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Experimental Analysis of Conical Basin Models with Vortex Turbines for Small-Scale Renewable Energy Generation

Iwan Kurniawan[a]*, Romy[a], Amir Hamzah[b], A. Farhan[a]

[a)] *Department of Mechanical Engineering, Faculty of Engineering, Universitas Riau, Indonesia*
[b)] *Department of Electrical Engineering, Faculty of Engineering, Universitas Riau, Indonesia*

*Corresponding author: iwan.kurniawan@lecturer.unri.ac.id

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ABSTRACT

This study investigates the performance of Gravitational Water Vortex Turbines (GWVT) using different conical basin configurations, focusing on the impact of vane designs on turbine efficiency. Four basin models were tested: model A (no vanes), Model B (180-degree vanes), Model C (90-degree vanes), and Model D (45-degree vanes). The basin was constructed from resin mixed with fiber, with the addition of vanes designed in various configurations to enhance vortex formation and energy extraction. Experimental testing was conducted under varying load conditions, with efficiency determined by the ratio of the potential energy of the water to the mechanical energy generated by the turbine. The results showed a significant improvement in efficiency with the introduction of vanes. Model B, featuring 180-degree vanes, demonstrates the highest efficiency, achieving an increase of up to 17.08% compared to the base model (Model A). Model C, with 90-degree vanes, and Model D, with 45-degree vanes, show efficiency increases of 14.56% and 12.08%, respectively. These results imply that the design and arrangement of vanes are essential in enhancing vortex formation and turbine performance.

KEYWORDS: *Gravitational Water Vortex Turbine (GWVT), Experimental study, Conical basin, Vane design, Energy efficiency.*

1.0 INTRODUCTION

The growing global demand for energy, coupled with the pressing need to reduce environmental degradation, has intensified the search for sustainable and clean energy solutions. The transition away from fossil fuels towards renewable energy sources is critical for mitigating climate change, ensuring energy security, and fostering long-term environmental sustainability. Among renewable energy technologies, wind, solar, and hydropower have gained significant attention for their potential to reduce carbon emissions and provide reliable, clean energy. While wind and solar energy systems have seen rapid deployment, hydropower, especially in its small-scale forms, remains a key player in providing sustainable energy solutions, particularly in remote or off-grid areas.

Every country worldwide must contribute to reducing CO2 emissions, including Indonesia. Indonesia has set an ambitious target to increase the share of renewable energy in its national energy mix. According to the National Energy General Plan (RUEN), the government aims for the portion of new and renewable energy (EBT) to reach 23% by 2025 and 31% by 2050 [1].

Small-scale hydropower, including pico-hydro and micro-hydro systems, offers significant potential for decentralized energy generation. These systems are especially advantageous in rural or isolated regions, where large-scale power infrastructure is not viable. However, the widespread implementation of small hydropower systems comes with its own set of challenges. While they provide renewable energy, these projects often involve changes to local ecosystems, particularly freshwater systems, raising concerns about their environmental impact. Therefore, understanding to optimize hydropower technologies for minimal environmental disruption, maximizing energy generation is essential for their successful integration into global energy systems.

The review aims to provide an in-depth synthesis of recent research on renewable energy systems, with a particular focus on small-scale hydropower were done by researchers. Dincer and Acar [2] discuss the broader context of clean energy solutions and their role in sustainability, stressing the importance of innovative approaches to energy storage and grid integration. Owusu and Asumadu-Sarkodie [3] explore the various renewable energy sources, examining their role in climate change mitigation, sustainability, and the challenges that accompany their adoption. Kuriqi and Jurasz [4] address the environmental implications of small hydropower systems, emphasizing the need for balancing energy generation with ecosystem conservation, particularly in fluvial environments.

Further, Rais and Basar [5] examine the design and performance optimization of pico-hydro turbines for low-head, low-flow conditions, focusing on how such systems can be tailored for use in regions with limited water flow. Similarly, Adanta et al. [6] explore the impact of blade gap design on pico-hydro turbine performance, providing valuable insights into how small-scale hydropower turbines can be optimized for greater efficiency. Collectively, these studies offer a comprehensive perspective on the current state of renewable energy, with an emphasis on small hydropower systems as a promising solution for sustainable energy generation.

