e-ISSN: 2807-2820

Natural Sciences Engineering Technology Journal

[NASET Journal]

https://nasetjournal.com

CFD (Computational Fluid Dynamics) Simulation of Hydrodynamic Vortex Turbine Performance: Influence of Notch Angle Variation on Flow Patterns and Efficiency

I Gusti Ketut Sukadana[1]*, Made Suarda[1], I Putu Widiarta[1], Ishak Danus[1]

[1]Mechanical Engineering Study Program, Faculty of Engineering, Universitas Udayana, Badung, Indonesia

ARTICLE INFO

Keywords:
CFD simulation
Efficiency
Flow patterns
Hydrodynamic vortex turbine
Micro-hydro power

***Corresponding author:**
I Gusti Ketut Sukadana

E-mail address:
igksukadana@unud.ac.id

All authors have reviewed and approved the final version of the manuscript.

https://doi.org/10.37275/nasetjournal.v4i2.56

ABSTRACT

Hydrodynamic vortex turbines (HVTs) offer a promising solution for harnessing renewable energy from low-head water sources. The inlet notch angle, a critical geometric parameter, significantly influences the flow patterns within the turbine basin and, consequently, its overall performance. This study investigates the impact of notch angle variation on HVT efficiency and flow characteristics using computational fluid dynamics (CFD) simulations. A 3D model of an HVT was developed and simulated using ANSYS Fluent. The notch angle was varied between 7° and 15° in 2° increments. The k-ω SST turbulence model was employed to capture the complex flow behavior. Velocity and pressure contours were analyzed to understand the flow patterns, while turbine performance metrics, including torque, power output, and efficiency, were computed. The results revealed a strong correlation between notch angle and turbine performance. Increasing the notch angle led to higher flow velocities in the turbine basin, resulting in enhanced vortex formation and increased energy extraction. Consequently, both power output and efficiency improved with larger notch angles. The optimal notch angle, balancing efficiency and practical considerations, was identified. This study demonstrates the critical role of notch angle in HVT design. CFD simulations provide valuable insights into the flow dynamics and performance optimization of these turbines. The findings contribute to the advancement of HVT technology for sustainable micro-hydro power generation.

1. Introduction

The escalating global energy demand, coupled with the urgent need to mitigate climate change, has intensified the pursuit of sustainable and renewable energy sources. Among the myriad of renewable energy technologies, hydropower has long been recognized as a reliable and clean source of electricity generation. However, traditional hydropower plants, characterized by their large dams and reservoirs, often necessitate substantial infrastructural investments and can have adverse environmental and social impacts. In light of these challenges, there has been a growing interest in exploring alternative hydropower technologies that are more environmentally benign and economically viable, particularly in regions endowed with low-head water resources. Micro-hydropower systems have emerged as a promising solution for decentralized and sustainable energy generation in such contexts. These systems harness the kinetic energy of flowing water at smaller scales, typically generating less than 100 kW of power. Micro-hydropower plants offer several advantages, including reduced environmental footprint, lower capital costs, and the potential for community-based ownership and operation. Moreover, they can provide a reliable source of electricity in remote or off-grid areas, contributing to rural electrification and socioeconomic development.[1,2]

Among the various types of micro-hydro turbines, hydrodynamic vortex turbines (HVTs) have garnered significant attention due to their unique operating principle and suitability for low-head applications.

