Design, Fabrication, and CFD-Based Performance Analysis of a Gravitational Water Vortex Turbine

Nasir Akbar*, Malik Sarmad Zahid†, Arshad Ali Khan‡, Hazrat Ali§, Muhammad Adil**

Abstract
Gravitational Water Vortex Turbines (GWVTs) provide a cost-effective and sustainable solution for rural electrification under low-head conditions. This research presents the fabrication and experimental evaluation of a cylindrical basin prototype (50 cm diameter, 50 cm height) to study the influence of vortex height, blade position, and orifice-to-basin diameter ratios on turbine performance. Orifice sizes of 8, 10, 12, and 14 cm (16–28% ratios) were tested with blade placements at 2 cm, 7 cm, and 10 cm, across vortex heights ranging from 18–48 cm. Results show that vortex height is the primary driver of performance, with Revolutions Per Minute (RPM) and power output increasing up to 40–43 cm before plateauing due to turbulence. The stable performance was leading to 24% orifice-to-basin ratio with the maximum power output of approximately 2.3mW as well as an overall hydraulic to mechanical energy conversion efficiency of approximately 8.8% at a vortex height of 35 cm, whereas the speed of the turbine was approximately 115 RPM at 40 cm. The blades' position of 22 cm maximized torque capture, whereas deeper blades generated higher speeds (125-155RPM) but minimized electrical power. Smaller orifice ratios (16–20%) concentrated flow and performed better at higher vortex heights, while the 28% ratio showed efficiency losses from turbulence. Overall, the findings confirm that a 24% orifice-to-basin ratio with mid-range vortex heights (30–40 cm) and blade depths of 10–22 cm provides the most effective balance of RPM, power, and efficiency, making GWVTs a practical low-head micro-hydro technology for decentralized rural energy generation.

Keywords: Gravitational Water Vortex Turbine, Micro-hydro Power, Vortex Height, Orifice-to-basin Diameter Ratio, Blade Height, Turbine Efficiency, Rotational Speed, Power Output.

Introduction

Hydropower is a reliable and widely adopted renewable energy source, with technologies ranging from dammed reservoirs and run-of-

*Department of Mechanical Engineering, University of Engineering & Technology Mardan, 23200, Pakistan, engr.nasir.akbar@uetmardan.edu.pk
†Department of Mechanical Engineering, University of Engineering & Technology Mardan, 23200, Pakistan, sarmad@uetmardan.edu.pk
‡Corresponding Author: Department of Mechanical Engineering, University of Engineering & Technology Peshawar-Jalozai Campus, 24100, Pakistan, engrarshad@uetpeshawar.edu.pk
§Department of Mechanical Engineering, University of Engineering & Technology Mardan, 23200, Pakistan, hazrat_ali001@icloud.com
**Department of Mechanical Engineering, University of Engineering & Technology Mardan, 23200, Pakistan, enggmuhammadadil@gmail.com

river systems to pumped storage, in-stream devices, and emerging gravitational vortex designs. Hydropower plants are further categorized by capacity into large, small, micro, and pico systems. A strong free-surface vortices analytical model of gravitational vortex hydropower systems has been achieved, which requires just head and geometric parameters to forecast volumetric flow rate, air-core diameter, and rotational constant. Tested on full-scale experimental depth discharge information, the model was found to be in good agreement with observations, as well as overcoming weaknesses of the previous semi-empirical methods, due to its consideration of velocity variations across the vortex radius. This offers a better design and scaling capability of turbines in the vortex-based energy systems (Alzamora & Glasscock, 2021).

One of the papers includes the evaluation of one of the prototypes of the turbines using the gravity-powered water vortex turbine on the basis of the statistical indicators, Best Efficiency Point (BEP), Nash–Sutcliffe Efficiency (NSE), Mean Squared Relative Error (MSRE), Relative Mean Error (RME), and BIAS (or Mean Bias Error), confirmed through Computational Fluid Dynamics (CFD) and experiment. The response variables were the vortex height, torque, power, and efficiency. At the optimal efficiency point, the experimental and numerical efficiencies were 58.13% and 54.62 with the vortex height considered as the performance factor that is critical. NSE and MSRE exhibited the highest adaptability to predict response, whereas RME and BIAS demonstrated deviation in torque and power. The electrical efficiency of the generator at BEP was 27.68%, reducing by approximately 3.1% with a change in the flow, highlighting the effect of generator conditions and height of the vortex in the overall optimization of the system (Ángel et al., 2024).

Another study introduces the design concept of a gravitational water vortex turbine that can be used in the roof to produce small-scale electricity. The House of Quality was used to translate the requirements of the respondents into product specifications, and a morphological chart was constructed to come up with three design alternatives. The Pugh method and a weighted-decision matrix were used to choose the final design, and it became the Design 3 with a 60° inlet opening, 30° pre-rotation angle, three blades, and Polyvinyl Chloride (PVC) body (Camillus et al., 2021).

Water vortex turbines (WVTs) tap the Free Surface Vortex (FSV) flow to generate energy; they are easy to build, but usually have low efficiency. We compared experimental observation of flat and curved blades and found them to have the same rotational speed at no load, suggesting that vortex circulation rather than blade geometry governs turbine speed. Curved blades were better under load, reducing vortex disturbance to enable them to reach a comparable efficiency of 22.2% to the 21.6 %of the flat blades (Kueh et al., 2017). Gravitational Water Vortex Hydraulic Turbines (GWVHTs) are a run-of-river micro-hydropower system capable of working with low head and flow. Efficiencies reported are 70-85, but more investigations should be done to optimize the basin geometry, inlet design, and runner arrangement. The literature recommends the use of conical over cylindrical basins, although the findings on the design of the runner blade are inconclusive (Maika et al., 2023).

Gravitational vortex hydro-turbines (GVHTs) produce electricity through the conversion of centrifugal energy of a free vortex that is generated in a circular basin with a tangential inflow. They are cheap, have a few moving parts, and hence their benefits include very low head operation, being environmentally friendly, and low maintenance. Efficiencies are reported to reach as low as about 30% in academic research and as high as about 50% in commercial assertions, though theory values are as high as 85%. Most of the current literature has concentrated on the turbine design, basin geometry, and inlet/outlet optimization yet the technology is at a prototyping level, with scarce literature on its application to large scales (Nikam et al., 2020).

One of the experiments carried out experimentally and analytically to assess the viability of a gravitational vortex water turbine at different flow rates. It was found that the power and efficiency of the turbines increased with the flow rate, and the tank and outlet losses were the predominant ones, in relation to insignificant losses of runners (Nishi et al., 2020). One study analyzes rotary turbines in small micro-hydropower plants (low pressure) by using 3D modeling (Kompas flow) and experiments. The findings indicate that rotational speed reduces with increasing load, and maximum efficiency is achieved within a given load range. This central gap on turbine blades did not impact on efficiency (Obozov et al., 2023; Srihari et al., 2019b).

