angular velocity is given as:

$$\omega_{\text{exp}} = \frac{2\pi}{T} \quad \text{or} \quad \frac{2\pi \cdot N}{60}, \tag{2.4}$$

where T is the period of one complete revolution in seconds, and N is the revolutions per minute [RPM]. The resulting angular velocity value was compared with data obtained from the tachometer.

The input power (P_{in}) is the power source supplied to the turbine for energy generation. The vortex height (H_v) is measured by using a measuring tape attached to the inner wall of the basin to record the water height. In Eq. (2.5), the power input is given as:

$$P_{\text{in}} = \rho g Q H_v, \tag{2.5}$$

where ρ is the density of the fluid, g is the acceleration due to gravity, and Q is the calculated flow rate.

Lastly, the performance of the GWVT was evaluated by its mechanical efficiency (n_{exp}) using Eq. (2.6). This efficiency is defined as the ratio of brake power ($P_{B\,\text{exp}}$) to the input power (P_{in}). A higher mechanical efficiency (n_{exp}) indicates that more output power is utilized in the system, making the turbine more efficient:

$$\eta_{\text{exp}} = \frac{P_{B\,\text{exp}}}{P_{\text{in}}} \cdot 100\%. \tag{2.6}$$

2.4. Statistical analysis

This study employed three statistical tools to evaluate the responses of the variables considered: the independent-samples t-test, the ANOVA, and regression analysis. These tools have a 95% confidence level ($p < 0.05$) as the criterion for selecting hypothesis in the study. The same statistical methods were also used to test the significant differences and relationships between variables in the studies by Dhakal *et al.* [23], Khan *et al.* [24], and Kim *et al.* [25]. The statistical analysis was conducted using the IBM® SPSS® statistics software version 22.0 [26] at the University Information Technology Office, Ateneo de Davao University, Davao City, Philippines.

Initially, the independent-samples t-test was used to determine if significant differences existed in the performance of the GWVT under two different conditions. The t-test formulated four hypotheses. The two null hypotheses stated that there was no significant difference in the GWVT performance between samples with guide vanes installed and samples with a standard basin without guide vanes, and between samples with nylon runner blades and samples with conventional steel runner blades. Correspondingly, the two alternative hypotheses suggested that significant differences did exist between these variables.

Second, the one-way ANOVA test determined if there was a significant difference in the GWVT performance among samples with blade-to-basin ratios of 0.55, 0.60, and 0.65 between the runner blade and basin diameters. The null hypothesis stated that there is no significant difference in the GWVT performance between the samples with 0.55, 0.60, and 0.65. In contrast, the alternative hypothesis stated otherwise (i.e., a significant difference in performance).

Third, a linear regression analysis was a used to find the correlation between revolutions per minute and torque from the experimental trials. Two hypotheses were formulated in this study. The first hypothesis (null) stated that there was no linear relationship between the variables considered (RPM and torque), while the second hypothesis (alternative) implied a linear correlation between the variables.

3. Results and discussion

3.1. GWVT performance

This study presents a comprehensive analysis of the GWVT performance results, evaluated through ANSYS CFD simulations and experimental testing. In addition, the mechanical efficiency of GWVT was used as a benchmark to assess whether different design parameters in the prototype enhanced its performance. Initially, two blade materials were tested in the normal basin. As shown in Table 5, the nylon blade material exhibited the lowest mechanical efficiency of 20.19%, with a basin-to-blade diameter ratio of 0.55. In contrast, the highest mechanical efficiency observed was 43.75%, achieved with the steel blade at a design ratio of 0.60. This value falls within the theoretical maximum efficiency of 59.3%, known as Betz's limit [27].

Subsequently, the study used the optimized basin to evaluate the performance of the turbine blades. Table 6 shows that the lowest mechanical efficiency of 26.39% was recorded with the nylon blade at a design ratio between the basin's and blade's diameters of 0.65, while the highest mechanical efficiency of 34.36% was achieved with the steel blade at the same design ratio. In this study, the design of the basin aimed to improve water flow and enhance interaction with the turbine blades, which was expected to boost efficiency. However, results from both Tables 5 and 6 indicate that the normal basin design outperformed the optimized basin design in terms of mechanical efficiency. This finding suggests that the optimized design did not achieve the anticipated performance improvements. On the other hand, the data reveal that the design ratio of 0.55 between the diameters of the basin and blade generated the highest RPM across both materials and basin designs. Nonetheless, considering mechanical efficiency of the GWVT, the most effective design ratio was 0.60, consistent with results reported by Ullah and Cheema [15].