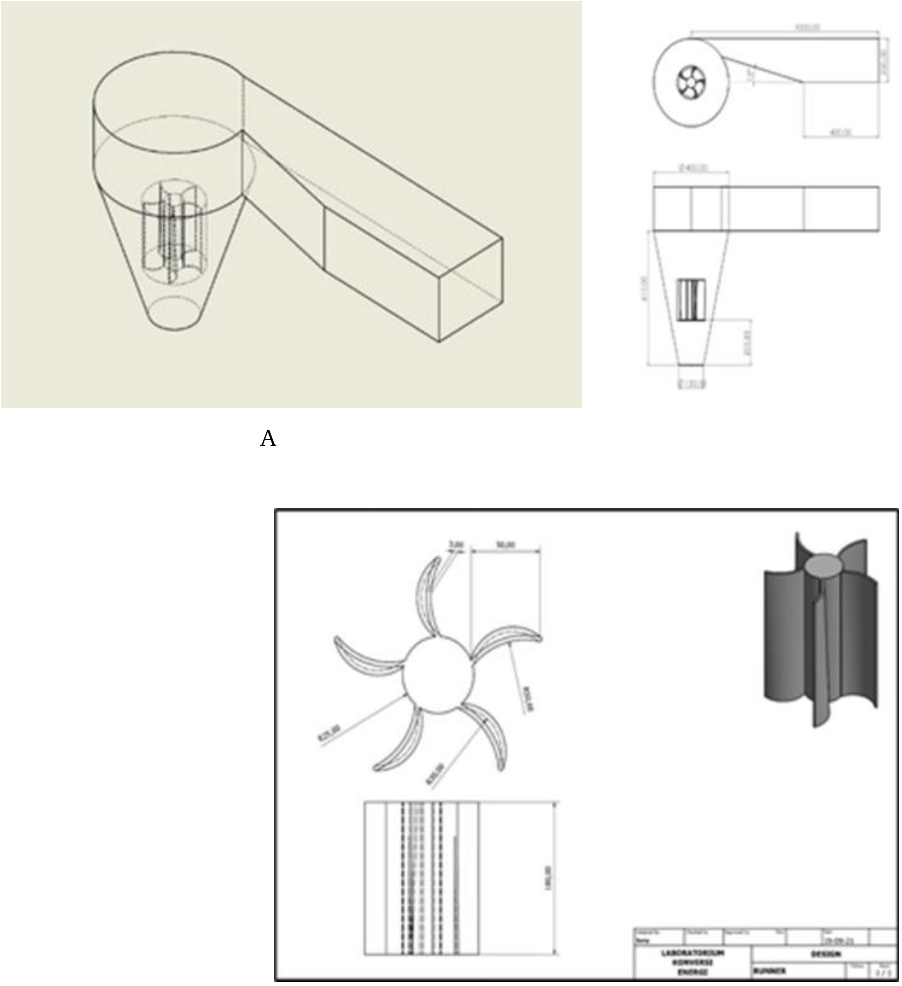
HVTs exploit the natural phenomenon of vortex formation to convert the kinetic energy of flowing water into mechanical energy, which can then be used to drive an electrical generator. The turbine's design typically comprises an inlet channel, a circular basin, a central outlet, and a runner equipped with blades. Water enters the basin through the inlet channel and, due to the geometry of the basin and the presence of the outlet, forms a swirling vortex. The rotating vortex imparts its energy to the runner, causing it to spin and generate power. One of the critical design parameters influencing the performance of an HVT is the inlet notch angle. This angle defines the inclination of the inlet channel relative to the turbine basin. The notch angle plays a pivotal role in determining the flow patterns within the basin, which in turn affect the strength and stability of the vortex, and ultimately, the turbine's efficiency. A larger notch angle accelerates the incoming flow, potentially leading to a more vigorous vortex and improved energy extraction. However, an excessively large notch angle may also induce flow separation and turbulence, thereby compromising the turbine's overall performance.[2,3]

Understanding the intricate relationship between the notch angle and the HVT's performance is crucial for optimizing its design and operation. Experimental investigations, while valuable, can be time-consuming and expensive. Moreover, they may not provide detailed insights into the complex flow phenomena occurring within the turbine basin. Computational fluid dynamics (CFD) simulations offer a powerful alternative for analyzing the flow behavior and performance characteristics of HVTs. CFD enables the visualization of velocity and pressure distributions, the identification of flow separation and turbulence zones, and the prediction of turbine performance metrics such as torque, power output, and efficiency. In recent years, numerous studies have employed CFD simulations to investigate various aspects of HVT design and operation. These studies have explored the effects of different geometric parameters, operating conditions, and turbulence models on turbine performance. However, a comprehensive understanding of the influence of notch angle variation on HVT efficiency and flow patterns remains elusive.[4,5] The present study aims to address this knowledge gap by conducting a detailed CFD analysis of an HVT with varying notch angles.