WVTs are environmentally friendly micro-hydropower technologies that may be used to achieve ultra-low head applications, but the technology is still mainly in the prototyping phase and has to be geometrically optimized. Experiments have shown that it is more or less 30% efficient, with commercial results of around 50% with 500 W to 20 kW, thus requiring additional optimization and scalability study in designing it (Rahman et al., 2017).

The use of gravitational vortex turbines (GVTs) allows power production on a micro-scale at low head and flow sites where hydropower is not efficient. Parametric studies also point at the role of basin geometry and inlet design on the formation of a vortex. The best results were obtained using a diameter of the outlet of the upper funnel being approximately 40% of the upper funnel diameter and a rectangular shape inlet passage at 60 degrees coupled with a 30-degree pre-rotational plate, which enhanced the velocity and symmetry of the vortexes (Rehman et al., 2017).

Under low-head and flow conditions, Gravitational Water Vortex Turbines (GWVTs) utilize man-made or naturally occurring vortices in a basin to generate electricity. Recent vortex generation and blade interaction studies on CFD have been conducted to optimize geometry, and it has been found that the parameters like radius coefficient and blade submergence play a great role in performance. The highest efficiency was achieved at a configuration of a 0.2 m pulse radius and 8 blades, with a total efficiency of approximately 64%. This efficiency was accompanied by a high level of blade submergence (90-95%), which, however, lowered efficiency due to braking effects. These results demonstrate the value of GWVT energy conversion through geometric optimization (Sinaga et al., 2025).

Research on two-stage GVWTs has demonstrated that blade geometry is a key determinant of performance. Savonius and curved blades were tested using a telescopic system with 2 shafts and a load of 0.5-2 kg. Stage 1, using Savonius blades, got 12.4 W mechanical power and increased torque and was more efficient under heavy loads, whereas Stage 2, using curved blades, got 11.1 W and more stable vortex formation. Findings emphasize the necessity of a trade-off between torque generation and vortex stability, as it is important to optimize the shape of blades, as well as contact area, to ensure a reduction in flow distortions (Sinaga et al., 2025).

Vortex amplification in conical basins of WVTs with five nozzle designs (Set I-V). The experimental findings indicate that the Set III basin had the highest performance, and the torque, power output, and efficiency were improved by 57.77, 54.42, and 54%, compared to the Dhakal et al. design, where the intensifier nozzles contributed greatly to the strength of the vortex and its efficiency (Srihari et al., 2019a).

The Zotloterer-turbine is an optimized design of gravitational water vortex power plants (GWVPPs) that work without guide vanes and nozzles. It has maximum efficiency at low heads (0.73 m 3 m) of up to 80% and is characterized by its robustness, simplicity, and fish-friendly nature, which are attributed to its low rotational speed and clean vortices. The total GWVPP efficiency is determined by the design of the turbine used, basin geometry, and generator system; however, the concept of Zotloterer can offer a feasible solution to sustainable low-head hydropower. Hydropower Gravitational water vortex hydropower has been considered as a micro and pico hydro solution in low and ultra-low head sites since 2006. The technology employs the large angular velocity of a free-surface vortex and is reported to have 1922 installations across the world, primarily in Europe and Asia. The reported efficiencies of 53 on average, which is greater than waterwheels, but lower than propeller turbines, allow it to be used in the small to medium flows, where more traditional methods are less efficient. The main merits are the fact that the design is easy to construct, has a rather high-power density, and can be made fish-friendly, although additional work is required to maximize the performance and confirm the use of ecological advantages (Timilsina et al., 2018).

Among the newest studies, one introduces a Gravitational Water Vortex Power Plant (GWVHP) that is studied by means of CFD simulations as well as experimental testing, which measures flow rate, torque, and efficiency. The Finite Element Analysis (FEA) was used to optimize and test the system (water tanks, channels, and rotor blades). Maximization and testing of the system (water tanks, channels, and rotor blades) were optimized with the help of the FEA. Experiments and simulations are very similar, with the maximum torque of 6 and 5.7 Nm and efficiencies of 58 and 56%, respectively, at 2 and 3m /min. The paper shows how CFD is valuable in experimental validation, scaling, and useful GWVHP development to be applied in the actual world to achieve renewable energy sources in practical sites (Vinayakumar et al., 2024).

This study will model, simulate numerically and experimentally, a small scale portable gravitational water vortex (GWV) power plant, which will be used in the low-head areas of rural use. A small vortex chamber was created to create a stabilized vortex with a minimum amount of water flowing through it and computations were done in COMSOL and the main parameters were optimized such as the height of the vortex chamber, number of blades, length of the blade, and the angle of blade tilt. An optimum configuration was chosen as a systematic parametric search was done to determine the effects of each parameter on rotor speed. An optimized design was then constructed and tested experimentally, and the results employed to test the numerical results (Vinayakumar et al., 2022).

A recent study also points to micro-hydropower, especially gravitational vortex power, as an environmentally friendly and sustainable alternative. Research highlights the role of FSV-formation and the appropriate turbine designs to enhance the energy conversion efficiency and contribute to sustainable water use (Yaakob et al., 2014) .

GWVT is a type of electricity generating power device based on artificially induced vortex in a free-surface basin. This paper uses the CFD two-phase flow simulation in order to determine vortices, interaction between blades, and geometries. Findings indicate that an increase in the radius coefficient increases the energy uptake by increasing the torque, although with a minor vortex asymmetry. The most efficient arrangement, 0.2 m pulse radius, 8 blades, the highest efficiency (64.23%) was obtained, and the high submergence of the blades (90 to 95) worsened the performance because of the braking activities (Zamora-Juárez et al., 2022).

The paper analyzes the operational, design, and economic considerations that influence the Gravitational Water Vortex (GWV) hydropower systems and their contribution to production of sustainable energy. The improvement in performance was achieved by testing the turbine blade angle, basin design, and material selection. Experimental, numerical and theoretical methods were used to assess power output through increasing and decreasing the flow rate, vortex height and turbine configuration. Findings show that a five-blade turbine with a 44 angle has an 82 percent efficiency and the high-tech material-based components have a 1.23 percent torque boost over the traditional ones. Also, there was an increase of 60% in power generation as well as decreased energy loss through the conical basins with optimized nozzles. The research offers an integrated optimization model of GWV turbines and can give information on how to enhance the efficiency of small hydropower and facilitate low-carbon energy generation (Zainal et al., 2022).

There is extensive literature on the GWVTs, yet much of it covers general design factors, including basin shape or blade profile. The impact of different orifice diameters, blade diameter, and blade height in cylindrical basins with a distinctive vortex dynamic has been rarely studied by anyone in a systematic way. The influence of these parameters on vortex strength, flow stability, and the overall turbine efficiency is yet to be explored. Most of the studies only optimize one or two parameters simultaneously leaving a lapse in the comprehensive analysis of the geometric parameters influencing the performance of the turbines. The aim of the study therefore is to experimentally and analytically determine the impact of orifice diameter, blade diameter, and blade height on a gravitational water vortex turbine device with a cylindrical basin to design the turbine and achieve the highest energy output and stability.

Methodology and Fabrication

The key components of the setup include a cylindrical basin, a water storage reservoir, an inlet channel, a turbine rotor assembly, and a water recirculation system.