Tables 5 and 6 illustrate the relationship between rotational speed [RPM] and torque variables, showing that torque decreases in the GWVT as rotational speed increases, highlighting an inverse relationship between the two variables, as described in Eq. (2.3). When the flow rate of water increases from zero to the selected value, the turbine experiences higher rotational speed due to the

TABLE 5. Normal basin experimental data.

Basin type	Blade type	Diameter ratio	Rotational velocity [RPM]	Torque $[\mathrm{N}\cdot\mathrm{m}]$	Weight [g]	Brake power $P_{B\,\mathrm{exp}}$ [W]	Vortex height H_v [cm]	Input power P_{in} [W]	Mechanical efficiency η_{exp} [%]
Normal	Steel	0.55	110.7	0.021	67.50	0.242	8.75	0.706	34.23
Normal	Steel	0.60	98.2	0.031	100.00	0.318	9.00	0.727	43.75
Normal	Steel	0.65	93.2	0.033	107.50	0.324	9.25	0.747	43.42
Normal	Nylon	0.55	120.0	0.012	40.00	0.151	9.25	0.747	20.19
Normal	Nylon	0.60	114.7	0.018	57.50	0.213	10.25	0.827	25.79
Normal	Nylon	0.65	104.5	0.024	77.50	0.262	9.25	0.747	35.10

TABLE 6. Optimized basin experimental data.

Basin type	Blade type	Diameter ratio	Rotational velocity [RPM]	Torque $[\mathrm{N}\cdot\mathrm{m}]$	Weight [g]	Brake power $P_{B\,\mathrm{exp}}$ [W]	Vortex height H_v [cm]	Input power P_{in} [W]	Mechanical efficiency η_{exp} [%]
Optimized	Steel	0.55	107.0	0.021	67.5	0.234	9.00	0.727	32.24
Optimized	Steel	0.60	95.5	0.027	87.5	0.270	9.75	0.787	34.34
Optimized	Steel	0.65	90.1	0.030	97.5	0.284	10.25	0.827	34.36
Optimized	Nylon	0.55	120.1	0.018	65.5	0.224	10.00	0.807	27.69
Optimized	Nylon	0.60	103.6	0.021	67.5	0.226	10.25	0.827	27.34
Optimized	Nylon	0.65	93.4	0.024	77.5	0.234	11.00	0.888	26.39

enhanced kinetic energy of the water. However, to maintain a constant power output, torque decreases accordingly. This behavior is characteristic of many turbines, including vortex designs, where peak efficiency often occurs at specific rotational velocity. Therefore, understanding torque is critical to minimizing energy waste and avoiding inefficiency.

Moreover, the data indicate that blade density significantly impacts angular velocity. Turbine blades made from nylon rods produce higher rotational velocity, which result in a reduction of torque. On the other hand, stainless steel turbine blades, having higher density, result in lower rotational speed but generate higher torque. As a result, stainless steel blades outperform nylon blades, by providing higher mechanical efficiency in both basin designs.

To further verify the results, ANSYS delivered essential values across different variations within the simulated zone. However, software constraints limited the mesh size to 512 000 cells. The meshing of the samples produced cell counts ranging from 160 000 to 250 000. Table 7 summarizes the RPM data obtained from different design parameters of the GWVT. The data confirmed that the GWVT prototype functioned effectively in terms of its various design parameters. Notably, both experimental and ANSYS data showed similar trends: low-density blades had higher RPMs than high-density blades, and the addition of guide vanes in the basin tended to decrease the RPM of the prototype. This result indicates that the experimental results effectively verified the ANSYS simulation outputs.

Table 7. ANSYS CFD simulation data.