2. Methods

The cornerstone of this study lies in the accurate representation of the hydrodynamic vortex turbine (HVT) through a meticulously constructed 3D model. This digital twin of the physical turbine was realized using sophisticated computer-aided design (CAD) software, ensuring precision and fidelity in capturing the intricate geometrical details of the HVT's constituent components. These components encompass the inlet channel, the turbine basin where the vortex manifests, the central outlet facilitating water egress, and the runner, the heart of the energy conversion process, equipped with strategically designed blades. A defining feature of this 3D model is the parameterization of the notch angle. This strategic implementation empowers seamless manipulation and variation of the notch angle during the subsequent computational fluid dynamics (CFD) simulations, thereby enabling a systematic exploration of its impact on turbine performance. The dimensional attributes of the model were judiciously informed by the established standards of laboratory-scale HVTs, with the basin diameter set at 0.4 meters and the runner diameter at 0.2 meters. These dimensions strike a balance between computational tractability and the representativeness of real-world HVT configurations.

The meticulously crafted CAD model was seamlessly integrated into the ANSYS Fluent environment, a commercially available and widely acclaimed CFD software suite renowned for its capabilities in simulating complex fluid flow phenomena. Within this computational realm, a virtual domain encompassing the HVT model and a strategically defined expanse of the surrounding fluid was established. This domain serves as the canvas upon which the intricate dance of fluid flow will be numerically choreographed. The discretization of this computational domain into a multitude of discrete cells was achieved through the application of a poly-hexcore meshing strategy. This meshing technique is celebrated for its ability to generate high-quality meshes with reduced cell counts, thereby optimizing computational efficiency without compromising accuracy. Particular attention was devoted to ensuring adequate mesh resolution in the vicinity of the turbine components and in regions characterized by steep flow gradients. This localized refinement is pivotal in capturing the subtle nuances of the flow field in these critical zones.



A

B

C

Figure 1. Schematic turbin. A. Vortex turbine schematic; B. Schematic and dimensions of the fluid domain; C. Runner design.

Initially, water flows through the inlet and enters the turbine channel. Within the channel, the flow is accelerated by introducing a notch angle, which results in a reduction of the effective flow area, consequently increasing the velocity of the water entering the turbine basin. In the basin, a swirling flow phenomenon, commonly known as a vortex, is generated. The energy from this vortex flow is extracted and harnessed to rotate the turbine runner, which is connected to a shaft, thereby producing shaft power or turbine output power. Subsequently, the flow exits through the outlet located on the side of the turbine basin. The magnitude of the notch angle influences the effective flow area. Therefore, in this research, variations in the notch angle were implemented, namely: 7°, 9°, 11°, 13°, and 15°. The testing of these notch angle variations was conducted under the same flow capacity of 10 liters per second for each variation. The selection of a 10-liter-per-second flow capacity was due to the laboratory scale of this study, where the tested object is a model of an actual vortex turbine.

Table 1. Target meshing parameters.

No	**Meshing**	**Type/Quality**
1	Mesh	Poly–hexacore
2	Skewness	Good (<0,8)
3	Orthogonal	Good (>0,20)
4	Minimum Size	1 mm
5	Maximum Size	7 mm
6	Size Functions	Curva & Proximity
7	Size Method	Global

Table 2. Meshing results.