Computer-Aided Design Modeling

The design began with individual Computer-Aided Design (CAD) modeling of each component, as shown in Figure 1. The vortex basin was a hollow cylinder of diameter 50 cm and a hole in the middle of the bottom. Plates with the orifice diameter of 8, 10, 12 and 14 cm were designed and equipped with quick-release interface so that they could be swapped in and out. Quick-release mounting makes small localized hydraulic losses in the form of small flow disruptions at the orifice-basin interface. But these losses are small, are independent of the various test configurations, and do not materially interfere with the final result of overall and comparative efficiencies of the mechanism, since the mechanism itself is stationary and does not cause mechanical losses. The inlet channel (22 × 11 cm) would be located tangentially at the upper edge of the basin, and a small metallic notch to direct the entry of the flow and increase the vortex was introduced. In the case of the turbine, the pipes of PVC (Ø 4 and 7 inches) were cut into different widths and lengths to be used as the curved blades. The curved shape was chosen to match the flow direction of the vortex which enhances the energy acquisition as opposed to flat blade designs.

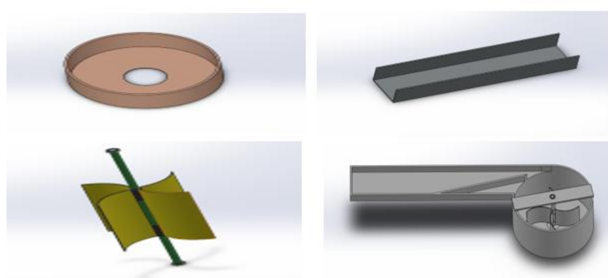

Figure 1: CAD modeling of basin, channel, blades connected to shaft and final geometry.

CFD Analysis of Water Vortex Turbine Without Blades

The flow of inlet streams is smooth entering the top horizontal pipe as shown in Figure 2 with a low to medium velocity (blue). The flow in the cylindrical chamber continues to swirl about the vertical axis forming a distinct vortex. The velocities grow to the bottom center and there the color changes to green, yellow and orange which are the signs of acceleration and the loss of pressure. Top velocity (approximately 0.7 m/s, red/orange) is measured at the center of the vortex in the range of the outlet and it is in line with the principle of Bernoulli. The tight spiral at the base confirms vigorous swirling motion, which is appropriate in energy harvesting in vortex turbine or separation system. The well-shaped vortex and smooth inlet entry prove that the entry of the tangential flow is effective, which is critical in proper vortex development. Table 1 shows design parameters of the gravitational water vortex turbine.

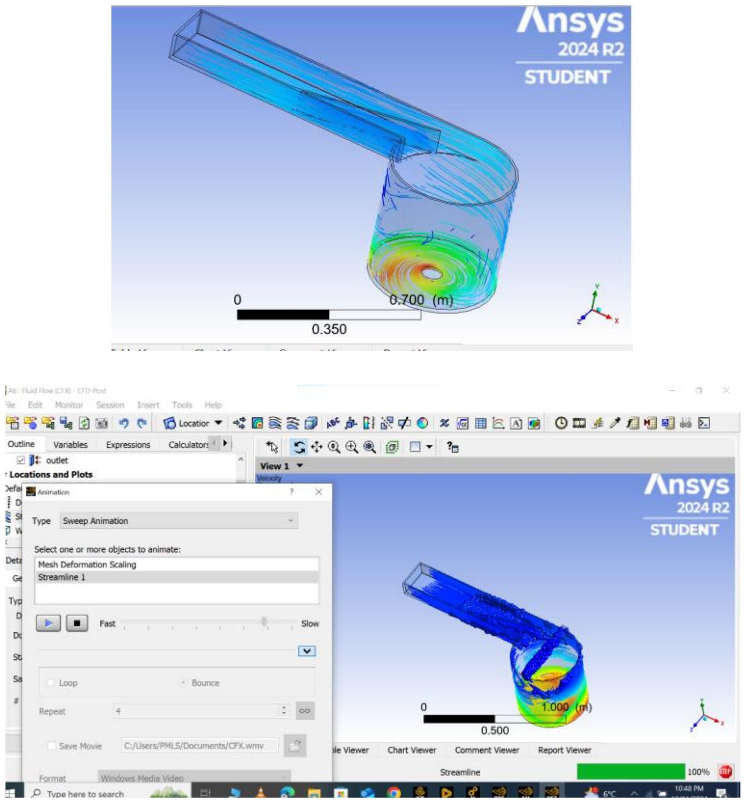

Figure 2: Vortex formation analysis using CFD.

Basin and Orifices Fabrication

The basin itself was a cut piece of mild steel sheet cut rolled and shaped into a cylindrical reaction pot using a 3 roll bending machine. A hole was used in the center bottom of the basin to allow the water to exit in a controlled manner, and a variety of sizes were tried to determine the best one. Machined mild steel shaft was used and fitted vertically with bearings in a frame to reduce friction and hold straight.

Table 1: Design parameters of Gravitational water vortex turbine.

Parts	Dimensions
Basin	Diameter= 50cm, Height=50cm
Channel	Length=100cm Width =22cm Height = 11cm
Shaft	Length = 60cm Diameter = 2.54cm
Blades	Diameter= 10.16cm, 17.78cm length=20.32cm,30.48cm
Notch angle	45 degrees
Bearing	Outer diameter =5.08cm Internal diameter = 2.54cm

Pulley	Diameter =12.7cm
Basin orifice	8cm ,10cm ,12cm, 14cm
Dynamo	12 volts

Blade and Rotor Fabrication

PVC pipe was cut into turbine blades and put into place in a central hub attached to the shaft in a symmetrical manner. PVC has been selected due to the formability, availability and wear resistance, but the material modifications can occur in the future.

Ironic copy of a central shaft with the length of 60 cm and diameter of 13 mm was designed. Since the shaft was formed to accommodate multiple positions of the blades, then there was the possibility of trying various positions of the blades along the length. The role of the hub is to install the turbine blades to the shaft. There were two bearings on the top and bottom of the design to hold the shaft. Figure 3 shows the final assembly of GWVT.

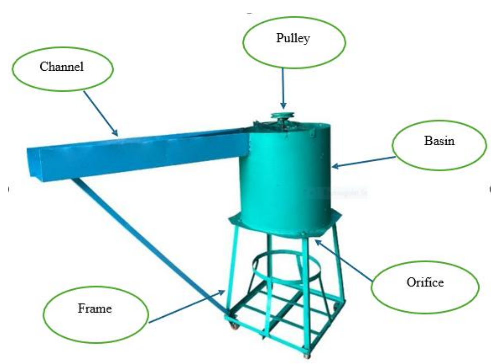

Figure 3: Final assembly of gravitational water vortex turbine.

Experimental Methodology

Recirculating water pump was switched on to jumpstart test procedure to ensure that the cylindrical vortex basin whirling was jumpstarted by tangentially circulating water around the basin. The flow control valve was used to adjust the height of the vortex manually when it became stable and reached its constant state of 25 cm. An adjustable measuring tape attached to the basin wall was used as the good reference of real-time monitoring and keeping the height of the vortex constant.