Gravitational Water Vortex Power Plants (GWVPP) is the energy from a vortex created by the gravitational pull of water in a specially designed basin, which rotates around a central axis. This rotational energy is then captured by a turbine to generate power. The advantage of these systems is that they are simple, low-maintenance, and particularly suitable for decentralized, off-grid applications, making them an appealing option for small-scale renewable energy production [7]. Recent studies have focused on optimizing various aspects of these systems, including basin geometry, inlet/outlet configurations, turbine design, and the placement of the runner [8].

Gravitational water vortex power plants operate on the principle of converting the rotational energy of a water vortex into mechanical energy through a turbine. Water enters the basin tangentially, creating a vortex that spirals downward due to the influence of gravity. The geometry of the basin significantly impacts the vortex's size, shape, and intensity, directly affecting the performance of the turbine and, consequently, the efficiency of the power generation process [9].

The main components of a GWVPP include the basin, turbine, runner, and inlet/outlet geometries. Each of these components plays a vital role in optimizing vortex formation and energy conversion. The basin's shape and dimensions are critical in determining the vortex characteristics, which in turn affects the turbine's operational efficiency. Over the past few decades, extensive research has been dedicated to understanding the fluid dynamics of vortex formation, optimizing turbine design, and improving system efficiency [9].

Basin design is fundamental to the vortex formation in GWVPPs. Two major basin types have been widely studied: cylindrical and conical basins. Dhakal et al. [10] and Sánchez et al. [11] compared the performance of cylindrical and conical basins. They found that conical basins are generally more efficient in generating stronger vortices due to their geometry, which directs the water flow towards the center more effectively. In particular, the conical basin allows for a sharper vortex core, which enhances the turbine's energy extraction efficiency. Moreover, Sánchez et al. [12] examined the concave and convex basin designs and concluded that the concave design generally provides better vortex stabilization and higher performance at lower flow rates.

The runner design in a GWVPP is closely linked to the basin and inlet configuration. Dhakal et al. [13] and Srihari et al. [14] investigated the influence of runner position and geometry on the efficiency of GWVPPs. They reported that the placement of the runner at the optimal position within the vortex is essential for maximizing energy extraction. Additionally, Marius et al. [15] explored the role of turbine blade design and found that increasing the number of blades can enhance performance by improving torque generation under specific flow conditions.

The inlet channel geometry plays a crucial role in the formation of the vortex and the overall efficiency of the GWVPP. A well-designed inlet channel ensures a smooth entry of water into the basin, which is critical for generating a stable vortex. Burbano et al. [16] and Velásquez et al. [17] studied the impact of inlet channel shapes and dimensions on vortex formation. These studies showed that a properly optimized inlet channel could significantly improve the torque generated by the turbine. In particular, the width, curvature, and angle of the inlet were found to have a direct influence on the velocity distribution and the stability of the vortex.

The outlet geometry also affects the vortex behavior. Sánchez et al. [11] and Ruiz Sánchez et al. [12] explored various outlet hole configurations and demonstrated that a larger outlet diameter can reduce the energy loss caused by turbulence and improve turbine efficiency. Similarly, computational studies by Kim et al. [18] examined the influence of draft tubes and blade number on the efficiency of GWVPPs, showing that a combination of optimized basin and outlet geometries leads to the best overall performance.

Advancements in computational fluid dynamics (CFD) have greatly contributed to the optimization of basin and runner designs. Jiang et al. [19] conducted multi-disciplinary optimization studies using CFD simulations to explore small-scale gravitational vortex hydropower systems. There have emphasized the importance of coupling hydro-structural analysis with hydrodynamic simulations to achieve a more holistic design optimization. Velásquez et al. [8] applied surrogate modeling methods for multi-objective optimization of the basin and inlet channel, which is particularly useful for balancing competing performance metrics such as energy output and construction cost.

Several experimental studies have focused on enhancing the efficiency of GWVPPs by modifying basin shapes, inlet configurations, and turbine characteristics. Sarker et al. [20] and Vinayakumar et al. [21] conducted experiments to investigate vortex intensification through modifications to the conical basin, suggesting that vanee-tuning basin and inlet geometries can lead to a significant increase in turbine efficiency. Nishi et al. [22] explored the losses in gravitational vortex turbines and highlighted that reducing frictional losses in both the basin and the turbine system is key to improving energy generation. Furthermore, Tamiri et al. [23] studied vortex profile variations under different diffuser sizes and found that optimizing the diffuser and outlet geometry could reduce vortex dissipation and improve system performance.