Blade type	Basin type	Diameter ratio	Rotational speed [RPM]
Steel	Normal	0.55	212.89
Steel	Normal	0.60	206.39
Steel	Normal	0.65	184.87
Nylon	Normal	0.55	222.30
Nylon	Normal	0.60	207.39
Nylon	Normal	0.65	185.03
Steel	Optimized	0.55	203.95
Steel	Optimized	0.60	185.71
Steel	Optimized	0.65	153.48
Nylon	Optimized	0.55	205.95
Nylon	Optimized	0.60	186.72
Nylon	Optimized	0.65	154.43

Additionally, Figs. 6 and 7 show the velocity contours of the water inside the GWVT, in which different colors represent different flow velocities within

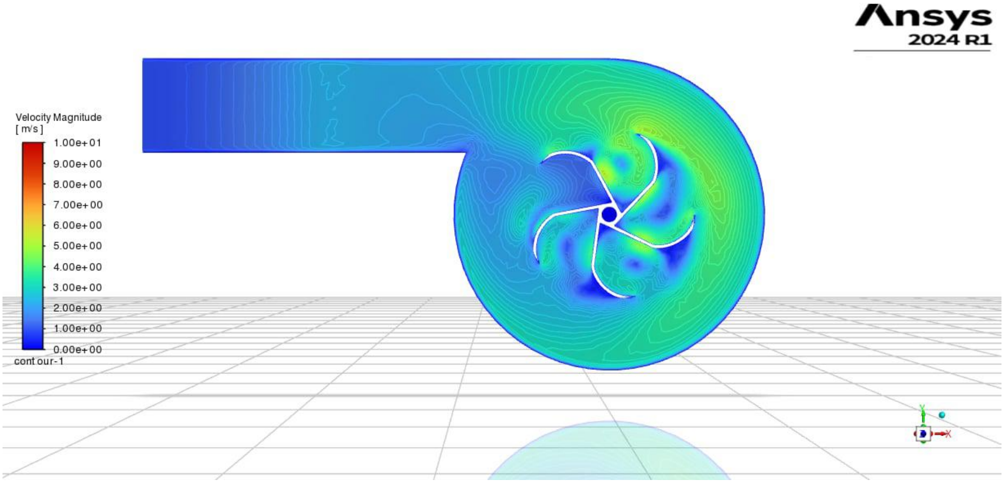

Fig. 6. Velocity contour diagram of water flow inside the optimized basin.

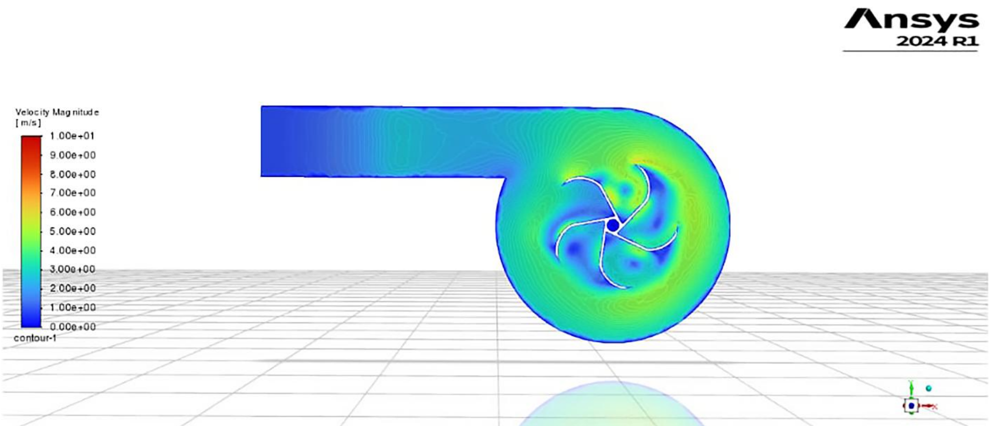

Fig. 7. Velocity contour diagram of water flow inside the normal basin.

the prototype. Blue indicates low-velocity values, green and yellow correspond to average velocity values, and red signifies high-velocity values in the turbine area. As observed from the velocity diagram, there were low velocities near the inlet channel's beginning, with a slight increase midway due to the slope present in the channel. In the vortex region, average velocities reflect rotational motion, which enhances velocity presence and directly impacts the turbine's performance by influencing its power output and efficiency.