The rate of flow was measured using a basic volumetric procedure and the vortex height maintained constant. To determine a time that would be spent until the 60-liter drum is filled, the latter was used to measure time as long as the discharge of water by the pump was directed to the 60-liter drum. The rate of flow (Q) by (V) of 60 liters divided by time (t) filled was then obtained with the help of this method: The accurate and realistic determination of the rate of water discharge through system of turbine under each test condition was obtained by this method.

A tachometer which measured the shaft rotation speed of the turbine in Revolutions Per Minute (RPM) was then monitored using a digital tachometer and directed at a reflective tape which was stuck to the rotor. To record the output in electrical terms, a multimeter that was connected to the dynamo of the turbine was used to measure the voltage (V) and current (I) simultaneously. The turbine blades were mounted 7cm above the bottom of the basin and the aperture diameter of the turbine blades was observed initially at 7cm.

Flow rate, RPM, voltage, and current were again measured at increased vortex height of 30 cm, 40 cm, and 45 cm respectively to study the effect of the vortex height on the turbine performance. Afterwards, the 7cm orifice was tried with each of the heights of the vortex. Then, the orifice plates were changed to 10 cm, 12 cm, and 14 cm diameter plates respectively. The measuring cycle, which consisted of measuring of the flow rate, RPM, voltage, current, and vortex height adjustment, was repeated in each of those orifice diameters. In order to determine the effect of blade placement on performance, the height of turbine blades on the bottom of the basin was increased to 7 cm in the final test stage. The above steps were repeated with each of the orifice sizes (8 cm, 10 cm, 12 cm, 14 cm) and with each vortex elevation (25 cm, 30 cm, 40 cm, 45 cm). In this way, therefore, comparisons of the behavior of turbines could be done in detail when the elevation of the blades was altered.

The values of the efficiency which refer to the overall hydraulic to mechanical energy conversion efficiency of the gravitational vortex turbine were computed by.

$$\eta = \frac{P\ \text{mech}}{P\ \text{hydraulic}}$$

Where $P\ \text{mech} = T\omega$, $P\ \text{hydraulic} = \rho Q g h$

Results and Discussions

The GWVT experiment involved the investigations of the impacts of the vortex height and the placement of blades on the important performance parameters, including electrical efficiency, RPM, and power output of the basin, with the blade positions tested at 2 cm, 7 cm, and 10 cm above the bottom of the basin. It was discovered that the higher the vortex height, the higher the water pressure, which then accelerated the speed of the turbine and the amount of power generated and the best placement of the blade with the vortex, increased the efficiency. These findings were confirmed by complementary CFD analysis which showed a smooth tangential flow of inlet, a steady swirling circulation around vertical axis, and peak velocity in the center outlet, all in accordance to the

Bernoulli principle. The simulations also showed the effect that the height of vortexes and orifice structure have on circulation, velocity distribution, and pressure drop to be consistent with experimental results. The experimental and CFD results indicate that vortex dynamics play a significant role in the streamlining process of the location of blades and developing a turbine so that it could have a successful GWVT operation.

Electric Power Versus Vortex Height

The performance measure assesses the efficiency of vortex energy conversion system in four ratios of Orifice/Basin Diameter (16%, 20, 24 and 28%). All the curves are the variation of the power output with the vortex height at constant blade height of 7 cm. The outcomes indicate that there is positive correlation between the height of the vortex and power generation with almost linear trends at all ratios. The 24% ratio has the steepest gradient which indicates it has optimal energy conversion efficiency, whereas the 28% ratio exhibits marginal returns beyond 40 cm as a result of turbulence and excessive flow speed. The better performance of the orifice to basin diameter ratio of 24% is explained by the fact that there is an optimum balance between the confinement of flows and the discharge capability that leads to a stable and coherent free-surface vortex with high-tangential velocities and efficient transfer of torque to the turbine blades. Conversely, a higher ratio of 28% will lead to over flow discharge, lesser vortex residence time, and high turbulence, which make angular momentum transfer weak and create efficiency degradation. During this analysis, the orifice to basin diameter ratio is employed and the results are given as a percentage in order to make it easier.

The findings in Figure 4 indicate that the power output is highly dependent upon the orifice-basin diameter ratio. The lowest output of 16% (0.4 -1.3mW) (milli watt) was caused by the restriction in flow. The 20% ratio was slightly more effective (0.6-1.8mW), which showed the increased vortex formation. The highest and most consistent output (~2.3mW) and an almost linear increase proves that the 24% ratio was the most efficient arrangement. The 28% ratio increased to approximately 2 mW after which it topped out at 40 cm vortex height, presumably owing to turbulence and lowered torque transfer. All in all, the 24% ratio gave an ideal balance of flow and stability thus it was the most appropriate design value in terms of efficiency maximization in the low-head vortex micro-hydro systems.

Findings in Figure 5 are represented by the x-axis (vortex height, 18-48 cm) and the y-axis (electric power, 0-4mW). All the curves will be Orifice/Basin Diameter Ratio: 16% (Blue), 20% (Orange), 24% (Gray) and 28% (Yellow) each. Reduced ratios inhibit water circulation, making the vortex weaker whereas increased ratios consent to greater flow. In all scenarios, the greater the vortex height, the greater the power output because higher velocity of water and more energy kinetic in the vortex is obtained by the turbine.

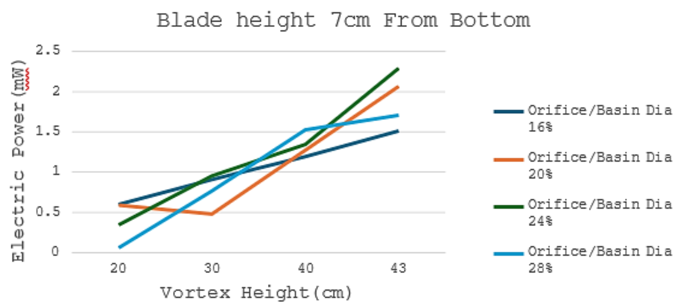

Figure 4: Vortex height versus electric power (blade height 7 cm from bottom).

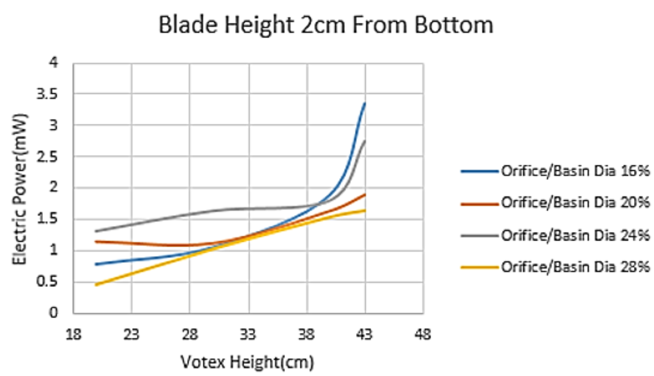

Figure 5: Vortex height versus electric power (blade height 2 cm from bottom).