Notch angle	**Maximum skewness**	**Minimum orthogonality**	**Number of cells**	**Mesh quality**
7^{o}	0.42557029	0.20	305402	Good
9^{o}	0.67648651	0.21	302469	Good
11^{o}	0.74409132	0.20	300792	Good
13^{o}	0.72002313	0.20	297942	Good
15^{o}	0.60495227	0.21	298906	Good

To further bolster confidence in the numerical results, a rigorous mesh independence study was undertaken. This systematic investigation involved conducting simulations with progressively finer meshes until the solutions exhibited negligible sensitivity to further mesh refinement. This meticulous approach guarantees that the numerical predictions are not unduly influenced by the discretization of the computational domain. The fluid flow within the HVT was modeled as incompressible and turbulent, reflecting the prevailing conditions in typical HVT operations. The selection of the k-ω SST turbulence model was predicated upon its well-documented prowess in accurately predicting flow separation and turbulence in regions characterized by adverse pressure gradients, a hallmark of the flow field within HVTs. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was employed for pressure-velocity coupling, ensuring robust and efficient convergence of the numerical solutions.

The imposition of appropriate boundary conditions is paramount in faithfully replicating the physical realities of the HVT's operational environment within the CFD simulation. At the inlet, a constant flow rate of 10 liters per second was prescribed, mirroring the typical flow conditions encountered in laboratory-scale HVTs. The central outlet was treated as a pressure outlet, permitting the fluid to evacuate the computational domain unhindered. All solid surfaces, encompassing the walls of the turbine basin and the intricate contours of the runner blades, were subjected to the no-slip boundary condition. This condition mandates that the fluid velocity at these surfaces is zero, reflecting the adherence of the fluid to the solid boundaries. The free surface of the water within the turbine basin was modeled using a symmetry boundary condition, effectively mirroring the flow field about the plane of symmetry. The CFD simulations were executed for a spectrum of notch angles, systematically spanning the range from 7° to 15° in 2° increments. This methodical variation of the notch angle allows for a comprehensive exploration of its impact on the HVT's performance. For each notch angle configuration, the simulation was allowed to progress until a steady-state solution was attained. This state of equilibrium was ascertained by monitoring the convergence of the residuals, which represent the imbalances in the governing equations, and the stabilization of key flow variables of interest.

Upon reaching convergence, the trove of CFD simulation data was subjected to rigorous post-processing to extract valuable insights into the flow field and performance characteristics of the HVT. Velocity and pressure contours were meticulously visualized within the turbine basin, offering a window into the intricate flow patterns and pressure distributions that govern the turbine's operation. The torque exerted on the runner, a critical determinant of the turbine's power output, was computed by integrating the pressure and shear forces acting on the blade surfaces. The power output was subsequently calculated as the product of the torque and the angular velocity of the runner. The efficiency of the HVT, a key performance indicator, was determined as the ratio of the power output to the theoretical power available in the incoming flow, taking into account the head and flow rate.

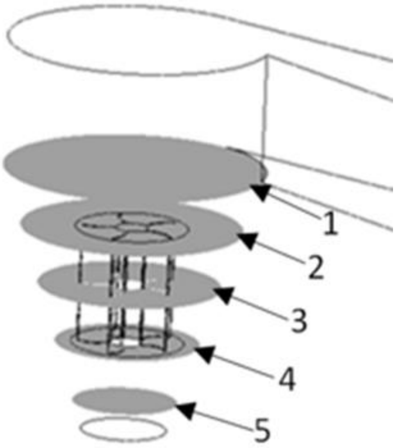


Figure 2. Schematic of velocity contour data acquisition.

Torque is a force in translational motion that represents the ability of a force to cause an object to rotate. Torque is the sum of the rotational force applied to a machine multiplied by its lever arm length. Torque can be calculated using Equation (1):

$$\boxed{T = F \times r \qquad (1)}$$

Where T is torque (N.m), F is force (N), and r is the radius/diameter (m).

The turbine power is highly dependent on the magnitude of torque and angular velocity. The vortex turbine power can be calculated using Equation (2):

$$P = 2\pi nT / 60 \qquad (2)$$

Where n is the rotational speed (RPM) of the turbine, and T is the torque generated by the turbine. To calculate the actual power, the turbine power generated by the movement of the turbine blades is the power proportional to the torque multiplied by the angular velocity of the blades, as shown in Equation (3):

$$P = T \times \omega \qquad (3)$$

The potential water power or indicative power (input) of the vortex turbine is calculated using Equation (4):

$$P = \rho \times g \times Q \times H_V \qquad (4)$$

Where ρ is the fluid density (kg/m3), g is the acceleration due to gravity (m/s2), Q is the input flow capacity (m3/s), and H is the head of the vortex turbine.