The velocity contour was defined within a range of 0 m/s to 10 m/s, reflecting the velocities observed in the simulation to illustrate water flow inside the basins. Both figures showed a significant difference in water velocity distribution between the optimized and normal basins. Water flow in the optimized basin exhibited lower turbulent flow compared to the normal basin, which showed higher water velocity. One factor that led to this outcome was the presence of guide vanes in the optimized basin, which controlled the water flow to produce higher tangential velocity at the blades, contradicting the findings of Bajracharya *et al.* [8]. These results indicate that the optimized basin provided enhanced, smoothed, and more controlled water flow, consistent with the findings of Abu-Thuraia [11].

Furthermore, there was a discrepancy in terms of rotational speed between the experimental and simulation data, due to differences in the volumetric flow rate at the inlet, as the experimental setup utilized a hose with a smaller inlet area, whereas the ANSYS simulation modeled the inlet as a larger area. However, both datasets showed consistent trends, with rotational speed following a similar pattern for both the ANSYS simulations and experimental results, demonstrating the relationship of the design ratio between the diameters of the runner blade and basin and rotational speed. This consistency indicates that the GWVT design proportions can withstand fluctuations in discharge flow rate, as evidenced by the stable flow rate performance observed throughout the simulation.

3.2. Effect of design variations on GWVT output

The design parameters, such as the design ratio between the diameters of the basin and the blade, the use of low-density blades, and the inclusion of guide vanes, were investigated to assess the GWVT performance. The different parameters studied included the blade position, set at 2.1 inches or 30% of the total basin height from the bottom, a cylindrical basin with a diameter of 10 inches, and a flow rate set at 0.823 L/s. These measurements were kept constant in all tests, and the blade's presence in the vortex regions affected the performance of the GWVT, as shown in Table 8.

Table 8. Effect of the design ratio between the diameters of the basin and blade on mechanical efficiency and rotational speed.

Blade type	Basin type	Diameter ratio	Rotational speed [RPM]	Mechanical efficiency η_{exp} [%]
Nylon	Optimized	0.55	120.10	27.69
Nylon	Optimized	0.60	103.60	27.34
Nylon	Optimized	0.65	93.40	26.39
Steel	Optimized	0.55	107.20	32.24
Steel	Optimized	0.60	95.50	34.34
Steel	Optimized	0.65	90.10	34.36

In Table 8, the optimum design ratio performance between the basin and blade diameters for the optimized basin was 0.55, with a steel blade achieving the second-highest rotational speed at 107.2 RPM and the third-highest mechanical efficiency at 32.24%. Observations showed that as the diameter increased, the rotational speed of the GWVT decreased. A related study by Ullah and Cheema [15], which tested design ratios of 0.47, 0.60, and 0.66 between the diameters of the basin and blade, reported the best performance at 0.60. However, this study refined the range with increments of 0.05 around 0.60 to improve precision and found that 0.55 delivered even better performance. Another study by Saleem *et al.* [21] also identified two regions in the vortex: the free vortex and the forced vortex. When the blade made contact with the free vortex, the rotational speed decreased due to the lower vorticity present compared to the forced vortex. Besides, blade density was found to be a significant parameter that affected the performance of the GWVT, as its influenced vortex formation. Two types of blades, with densities of 7830 kg/m^3 and 1140 kg/m^3, respectively, were also investigated. Table 9 shows the different angular velocities measured, along with the corresponding basin-to-blade diameter ratios.

Table 9. Effect of blade density on rotational speed at different basin-to-blade diameter ratios.