The Blue curve (16%) has a low output at short vortex heights but it increases steeply past 40 cm beyond 3.5mW. There is a gradual but consistent increase recorded in the orange curve (20%) to an almost constant level of approximately 2mW, which means stable but average performance. The grey curve (24%) has the highest output in the medium heights of the vortex (28-36 cm) but decreases at a higher height thus most useful in the mid-range. The Yellow curve (28) represents the lowest total output, with minimal increases in the total output with the height of the vortex, because the bigger orifice causes the energy to be dispersed. Comprehensively, smaller orifices (16%) offer better heights of vortices, whereas middle range ratios (24%), offer the best heights of medium vortices. range ratios (24%) perform best at medium vortex heights.

Figure 6 reveals the comparison of electric power output of two heights of the blade (12 cm and 22 cm) at different vortex heights. Low power is generated with the 12 cm blade with a maximum power of about 2mW at 41-45 cm and then energy capture is limited. On the contrary, the 22 cm blade has a far greater output, which increases with a decrease in length to 43mW at 35 cm to 58mW at 45 cm because of increasing contact with the vortex. The results have shown that longer blades are more effective in harnessing vortex energy and it is wise to maximize the blade height in order to increase the effectiveness of vortex turbines.

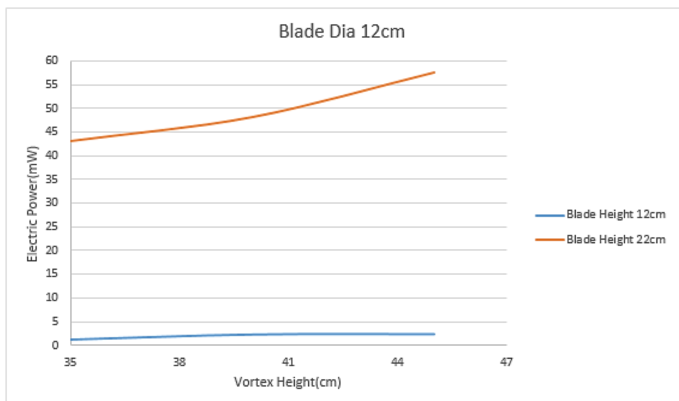

Figure 6:* *Vortex height versus electric power (blade height 12 cm and 22 cm from bottom).

Orifice/Basin Diameter % Versus RPM (Blade Height 7 cm from Bottom)

Ratio of Orifice/Basin (16-28%) is shown in the x-axis and the rotational velocity of turbines (in RPM) is shown in the y-axis of Figure 7. The curve is proportional to the height of the vortex 20cm (Blue), 30cm (Orange), 40cm (Gray) and 43cm (Yellow). The non-linear increase in the RPM with the height of the vortex at all ratios and the maximum is 24-26%. The reduction of RPM towards the end of this range is also slightly reduced which means that the flow or turbulence is not efficient enough.

The ratio of orifice to basin diameter and vortex height have great influence on the turbine RPM of 7 cm blade height. The vortex at the 20 cm with the lowest RPM of (65-90) has a constant growth with the large orifices. Peaks of 30 cm and 40 cm of RPM are about 24-25% (that is, about 108 and 115) then it slightly drops. The highest values (110 -125) are the highest at the 43 cm vortex, which plateaus to the 25-26.

Comprehensively, the RPM increases as the height of the vortex increases and optimal performance is always attained at 24-26% diameter ratio. Smaller ratios limit flow whereas bigger ratios lead to turbulence and ineffectiveness. Therefore, vortex heights of 40 to 43 cm and a 24 to 26% ratio give the ideal turbine speed that offers a useful guide to designing a vortex based micro-hydro.

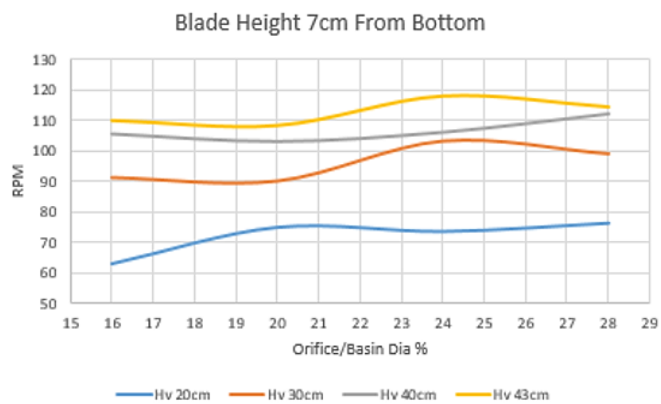

Figure 7: Orifice/basin Dia % Vs turbine RPM (blade height 7cm).

The x-axis in Figure 8 is the Orifice/Basin Diameter Ratio (15-29%), whereas the y-axis is the speed of a turbine measured in RPM, which is one of the main parameters of the available mechanical energy. All curves in Figure 8 are associated with the height of the vortex: 20 cm (Blue), 30 cm (Orange), 40 cm (Gray), 43 cm (Yellow). The height of vortex is an indicator of the columnar swirling water, and higher the height, the higher the energy potential.

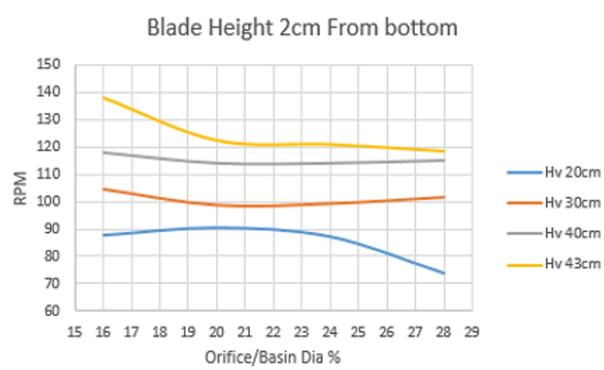

Figure 8: Orifice/basin Dia % versus turbine RPM (blade height 2cm).

The graph in Figure 8 also indicates that the vortex height is the main factor that affects the turbine RPM. Smaller orifices (15-18 % orifice/ basin Dia) are the most efficient at lower heights (e.g. 20 cm) and do not dissipate as much power. Increasing in height (40 43 cm), RPM is high (110-135) not so sensitive to orifice size, and has a higher degree of design freedom. In general, smaller orifices are more advantageous in regard to low vortex heights and, in high vortex heights, the system maintains a high amount of rotational energy despite having large orifices.

RPM Versus Vortex Height

Vortex height (20-45 cm) was indicated on the x-axis and turbine speed (RPM) on the y-axis at a blade height of 7 cm. Curves in Figure 9 have an Orifice/Basin Ratio of 16% (Blue), 20% (Orange), 24% (Gray), and 28% (Yellow). The non-linearity in the rise of RPM is with the height of the vortex, and the greatest enhancement occurs between 20 and 35 cm and hence levels off. The 16% ratio increases between 68 and 110 RPM, whereas the 20% goes between 75 and 112 RPM. The 24% ratio is consistent, almost ideal (80-115 RPM), and the 28% ratio up-steps highest (85) and levels beyond 35-40 cm (117 RPM). Generally, RPM is primarily caused by vortex height, and its orifice ratio determines trends in efficiency. The 24% ratio provides the most balanced performance, as 28% provides low heights, but even out at the beginning. Maximum efficiency is at 24-28% ratios with heights of vortices over 35 cm.