Based on previous study, the basin is a crucial component in enhancing the efficiency of gravitational water vortex power plants. While cylindrical and conical basins have been extensively studied, the novelty of this study lies in its experimental investigation of the impact of adding vanes to the basin of a Gravitational Water Vortex Power Plant (GWVPP), an area that has not been fully explored in previous research. While existing studies have focused on optimizing aspects like basin geometry, inlet/outlet configurations, and turbine design, the potential benefits of incorporating vanes to enhance vortex formation and, consequently, system efficiency remain under-explored. By systematically comparing the performance of a basin with vanes to one without, this study aims to provide new insights into how vane addition can optimize vortex dynamics and increase the overall energy generation efficiency of GWVPPs.

2.0 METHODOLOGY

Gravitational Water Vortex Power Plants (GWVPPs) offer a sustainable approach to generating energy using small-scale hydropower. These systems utilize the natural force of gravity to create a water vortex, which drives turbines for electricity production. GWVPPs represent a viable option for localized and environmentally conscious energy solutions. One of the key components influencing the efficiency of these systems is the basin geometry, as it directly impacts vortex formation and energy capture. Among the various basin shapes, the conical basin has shown significant promise due to its ability to intensify the vortex, thus improving turbine performance. This paper builds on the optimization work conducted by Velásquez et al. [24], who explored the effectiveness of conical basins in gravitational water vortex turbines. The optimized conical basin design is shown in Figure 1.

In this study, a conical basin made of resin mixed with fiber has been selected for optimization. The fiber is incorporated at a specific ratio to ensure the structural integrity and durability of the basin. To further enhance vortex formation and power generation, vanes are added inside the basin, following a spiral or "snail" pattern, Figure 2. These vanes guide the water in a more controlled manner, contributing to vortex intensification, which is crucial for maximizing turbine efficiency. The experiment will test four different basin models, each with varying configurations of vanes, Figure 3.

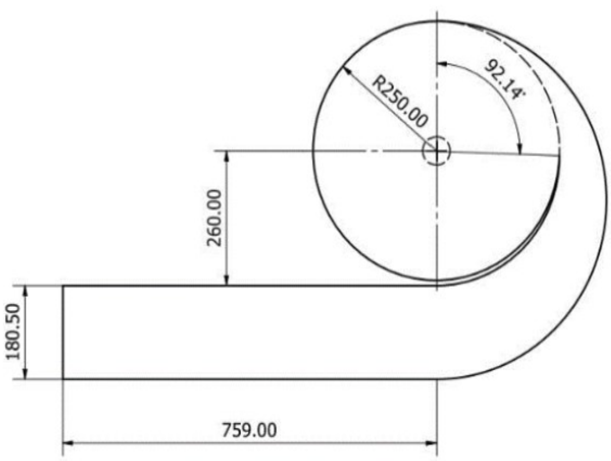
Basin model A will serve as a baseline, featuring a conical shape without any vanes. Basin model B will incorporate vanes that follow a snail pattern, covering a 180-degree circle, while model C will include vanes with a 90-degree circle and model D will feature vanes with a 45-degree circle. The vanes in all models will have dimensions of 4 mm in thickness and 25 mm in width, designed to effectively guide the water flow while maintaining structural stability.

The aim of this study is to compare these four basin models to determine which configuration provides the highest efficiency in vortex formation and power generation. By evaluating the impact of vane configuration on vortex dynamics and energy conversion, this research seeks to identify the optimal basin design for improved performance in GWVPPs.