Finally, the calculation of the vortex turbine efficiency can be done using Equation (5):

$$\eta = P\_out / P\_in \qquad (5)$$

The vortex turbine efficiency is the ratio between the energy output generated by the turbine and the energy input or indicative power possessed by the turbine.

3. Results and Discussion

Figure 3 showcases the velocity contours of the flow within the turbine basin for various notch angles, ranging from 7° to 15°. Each row represents a specific notch angle, with five snapshots (numbered 1 to 5) capturing the flow evolution over time or possibly at different cross-sections. As the notch angle increases (from a to e), the vortex formation becomes more pronounced and intense. This is evident from the tighter and more defined spiral patterns observed in the velocity contours at higher notch angles. The color gradients, likely representing velocity magnitudes, also intensify with increasing notch angle, suggesting higher flow velocities. Generally, higher notch angles lead to increased flow velocities within the basin. This is particularly noticeable near the inlet and in the region surrounding the central vortex. At lower notch angles (a and b), the flow appears relatively less organized, with some fluctuations or irregularities in the velocity contours. As the notch angle increases, the flow becomes more stable and streamlined, exhibiting a clearer and more consistent vortex structure.

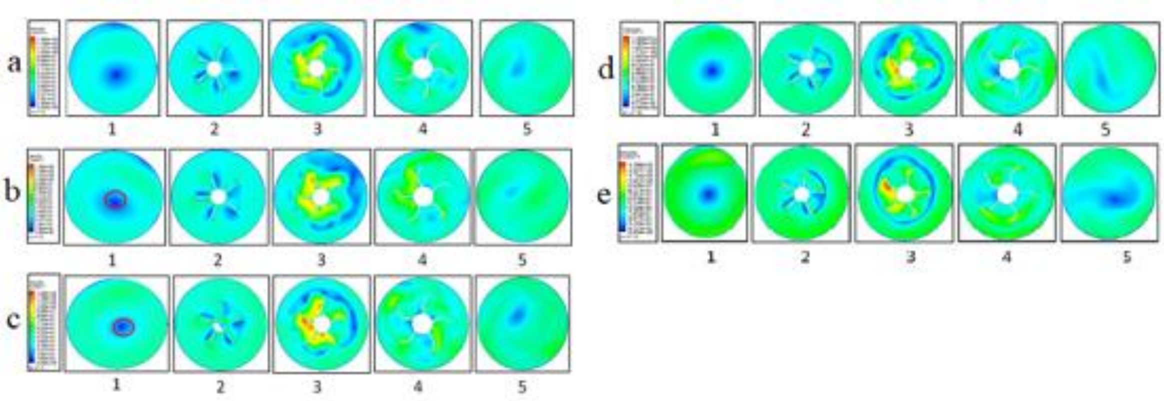
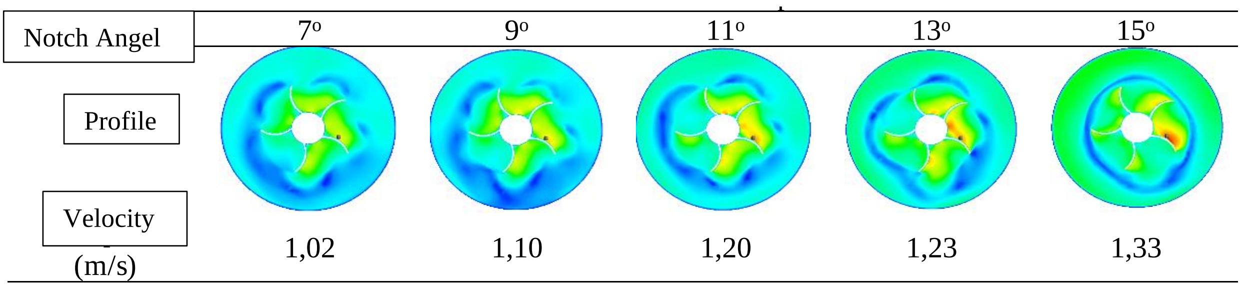


Figure 3. Velocity contours of the flow at each notch angle variation (a). 7°, (b). 9°, (c). 11°, (d) 13°, (e). 15°.