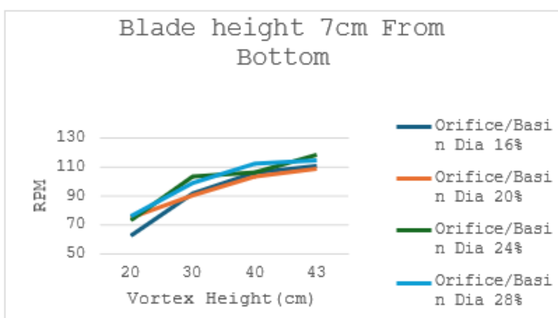

Figure 9: RPM versus Vortex height.

X-Axis (Horizontal) as Vortex Height (cm) 18cm to 45cm, in Figure 10, which shows the vortex height formed on the water surface above the orifice. Y-Axis (Vertical) as RPM (Rotations Per Minute) is a measure of the speed of the turbine, which is a proxy of mechanical power output. Every line is associated with another orifice/basin diameter ratio Blue -16%, Orange 20%, Gray 24%, Yellow 28%. RPM rises with the height of the vortex, notwithstanding the size of the opening. This is reasonable, where the higher the vortex, the higher the kinetic and potential energy, which leads to more turbine rotation speed.

The graph is a plot of vortex height (10 cm 0-50 cm) versus speed of the turbine (RPM) when the blade height is 10 cm and the Orifice/Basin Ratio is 24% (Figure 11). RPM grows with the height of the vortex increasing between around 85 at 20 cm to slightly over 100 at 40 cm, with a strong positive correlation. According to Figure 11, the taller and well-formed vortices have more energy to impart on the blades, which increases the performance of the turbine. The findings lay emphasis on the need to optimize the vortex height and basin depth in order to achieve maximum efficiency.

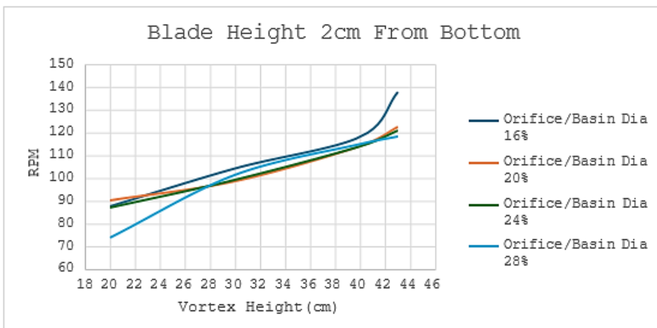

Figure 10: Vortex height versus RPM (blade height 2 cm).

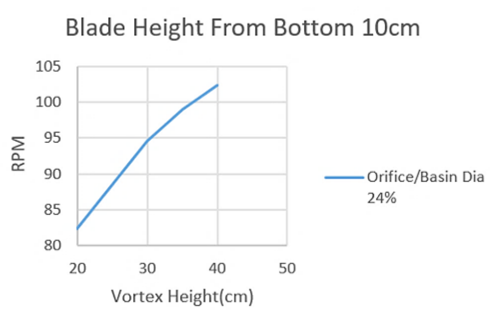

Figure 11: Vortex height versus RPM (blade height 10 cm).

The comparison of the RPM of 35-45 cm at the vortex heights of 12 cm and 22 cm, at the height of the blade in 12 cm and 22 cm is demonstrated in the Figure 12. There is a higher RPM increment (125-132) in the 12 cm blade, and the 22 cm blade records a slower improvement (118-132). The shorter blade has a faster rotation as the inertia is smaller, whereas the taller blade pulls out more power and consequently more power as indicated in the graph of power output. This has pointed out the fact that increased RPM does not necessarily imply that the height of power blades and power capture of torque are the key factors to effective operation of a vortex turbine.

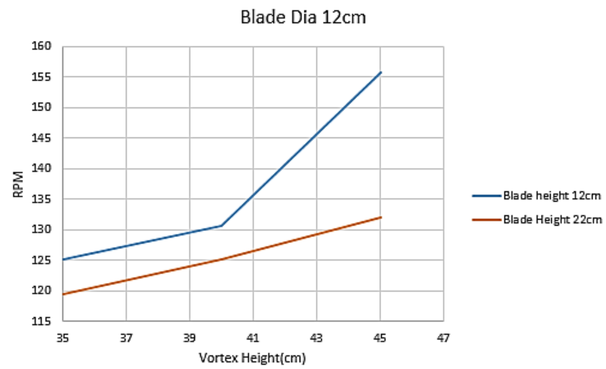

Figure 12: RPM versus Vortex height (blade Dia 12 cm).

Efficiency Versus Vortex Height

Figure 13 indicates efficiency versus vortex height at blade height of 2cm. There are four Orifice/Basin Ratios 16% (Blue), 20% (Orange), 24% (Gray) and 28% (Yellow). In the case of 16, 20, and 24, efficiency peaks within the low vortex heights (15-21 cm) and tends to decrease until the approximate of 36 cm, and slightly rebounds beyond this point, which is most evident in the 16%. The lowest ratio is 28% which shows almost a flat curve.

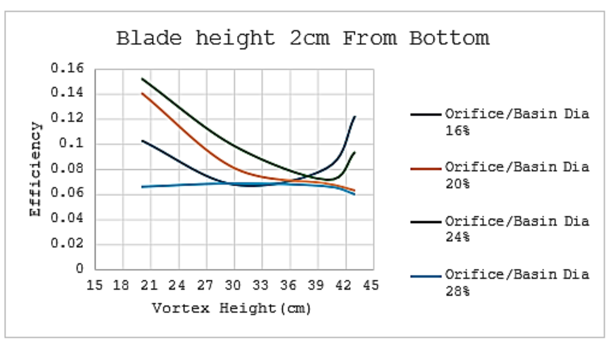

Figure 13: Efficiency versus Vortex height (blade height 2cm).

The best turbine-vortex interaction is that the 16% orifice /basin ratio has the highest efficiency at low and high vortex heights (36-45 cm). Every ratio drops in efficiency between 21-36 cm, probably as a result of turbulence, or a fixed 2 cm blade height. Ventricular outflows of larger size (28%) always fare the worst, since the surplus disorganizes the vortex. The result is that the 16% ratio is the most stable energy capture bearing in mind the necessity to optimize orifice size and the position of the blades to reduce efficiencies in the mid-range.

The graph plots efficiency against vortex height (20–43 cm) at a fixed blade height of 7 cm. Four Orifice/Basin Ratios are compared: 16% (Blue), 20% (Orange), 24% (Gray), and 28% (Yellow). The 20% ratio in Figure 14 shows a dip at 30 cm before recovering, while the 28% ratio rises sharply after 20 cm and peaks near 35 cm. The 24% ratio increases steadily, achieving the highest efficiency at 43 cm, whereas the 16% ratio starts strong, dips at 30 cm, then rises again.