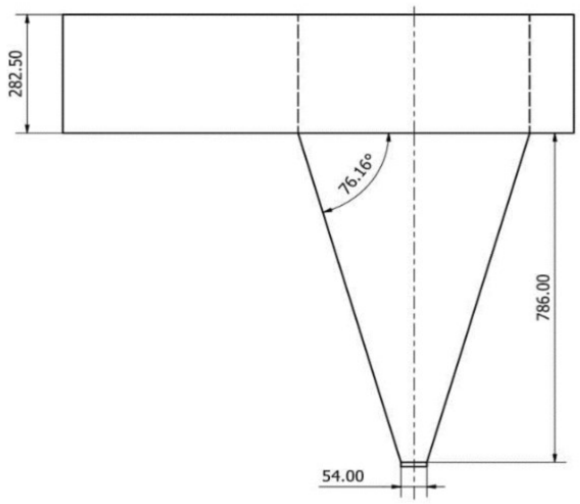
2.1 Experimental Set-up

Gravitational Water Vortex Power Plants (GWVPPs) represent a promising solution for small-scale, sustainable hydropower generation, with applications in remote or off-grid locations. The efficiency of these systems largely depends on the design and optimization of the basin that facilitates vortex formation, as well as the characteristics of the turbine that is driven by this vortex. In this study, the performance of a conical basin with various vane configurations is investigated to optimize the power output of the GWVPP.

The Figure 4, the setup consists of a lower and an upper reservoir, with water being pumped from the lower reservoir to the upper one. The water flow is controlled and measured via a V-notch weir that connects the upper reservoir to the inlet of the basin. The weir's geometry allows for precise measurement of the flow rate, which is essential for assessing the impact of different basin and turbine configurations on power generation. Once water reaches the upper reservoir, it flows into the conical basin, where it begins to rotate and generate a vortex flow. This vortex is crucial for driving the turbine at the basin's bottom, creating rotational energy



(a) top view



(b) front view

Figure 1: Scheme of the GWVPPs in mm scale, (a) top view and (b) front view [24]

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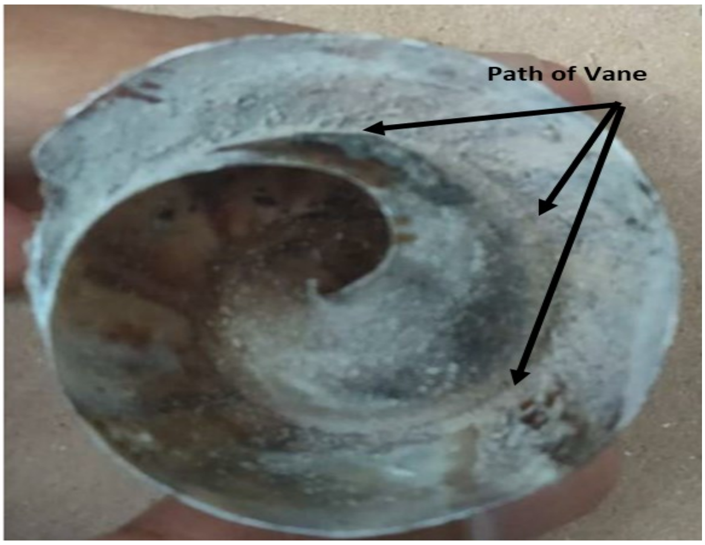
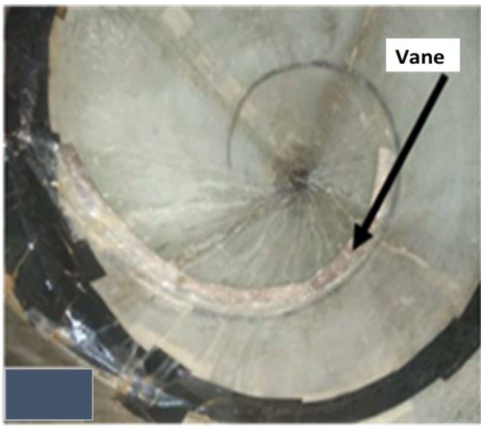


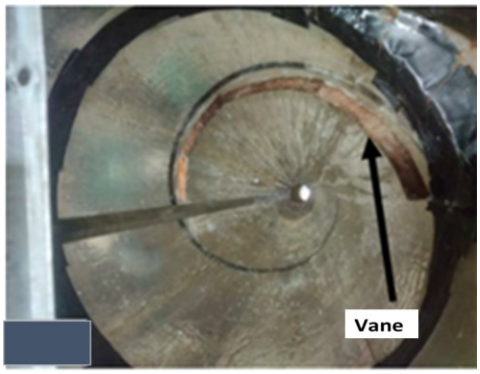
Figure 2: Vane patterns found on snail shell

At the bottom of the conical basin, the vortex turbine (figure 5) is positioned to harness the kinetic energy of the vortex. The turbine's shaft is connected to a pulley, which is held in place by a nylon rope. This rope setup is essential for capturing the mechanical energy generated by the turbine's rotation. The ends of the nylon rope are connected to weights and a spring scale, enabling the measurement of the torque produced by the turbine. Additionally, a tachometer is used to record the turbine's rotational speed, providing a direct measure of its performance under varying load conditions.