Blade type	Basin type	Diameter ratio	Rotational speed [RPM]
Steel	Normal	0.55	110.70
Steel	Normal	0.60	98.20
Steel	Normal	0.65	93.20
Nylon	Normal	0.55	120.00
Nylon	Normal	0.60	114.70
Nylon	Normal	0.65	104.50
Steel	Optimized	0.55	107.20
Steel	Optimized	0.60	95.50
Steel	Optimized	0.65	90.10
Nylon	Optimized	0.55	120.10
Nylon	Optimized	0.60	103.60
Nylon	Optimized	0.65	93.40

The highest rotational speed measured was 120.10 RPM for the optimized design ratio of 0.55 between the diameters of the basin and blade, using a low-density nylon blade. In comparison, the lowest rotational speed measured was 90.10 RPM for the optimized design ratio of 0.65, featuring a high-density steel blade type. Similar results were obtained in the study by Sritram *et al.* [13], where the authors found that lower-density aluminum blades performed better than steel blades in their experiment. They also pointed out that low-density blade resulted in faster rotational speed than high-density blades, thereby making the first ones more efficient in producing power. Similarly, Li *et al.* [28] found that composite blades with lower density than steel also exhibited higher efficiency and power output.

Furthermore, the experiments showed that as the blade diameter increased, the mass of the blade also increased, which affected the performance of the GWVT by reducing rotational speed and an increasing torque. Likewise, existing studies showed that guide vanes significantly influenced the tangential velocity of water and angular momentum when used in various hydro turbines and when used as a replacement for the runner blade in the GWVT. Two variations of basin design were investigated: a normal basin without guide vanes and an optimized basin with guide vanes. Table 10 presents the obtained rotational speed and mechanical efficiency results for both basin types.

Table 10. Effect of guide vanes on mechanical efficiency.

Basin type	Diameter ratio	Rotational speed [RPM]	Mechanical efficiency η_{exp} [%]
Normal	0.55	110.70	34.23
Normal	0.60	98.20	43.75
Normal	0.65	93.20	43.42
Optimized	0.55	107.20	32.24
Optimized	0.60	95.50	34.34
Optimized	0.65	90.10	34.36

It is observed from Table 10 that both rotational speed and mechanical efficiency decrease when guide vanes were added to the basin design. The same result was also reported in the study by Abu-Thuraia [11], where the power coefficient decreased with the addition of guide vanes, although they notably helped control the flow within the turbine. However, after further optimizations, power coefficient improved. Consequently, these results contradicted the findings of Tran *et al.* [12], Bajracharya *et al.* [8], and Joy *et al.* [10], who reported that guide vane optimization improved turbine performance. This implies that, while guide vanes can be more efficient in other hydro turbines and serve effectively as blade replacements, their use alongside the runner blade in this design led to inferior performance, likely due to increased backflow within the turbine caused by the interaction of two flow-controlling elements. Additionally, the experiment showed an increase in vortex height for the optimized basin. The study of Saleem [21] explained that a slight rise in vortex height could decrease rotational speed due to the added water head above the runner blades. On the other hand, a high increase in vortex height tends to increase torque, rotational speed, power output, and efficiency.

3.3. Mechanical efficiency

The GWVT performance was assessed using the mechanical efficiency equation given in Eq. (2.6). Table 11 displays the mechanical efficiency values for various design parameters along with their corresponding brake power and power input.

TABLE 11. Mechanical efficiency values at different design parameters.

Blade type	Basin type	Diameter ratio	Brake power $P_{B\,\mathrm{exp}}$ [W]	Input power P_{in} [W]	Mechanical efficiency η_{exp} [%]
Steel	Normal	0.55	0.242	0.706	34.23
Steel	Normal	0.60	0.318	0.727	43.75
Steel	Normal	0.65	0.324	0.747	43.42
Nylon	Normal	0.55	0.151	0.747	20.19
Nylon	Normal	0.60	0.213	0.827	25.79
Nylon	Normal	0.65	0.262	0.747	35.10
Steel	Optimized	0.55	0.234	0.727	32.24
Steel	Optimized	0.60	0.270	0.787	34.34
Steel	Optimized	0.65	0.284	0.827	34.36
Nylon	Optimized	0.55	0.224	0.807	27.69
Nylon	Optimized	0.60	0.226	0.827	27.34
Nylon	Optimized	0.65	0.234	0.888	26.39