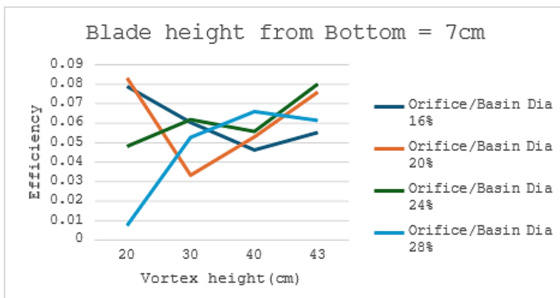

Figure 14: Efficiency versus Vortex height (blade height 7cm).

Altogether, both the vortex dynamics and the positioning blades affect efficiency trends. The 24% ratio is the best at a higher vortex height whereas the 28% ratio is significantly improved. These findings imply that the ideal orifice sizes are related to the height of the blades and the nature of the vortices, and in design the adjustable placement of the blades or the adjustable orifice shapes may prove beneficial in the future.

The graph illustrates height of the vortex (0-60 cm) to the efficiency of the turbine over the Orifice/ Basin Ratio of 24% with the blades attached at 10 cm above bottom of the basin (Figure 15). The overall hydraulic to mechanical energy conversion efficiency increases gradually between 20 cm with a peak of approximately of 0.088 (8.8%) at 35 cm which decreases with the further increase in the height of the vortex. This implies the maximum height of a vortex to transfer energy after which turbulence or flow instabilities will decrease the performance. The findings indicate the need to optimize the vortex height and the position of the blades to achieve maximum efficiency where the 24% ratio offers stable performance until the optimum.

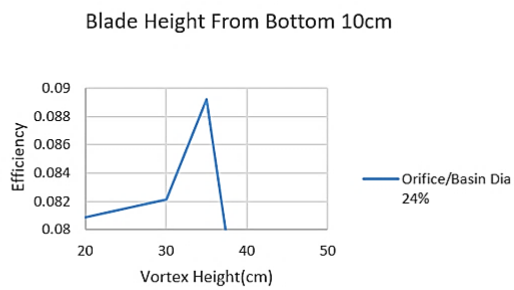

Figure 15: Efficiency versus vortex height (blade height 10cm).

Effect of RPM on Electric Power

Figure 16 represents turbine speed (0 -150 RPM) versus electric power output (0 -2 mW) under an Orifice/Basin Ratio of 24% at a blade height of 10 cm. RPM responds positively to power output and rises sharply between 85-95 RPM after which it levels off to the efficiency limit of the turbine. The best working range is between 90 and 100 RPM in which the interaction with the vortex blades is the most effectively working. The 24% ratio offers a steady vortex and steady stream of power which proves that the size of orifice and the height of the blade must be adjusted so that the efficiency of the generator can be maximized. The findings clearly point at designing methods that can be followed to enhance vortex-based turbines by the ways of enhancing the blade geometry and orifice shape.

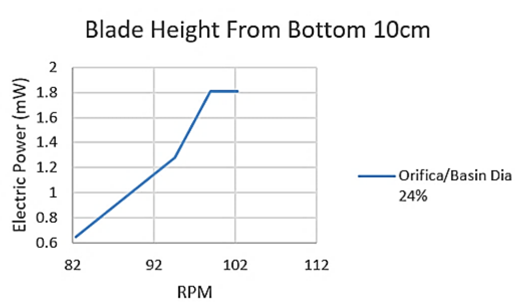

Figure 16: Electric power versus RPM.

Discussion

Earlier research on GWVTs has predominantly focused on individual design parameters or basin-specific designs, including basin shape, blade geometry, inlet design, and nozzle design. Although these studies managed to show the viability of GWVT systems, and in certain experiments had relatively high efficiencies, they were mostly only based on single-variable analysis or fixed geometries. Specifically, most studies either focused on conical basins or used nozzles to improve performance, which does not clearly show the underlying effects of basic geometric parameters. As a result, synergistic interactions between basin geometry, orifice size, vortex height, and blade submergence, particularly in simple cylindrical basins, have not been adequately studied, thus constraining the generation of generalized and scalable design principles in low-head hydropower projects.

Table 2: Comparison of the Present Study with Previous Works on GWVTs.

Study	Basin Type & Parameters Considered	Key Findings	Research Gap / Contribution of the Present Study
Yaakob et al. (2014)	Cylindrical; vortex formation & turbine design	Demonstrated strong dependence of performance on vortex stability	Did not quantify the effects of orifice size or blade geometry
Rahman et al. (2017)	Conical; general basin geometry	Achieved 30% efficiency; emphasized the need for optimization	No systematic parametric variation
Nikam et al. (2020)	Cylindrical & conical; basin shape, inlet design	Reported efficiency range of 17–85%; conical basin superior	Orifice ratio and blade depth were not studied
Kueh et al. (2017)	Cylindrical; blade shape (flat vs curved)	Curved blades slightly improved efficiency (22%)	Vortex height and orifice effects are ignored
Srihari et al. (2019)	Conical with nozzles; nozzle configuration	Improved torque and efficiency (54%)	Geometry effects coupled with nozzle dependency
Zamora-Juárez et al. (2024)	Cylindrical; vortex height, torque, power	58% efficiency near BEP	Single geometry; no multi-parameter interaction
Sinaga et al. (2025)	Conical (single & two-stage); blade type & submergence	Maximum efficiency ~64%	No combined vortex–orifice–blade study
Proposed Study	Cylindrical; orifice ratio (16–28%), blade height (2–22 cm), vortex height (18–48 cm)	Optimum at 24% orifice ratio and 35–40 cm vortex height; balanced RPM & torque	First experimental study quantifying the interaction of key geometric parameters

The gap in the present study is that a systematic experimental investigation of interacting geometric parameters in a cylindrical GWVT system has been developed. The study varies orifice-to-basin ratio (16-28%) and blade height (2-22 cm) and vortex height (18-48 cm) simultaneously and finds a definite optimum range of operating values that provides the necessary balance between rotational speed and torque. According to the results, an orifice ratio of about 24% and a vortex height of 3540 cm are the most stable and most successful in terms of overall performance. The work is the first experimental confirmation of the effects of geometric interactions in a cylindrical GWVT and is useful to offer practical, nozzle-free design findings, as well as to develop knowledge on efficient, low-head vortex-based hydropower systems.

In Table 2, early studies, such as (Yaakob et al., 2014), established the strong dependence of turbine performance on vortex stability in cylindrical basins but did not quantify the effects of critical geometric parameters like orifice size or blade geometry. (Rahman et al., 2017) and Nikam et al., 2020) examined conical and cylindrical basins and reported efficiencies in the range of 30–85%, emphasizing the importance of basin geometry; however, systematic parametric variations of orifice ratio and blade depth were not explored. Subsequent works focused on isolated geometric aspects, including blade curvature (Kueh et al., 2017), nozzle configurations (Srihari et al., 2019), and vortex height or operating conditions near the best efficiency point (Zamora-Juárez et al., 2024), yet these studies largely neglected coupled effects among multiple parameters. More recent research by (Sinaga et al., 2025) investigated blade type, submergence, and multi-stage configurations, achieving efficiencies up to ~64%, but still lacked a combined vortex–orifice–blade interaction analysis.