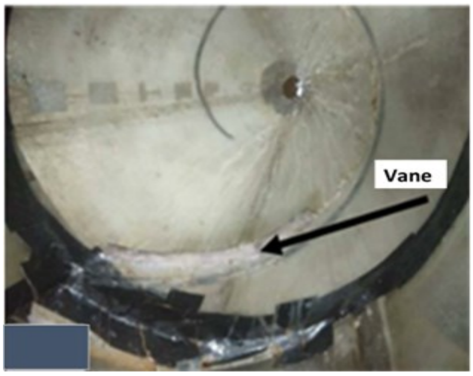
Model A



Model C



Model B



Model D

Figure 3: Basin Models for testing: (1) model A, (2) model B, (3) model C and (4) Model D

To evaluate the turbine's efficiency, load variations are systematically applied, ranging from no load to the maximum load the turbine can handle. The experiment continues until the turbine ceases to rotate, ensuring that the upper limits of the system's power generation capacity are identified. By analyzing these parameters, the performance of the vortex turbine and the influence of different basin configurations on the power output will be thoroughly assessed.

This study examines four conical basin models designed for gravitational water vortex power plants. Model A serves as the baseline, featuring a simple conical basin without vanes. Models B, C, and D incorporate vanes to enhance vortex intensity and power generation. Vanes, measuring 4 mm in thickness and 25 mm in width, are arranged in circular patterns: 180° for Model B, 90° for Model C, and 45° for Model D. In Models B, C, and D, the vanes exhibit a spiral configuration to direct water flow and maximize vortex strength, thereby optimizing turbine power output.

2.2 Performance vortex Turbine

The experimental method used in this study is adapted from the work of Saleem et al. [25], The experimental setup in the referenced study is similar to that employed in this research, with modifications to account for the specific configurations of the conical basin and the vanes.
To calculate the torque of the turbine (Nm) during testing, (1) is used: the load (N) is multiplied by the radius of the pulley (m).

$$T = f.r \tag{1}$$

Thus, the power output of the turbine is obtained by multiplying the torque by the angular velocity ω (1/s) produced by the turbine, as given by (2):

$$P_{turbine} = T.\omega \tag{2}$$

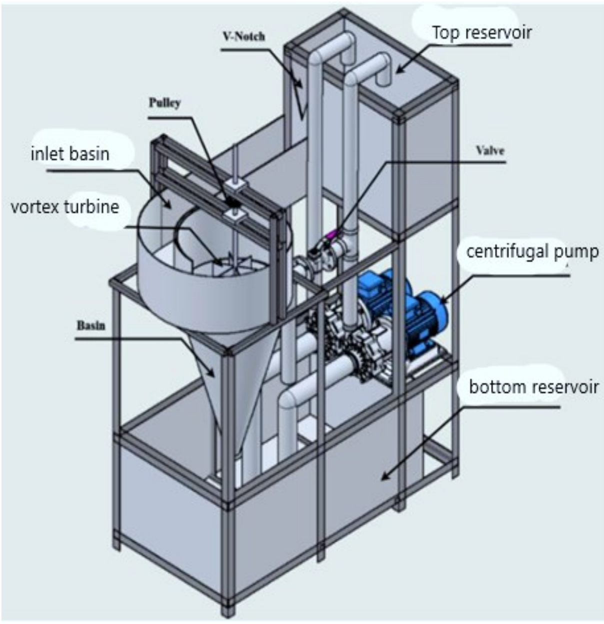


Figure 4: Experimental set-up

Figure 5: Vortex turbine for power extraction

The potential power of the water can be calculated using (3):

$$P_{water} = \rho.Q.g.H \tag{3}$$

The density of water ρ =1000 kg/m³, the flow rate Q = 0.003 m³/s, the gravitational acceleration g = 9.81 m/s², and the difference in height between the water entering the basin and the water exiting the basin H (m) are used in (3) to calculate the potential power of the water. The turbine efficiency is determined using (4):

$$\eta = \frac{P_{turbine}}{P_{water}} \tag{4}$$

.