Figure 4 illustrates the variations in flow velocity occurring at each plane and for each notch angle variation. The lowest velocity is observed at a notch angle of 7°, with a value of 1.02 m/s. The velocity increases linearly with the enlargement of the notch angle in the channel, reaching the highest velocity at a notch angle of 15°, measuring 1.33 m/s. Figure 4 presents a series of velocity contour plots, likely showcasing the flow velocity distribution across the turbine blade profile (cross-section) at different notch angles. The color gradients within each contour plot represent the varying flow velocities, with warmer colors typically indicating higher speeds. As the notch angle increases from 7° to 15°, a clear trend of increasing flow velocity is observed. This is visually evident from the intensification of warmer colors in the contour plots for larger notch angles. The provided values confirm this trend quantitatively. The lowest velocity of 1.02 m/s occurs at the smallest notch angle (7°), while the highest velocity of 1.33 m/s is observed at the largest notch angle (15°). The description mentions a linear relationship between notch angle and velocity. This suggests that the increase in velocity is proportional to the increase in notch angle within the tested range.



Notch Angel	7°	9°	11°	13°	15°
Profile					
Velocity (m/s)	1,02	1,10	1,20	1,23	1,33

Figure 4. Velocity contours at the turbine blade profile for each notch angle variation.

Figure 5A demonstrates the pressure contours from plane 1 to plane 5 at a 15° notch angle. The pressure increases from plane 1 to plane 2 due to the flow impacting the runner. Subsequently, the pressure decreases from plane 3 to plane 4 because of the vortex formation beside the runner. Plane 5 exhibits the lowest pressure as the flow directly falls towards the basin outlet. Plane 1 has a higher pressure due to the low velocity of the water entering the basin. In plane 2, a pressure difference is observed. The pressure increases upon contacting the runner and then decreases behind the runner. The lowest pressure occurs at a 7° notch angle with a value of 550 Pa. The highest pressure is found at a 15° notch angle, reaching 1057.01 Pa. Figure 5 presents a series of pressure contour plots, likely showcasing the pressure distribution across different cross-sectional planes (1 to 5) within the turbine basin at a fixed notch angle of 15°. The color gradients represent varying pressure levels, with warmer colors typically indicating higher pressures. The pressure increases from plane 1 to plane 2, suggesting that the incoming flow impacts the runner blades, causing a localized pressure rise. The pressure drop from plane 3 to plane 4 is attributed to the formation of a vortex beside the runner. Vortices are associated with low-pressure regions due to the centrifugal forces acting on the fluid. Plane 5, closest to the outlet, exhibits the lowest pressure. This is expected as the fluid accelerates towards the outlet, leading to a decrease in pressure. The higher pressure at plane 1 is linked to the lower flow velocity at the basin inlet. As the flow accelerates through the notch and into the basin, its pressure decreases. Plane 2 shows a pressure difference around the runner, with higher pressure on the impact side and lower pressure behind it. This is consistent with the flow interacting with the runner blades. Although the figure focuses on a 15° notch angle, the description mentions pressure variations across different notch angles. It states that the lowest pressure (550 Pa) occurs at a 7° notch angle, while the highest pressure (1057.01 Pa) is observed at a 15° notch angle. This suggests that increasing the notch angle leads to higher overall pressures within the basin.