Conclusion

The experimental study of the turbine of a gravitational vortex of water proves the fact that the geometric and fluid dynamic factors are very important to calculate the efficiency of the system and its output. Key findings include:

- Vortex height directly correlates with turbine RPM and power output, with optimal performance observed between 35–45 cm due to enhanced water velocity and kinetic energy capture.
- Blade height strongly influences energy transfer: lower blades extract more torque and power, while higher blades achieve greater RPM but reduced electrical output.
- The ratio of orifice/basin and basin diameter greatly affects the dynamics of the flow, with the 24% set-up providing the best and most consistent results. Smoother ratios (16-20%), which limited flow at low levels but enhanced performance at higher vortices, were found, but bigger ratios (28r) created turbulence and decreased stability.
- Efficiency maximizes at intermediate vortex heights and relies on a compromise between concentration of the flow and minimization of turbulence, and neither extreme sizing of orifices nor excessive vortex height can be relied on to maximize efficiency.
- Finally, an orifice-to-basin ratio of 24%, vortex heights of 35-45 cm, and well-positioned blades all maximize energy harvesting, maintain constant vortex formation, and optimize the turbine's overall performance. This offers a powerful guideline to the design, scaling, and operational optimization of the gravitational vortex wind turbine in practice. These findings also provide a guideline on how to develop cost-effective, efficient, and sustainable vortex turbines to be used in rural electrification and decentralized renewable energy generation.

References

Alzamora Guzmán, V. J., & Glasscock, J. A. (2021). Analytical solution for a strong free-surface water vortex describing flow in a full-scale gravitational vortex hydropower system. *Water Science and Engineering, 14*(1), 72–79.

Ángel Zamora-Juárez, M., Hugo Guerra-Cobián, V., Leonardo Ferriño-Fierro, A., Luis Bruster-Flores, J., Roberto Fonseca Ortiz, C., Miguel López-Rebollar, B., & Miguel López-Rebollar bmlopezr, B. (2024). *Assessment of a prototype of gravitational water vortex turbine: experimental validation of efficiency. 26*, 691–711.

Camillus, J., Tokit, E. M., Rosli, M. A. M., Sa'at, F. A. Z. M., Herawan, S. G., & Syahputra, S. I. A. (2021). Conceptual design of gravitational water vortex turbine for green energy generation. *Journal of Physics: Conference Series, 2051*(1).

Kueh, T. C., Beh, S. L., Ooi, Y. S., & Rilling, D. G. (2017). Experimental study to the influences of rotational speed and blade shape on water vortex turbine performance. *Journal of Physics: Conference Series, 822*(1), 012066.

Maika, N., Lin, W., & Khatamifar, M. (2023). A Review of Gravitational Water Vortex Hydro Turbine Systems for Hydropower Generation. *Energies 2023, Vol. 16*, Page 5394, 16(14), 5394.

Nikam, S., Pawaskar, S., Thakur, M., & Pawar, S. (2020*). Performance Analysis of Gravitational Vortex Hydro-Turbine.*

Nishi, Y., Suzuo, R., Sukemori, D., & Inagaki, T. (2020). Loss analysis of gravitation vortex type water turbine and influence of flow rate on the turbine's performance. *Renewable Energy, 155*, 1103–1117.

Obozov, A., Akparaliev, R., Mederov, T., Ashimbekova, B., Tolomushev, A., & Orazbaev, K. (2023). Research and development of a gravitational water vortex micro-HPP in the conditions of Kyrgyzstan. *Energy Reports, 10*, 544–557.

Rahman, M. M., Tan, J. H., Fadzlita, M. T., & Wan Khairul Muzammil, A. R. (2017). A Review on the Development of Gravitational Water Vortex Power Plant as Alternative Renewable Energy Resources. *IOP Conference Series: Materials Science and Engineering, 217*(1), 012007.

Rehman, W., Ijaz, M., & Munir, A. (2017). Designing of Micro Gravitational Vortex Turbine's Vortex Pool. *American Society of Mechanical Engineers, Power Division (Publication) POWER, 2*.

Sinaga, D. A., Arifin, Z., Prasetyo, S. D., Andriyanto, S., Septiyanto, M. D., & Hadi, S. (2025a). Experimental Study of the Blade Geometry Effect of Two-Stage Gravitational Water Vortex

Turbine. *Journal Europeen Des Systemes Automatises, 58*(1), 47–54.

Sinaga, D. A., Arifin, Z., Prasetyo, S. D., Andriyanto, S., Septiyanto, M. D., & Hadi, S. (2025b). Experimental Study of the Blade Geometry Effect of Two-Stage Gravitational Water Vortex Turbine. *Journal Europeen Des Systemes Automatises, 58*(1), 47–54.

Srihari, P. S. V. V., Narayana, P. S. V. V. S., Kumar, K. V. V. S. S., Raju, G. J., Naveen, K., & Anand, P. (2019a). Experimental study on vortex intensification of gravitational water vortex turbine with novel conical basin. *AIP Conference Proceedings, 2200*(1).

Srihari, P. S. V. V., Narayana, P. S. V. V. S., Kumar, K. V. V. S. S., Raju, G. J., Naveen, K., & Anand, P. (2019b). Experimental study on vortex intensification of gravitational water vortex turbine with novel conical basin. *AIP Conference Proceedings, 2200*(1).

Timilsina, A. B., Mulligan, S., & Bajracharya, T. R. (2018). Water vortex hydropower technology: a state-of-the-art review of developmental trends. *Clean Technologies and Environmental Policy, 20*(8), 1737–1760.

Vinayakumar, B., Antony, R., Binson, V. A., & Youhan, S. (2024). Experimental and numerical study on gravitational water vortex power plant for small water bodies. *E-Prime - Advances in Electrical Engineering, Electronics and Energy, 7*, 100460.

Vinayakumar, B., et al. "Gravitational water vortex: Finite element analysis based design and implementation." *Chemical and Process Engineering: New Frontiers 43.3 (2022): 357-368*.

Yaakob, O. B., Ahmed, Y. M., Elbatran, A. H., & Shabara, H. M. (2014). A review on micro hydro gravitational vortex power and turbine systems. *Jurnal Teknologi (Sciences and Engineering), 69*(7), 1–7.

Zamora-Juárez, M. A., Guerra-Cobián, V. H., Fonseca Ortiz, C. R., López-Rebollar, B. M., Ferriño Fierro, A. L., & Bruster Flores, J. L. (2022). Performance of modified gravitational water vortex turbine through CFD for hydro power generation on micro-scale. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 44*(11), 1–19.

Zainal, Hussein M., and Omer K. Ahmed. "Operational, design, and economic factors impacting gravitational water vortex hydropower systems." *Journal of Thermal Engineering 11.6 (2025).*