The highest mechanical efficiency obtained was 43.75%, with the design ratio of 0.60 between the diameters of the basin and blade in the normal basin with a steel blade. In contrast, the lowest mechanical efficiency was 20.19%, observed with a design ratio of 0.55 in the normal basin using a nylon blade. Similarly, the study by ULLAH and CHEEMA [15] found that the vortex's rotating capability to generate power was higher due to its significant tangential velocity. This notion resulted in an inverse relationship between rotational speed and power. Thus, the study utilized a cylindrical basin in the GWVT, which provided lower brake power and power input compared to a conical basin due to the formation of vortex height. Figure 8 shows a line graph illustrating the obtained mechanical efficiency for the varying design parameters. It is evident that the normal basin with a steel blade achieved the highest mechanical efficiency value among all design ratios. Table 11 shows that the 0.60 design ratio for the normal basin with a steel blade resulted in the highest mechanical efficiency of 43.75%, as plotted in the Fig. 8.

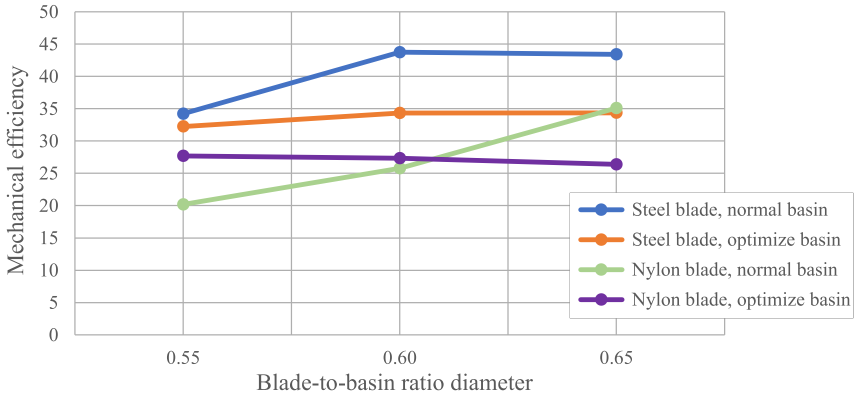

FIG. 8. Design ratio between the diameters of the basin and blade versus mechanical efficiency.

The maximum efficiency obtained was considerably higher than that of many existing GWVT designs. Given its more practical and economical advantages, the nylon-rod blade on a normal basin at a 0.65 design ratio offers a close alternative to the optimal 0.60 design ratio found for the steel blade. The proposed optimizations of the basin with guide vanes were less efficient than their counterparts using steel blades. However, at a 0.55 design ratio, the nylon rod on the optimized basin was more efficient than its counterpart, while the steel blade showed similar values in both basin types. Additionally, the 0.55 design ratio required the least material, making it the most economical option. These results could help decide whether to prioritize mechanical efficiency and cost-effectiveness, or to find a compromise between the two. Regarding power generation, the proposed designs could be well-suited for use near rivers and streams with flow rates of 1 m/s or higher. Given the abundance of rivers and other suitable inland water bodies across the Philippines, the results of this study could significantly contribute to improving hydropower generation via GWVTs as a primary source of electricity.

3.4. Relationship between variations and variables

This section explores the relationship between torque and rotational speed, as well as the significant differences observed in the obtained results based on basin design, blade material, and the design ratio between the diameters of the basin and blade. Table 12 presents the results of the independent samples t-test, one-way ANOVA, and regression analysis conducted to evaluate these relationships. power input.

For the first comparison using the independent samples t-test, the computed p-value of 0.0160 was less than the set significance level (0.05). This indicates a significant difference in the performance of the GWVT between the standard

TABLE 12. Results of t-test, ANOVA, and regression analysis on GWVT performance.

Variables	Level of significance (α)	Selected hypothesis
t-test Test: mechanical efficiency (grouping: basin type)	$p = 0.0160$ $\alpha = 0.05$ $p < \alpha$	Reject the null hypothesis in favor of the alternative hypothesis
t-test Test: mechanical efficiency (grouping: blade type)	$p = 0.0000$ $\alpha = 0.05$ $p < \alpha$	Reject the null hypothesis in favor of the alternative hypothesis
ANOVA Independent: ratio-diameter Dependent: mechanical efficiency	$p = 0.0002$ $\alpha = 0.05$ $p < \alpha$	Reject the null hypothesis in favor of the alternative hypothesis
Regression analysis Torque versus rotational speed	r-value $= -0.8848$ $R^2 = 0.7829$ $p = 0.0000$ $\alpha = 0.05$ $p < \alpha$	Reject the null hypothesis in favor of the alternative hypothesis

basin and the optimized basin with guide vanes. Thus, the result rejects the null hypothesis between the variables and favors the alternative hypothesis. Similar results were also reported in the study by BAJRACHARYA *et al.* [29], who observed different results with various guide vane optimizations compared to a normal basin without any guide vanes.