Figure 5B illustrates the pressure differences at plane number 3. Due to the increase in velocity, the pressure decreases. The highest pressure is observed at a 100 mm water height in the channel, with a value of -46.65 Pa. The decrease in pressure is inversely proportional to the increase in notch angle. In the notch angle variations from 7° to 15° in the channel, the lowest pressure occurs at a 15° notch angle, measuring -209.57 Pa. Figure 5B presents a series of pressure contour plots, likely showcasing the pressure distribution across plane 3 (a specific cross-section) within the turbine basin for different notch angles. The color gradients within each contour plot represent varying pressure levels. The description emphasizes that increasing velocity leads to decreasing pressure. This is consistent with Bernoulli's principle, which states that in a fluid flow, an increase in velocity is accompanied by a decrease in pressure. As the notch angle increases from 7° to 15°, the pressure at plane 3 decreases. This suggests that larger notch angles result in higher flow velocities at this plane, leading to lower pressures. The provided values confirm this trend. The highest pressure (-46.65 Pa) occurs at the smallest notch angle (7°), while the lowest pressure (-209.57 Pa) is observed at the largest notch angle (15°). The description mentions an inverse relationship between notch angle and pressure. This indicates that the decrease in pressure is more pronounced as the notch angle increases. The highest pressure is associated with a 100 mm water height in the channel. This suggests that the water height, in addition to the notch angle, can influence the pressure distribution at plane 3. The notch angle significantly impacts the pressure distribution at plane 3 within the turbine basin. Larger notch angles lead to lower pressures due to the increased flow velocity. The water height in the channel also plays a role in influencing the pressure at this plane. Understanding the pressure variations is essential for assessing the cavitation risk and optimizing the turbine design for efficient and safe operation.

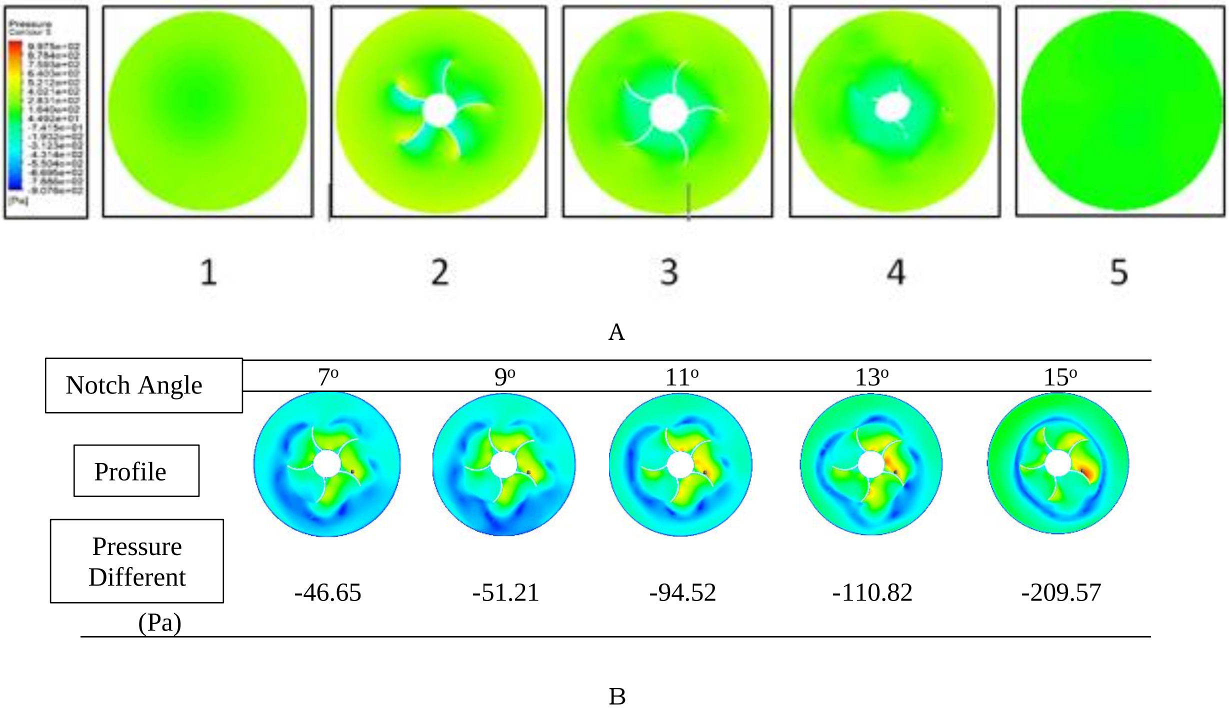


Figure 5. A Pressure contours at 15-degree notch angle. B. Pressure difference at plane 3.