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3.0 RESULTS AND DISCUSSION

The performance of a vortex turbine is assessed based on the efficiency it can achieve. Efficiency is divined as the ratio of the potential energy of the water to the mechanical energy of the turbine. The higher the efficiency of a turbine, the greater the amount of potential energy from the water in the basin was extracted. Both the basin and the type of blade affect the turbine's efficiency.

3.1 Performance vortex Turbine

In Figure 6 illustrates the efficiency variation of turbines with different basin model based on experimental data. The results indicate that the Gravitational Water Vortex Turbine with model B demonstrates superior efficiency compared to other model. This enhanced efficiency is due to the model B more effective extraction of potential energy from the water flow.

The results indicating that Model B (180-degree vanes) produces the highest efficiency, followed by Models C (90-degree vanes), D (45-degree vanes), and vane A (no vanes), suggest that the efficiency of the vortex turbine is closely linked to how the vanes influence the vortex formation and the interaction between the water and the turbine. The 180-degree vanes cover a larger portion of the basin's circumference, creating a more balanced and strong vortex flow. This results in a more consistent rotational movement of water, which is critical for efficiently transferring energy to the turbine. The stability of the vortex is paramount for maximizing turbine efficiency. Models with more symmetrical or evenly distributed flow, like Model B, will produce a stable vortex with minimal fluctuations, leading to better energy extraction

In Model B, the water flow is more evenly distributed around the basin due to the 180-degree vanes. This ensures that the vortex interacts with the turbine over a longer period and a larger area, allowing for better energy transfer from the vortex to the turbine blades. The larger interaction surface leads to higher torque and, therefore, higher mechanical energy conversion efficiency. As the number of vanes decreases (from Model B to Model D), the flow becomes less optimized. With fewer vanes, the vortex is weaker and more turbulent, reducing the efficiency of energy transfer to the turbine.

The performance of vortex turbines, specifically models A, C, and D, varied significantly in terms of optimal angular velocity for achieving peak efficiency. Model A demonstrated its highest efficiency at a relatively high rotational speed of 19.86 revolutions per second (rev/s). This suggests that Model A's design characteristics are optimized for higher flow rates or specific hydrodynamic conditions that favor faster rotation. In contrast, models C and D exhibited peak efficiencies at lower angular velocities. Model C's optimal performance was observed at 13.21rev/s, while model D achieved its best performance at 19.47 rev/s and model B at 15.67rev/s.

These differences in optimal angular velocities likely stem from variations in turbine blade geometry, channel design, or other factors influencing the interaction between the water flow and the turbine. This highlights the importance of tailoring turbine design to specific operating conditions to maximize efficiency.The differences in optimal angular velocities across the different basin models are reflective of the vortex strength, stability, and the resulting energy transfer efficiency. Model B (180-degree vanes) produces the most stable and effective vortex, allowing the turbine to operate at the highest efficiency at 19.86 rev/s with efficiency 38.83%. On the other hand, Model A (no vanes) struggles with vortex instability, achieving only moderate efficiency 21.75% at 15.67 rev/s, while Model C with efficiency 36.31% and Model D with efficiency 33.83% fall between these two extremes, with their respective optimal angular velocities of 13.21 rev/s and 19.47 rev/s. These finding underline the importance of the basin's vane configuration in optimizing vortex formation and enhancing turbine performance.

It can be seen in Figure 7, the efficiency of the gravitational water vortex turbine improved by specific percentages when using different basin configurations (models B, C, and D) compared to the base model (model A), which does not have any vanes inside the basin. Model B (180-degree vanes): The turbine's efficiency increases by 17.08% when this basin model with 180-degree vanes is used.