Further comparison using independent samples t-test obtained a p-value of 0.0000, which was well below the significance level (0.05). This result implies a significant difference in GWVT performance between cases that utilized the standard steel blades and low-density nylon rod blades. Thus, the null hypothesis was again rejected. In line with this, the study of SRITRAM *et al.* [13] also obtained similar results when comparing standard steel blades with lower-density materials such as aluminum for the blade.

Moreover, a p-value of 0.0002 was obtained using the one-way ANOVA test, which is also below the significance level (0.05). This result indicates a significant difference in GWVT performance among the 0.55, 0.60, and 0.65 design ratios between the diameters of the runner blade and basin, thus rejecting the null hypothesis. These results are consistent with the study by ULLAH and CHEEMA [15], which stated that the varying design ratios between the basin and blade diameters resulted in significantly different power outputs. To support this, the study by KHAN [16] showed that changes in the design ratio from 0.13 to 0.17 with 0.01 increments, influenced both vortex height and tangential velocity.

Lastly, the regression analysis showed that torque and rotational speed had a linear relationship. The null hypothesis was rejected since the computed p-value of 0.0000 was less than the significance level (0.05). The analysis showed a significant correlation coefficient R^2 of 78.29% between torque and rotational speed, indicating a strong correlation as values between 60% and 79% are considered strong. This analysis confirmed that as torque increased, rotational speed decreased, with only 21.71% of the correlation influenced by other factors. The same results were also reported in the studies by Khan *et al.* [24] and Kim *et al.* [25], where an inverse relationship between torque and rotational speed was observed. This result also illustrated that the torque decreased in GWVT as the rotational speed increased. This was further confirmed by the calculation using Eq. (2.3), which shows that as the water flow rate increases from zero to the selected flow rate, the turbine experiences higher rotational speed.

4. Conclusion and recommendation

This study highlighted the complex relationship between low-density blades, the design ratio between the diameters of the basin and blade, and the presence of guide vanes in a GWVT. It also explored the impact of low-density turbine blades on the performance of the GWVT. A reduction in blade mass led to increased rotational speed, which in turn resulted in higher electrical power output. However, an increasing rotational speed displayed an inverse relationship with torque and power input, resulting in lower mechanical efficiency. This inefficiency may result in the loss of energy stored in the GWVT due to mechanical issues.

The study also examined the design ratio between the diameters of the basin and blade of the GWVT, correlating it with blade density and changes in blade mass. A higher design ratio resulted in larger area in contact with the free vortex. This, however, led to decreased rotational speed due to the lower vorticity in that region but an increase in torque and power input, ultimately resulting in improved mechanical efficiency. Other than that, the inclusion of guide vanes in the GWVT was included in the investigation. Their presence affected the overall performance of the turbine by decreasing both rotational speed and torque while increasing power output. This led to lower mechanical efficiency compared to a setup without guide vanes. The results subsequently indicated that for optimal performance, guide vanes must be positioned in the free vortex region to achieve low vorticity.

The study further showed that different design parameters influenced the GWVT's mechanical efficiency in various ways. It concluded that the use of heavier blades, such as steel with a 0.60 design ratio between the diameters of the basin and blade in a standard basin, provided optimal performance, achieving an average rotational speed of 98.2 RPM and the highest mechanical efficiency of 43.75%, thereby preventing energy loss and producing more electricity. This study also modified the design and performance of the GWVT, leading to more efficient energy generation. These results can also be used as a benchmark for developing new design strategies aimed at maximizing energy extraction and minimizing energy losses. Lastly, the authors suggest conducting future studies to explore optimal guide vane placement, refine blade designs based on existing research, and consider the utilization of both vortex regions to further improve turbine performance and efficiency.

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