The vanes inside the basin help create a more stable and efficient vortex, leading to better energy conversion from the water's potential energy to mechanical energy. Model C (90-degree vanes): The efficiency increase is 14.56% for this model. The vanes here are smaller and span a smaller portion of the basin's circumference (90 degrees). While still improving efficiency, it is not as much as in Model B, as the vortex formed by these vanes is less optimal. Model D (45-degree vanes): The efficiency increase is 12.08% for this model. The vanes in this configuration are even smaller and cover an even smaller part of the basin. This results in the least efficiency improvement among the three modified models, but still shows an increase over the base model. This improvement occurs because the vanes inside the basin help optimize the water flow, stabilize the vortex, and better convert the potential energy of the water into mechanical energy for the turbine.

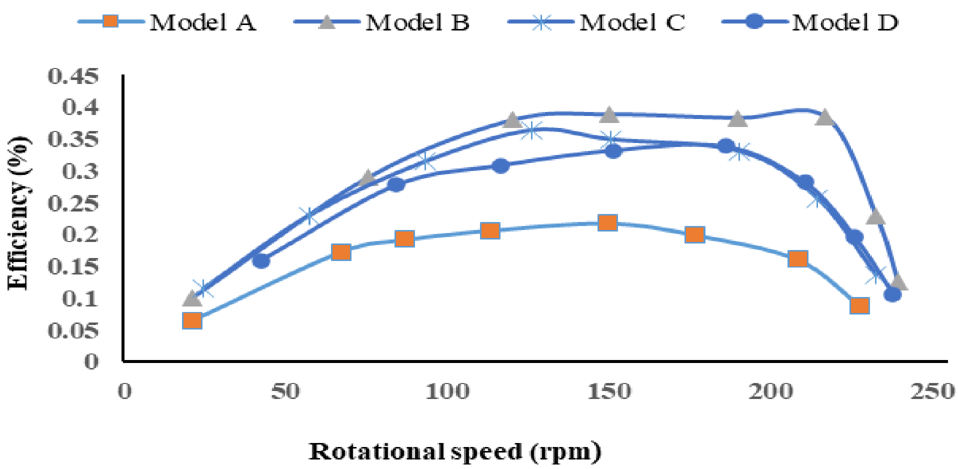

Figure 6: Performance of curve for basin model

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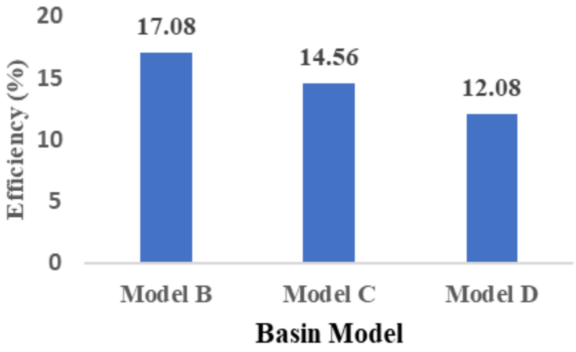

Figure 7: Efficiency improvements for the basin model

4.0 CONCLUSIONS

In this study, the performance of a gravitational water vortex turbine was evaluated using different basin configurations, including a base model without vanes (Model A) and three modified models with vanes (Models B, C, and D). The results clearly demonstrate that the addition of vanes significantly improves the turbine's efficiency. Model B, with 180-degree vanes, achieved the highest efficiency increase of 17.08% compared to the base model, resulting in an efficiency of 38.883%. This suggests that a larger surface area for the vanes enhances the vortex formation and energy extraction. Model C, with 90-degree vanes, showed an efficiency increase of 14.56%, reaching an efficiency of 36.31%. Model D, with 45-degree vanes, produced a lower but still significant efficiency increase of 12.08%, with an efficiency of 33.83%. The findings highlight the importance of vane design in optimizing the vortex flow and maximizing the turbine's energy conversion efficiency. Model B (180-degree vanes) consistently demonstrated the best performance, followed by Model C (90-degree vanes) and Model D (45-degree vanes). The results suggest that the vane configuration significantly affects the overall turbine performance, with larger vanes contributing to higher efficiency. The study concludes that the use of vanes inside the conical basin, particularly the 180-degree configuration (Model B), plays a crucial role in enhancing the overall performance of the gravitational water vortex turbine. Further optimization of vane dimensions and basin configurations could lead to even higher efficiency, offering potential for more sustainable small-scale hydropower generation using vortex-based technologies.

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