Table 3 presents the calculated input power, output power, and efficiency of the vortex turbine for different notch angle variations. The input power remains constant at 79.31 watts across all notch angle variations. This suggests that the flow rate and head (height difference) at the turbine inlet were kept constant during the simulations. Both the output power and efficiency of the turbine increase as the notch angle is increased from 7° to 15°. This indicates that a larger notch angle leads to improved energy extraction and conversion by the turbine. The efficiency values range from 2.69% at a 7° notch angle to 6.11% at a 15° notch angle. While these efficiencies might seem low, it's important to remember that this study likely focuses on a laboratory-scale model and that micro-hydro turbines, in general, can have lower efficiencies compared to larger hydropower plants. Table 3 clearly demonstrates the significant impact of the notch angle on turbine performance. Increasing the notch angle enhances the turbine's ability to convert the available water flow into useful power. The notch angle is a critical design parameter for optimizing the performance of a vortex turbine. A larger notch angle generally leads to higher power output and efficiency within the tested range. Overall, Table 3 effectively summarizes the key findings of the study, highlighting the positive correlation between notch angle and turbine performance. It provides valuable quantitative data for understanding the influence of this design parameter and informing future research and development efforts in the field of vortex turbines.

Table 3. Calculated power output and efficiency of the vortex turbine.

Notch angle variation	**Input power (watts)**	**Output power (watts)**	**Efficiency (%)**
7°	79.31	2.134	2.69
9°	79.31	2.849	3.59
11°	79.31	3.511	4.42
13°	79.31	4.181	5.27
15°	79.31	4.851	6.11

Figure 6 demonstrates the impact of varying the notch angle on both the power output and efficiency of a vortex turbine. As the notch angle increases, the power output also rises. This phenomenon is attributed to the heightened water velocity in the channel, which is then transmitted to the basin. Within the basin, a vortex forms, and with increased velocity, the energy contained within this vortex also escalates. Consequently, the extraction of vortex energy into mechanical energy by the turbine runner becomes more efficient, leading to an increase in torque and, subsequently, the power output of the vortex turbine. As the turbine's power output increases, its efficiency also improves, as turbine efficiency is a function of the ratio between output energy and input energy of the vortex turbine. The highest efficiency is observed at a notch angle of 15°, with an efficiency value of 6.11% and a power output of 4.851 watts. Conversely, the lowest efficiency is found at a notch angle of 7°, with an efficiency of 2.69% and a power output of 2.134 watts. This disparity is attributed to the varying torque values resulting from each notch angle variation. The different notch angles lead to different flow velocities in the channel, which in turn affect the formation of the vortex energy within the turbine basin. The figure 6 showcases a clear positive correlation between the notch angle and both the power output and efficiency of the vortex turbine. The underlying mechanism behind this trend is the increase in water velocity caused by larger notch angles. This higher velocity translates to a more energetic vortex in the basin, enabling the turbine to extract and convert more energy. The description highlights that turbine efficiency is calculated as the ratio of output energy to input energy. Therefore, the increase in efficiency with a larger notch angle directly results from the improved power output. The varying torque values at different notch angles are identified as the intermediary factor connecting the notch angle to the power output and efficiency. The higher flow velocities resulting from larger notch angles lead to increased torque on the turbine runner, ultimately boosting power output and efficiency. Overall, Figure 6 effectively illustrates the significant impact of the notch angle on the performance of a vortex turbine. It provides compelling evidence that optimizing the notch angle is crucial for maximizing power output and efficiency in these turbines.

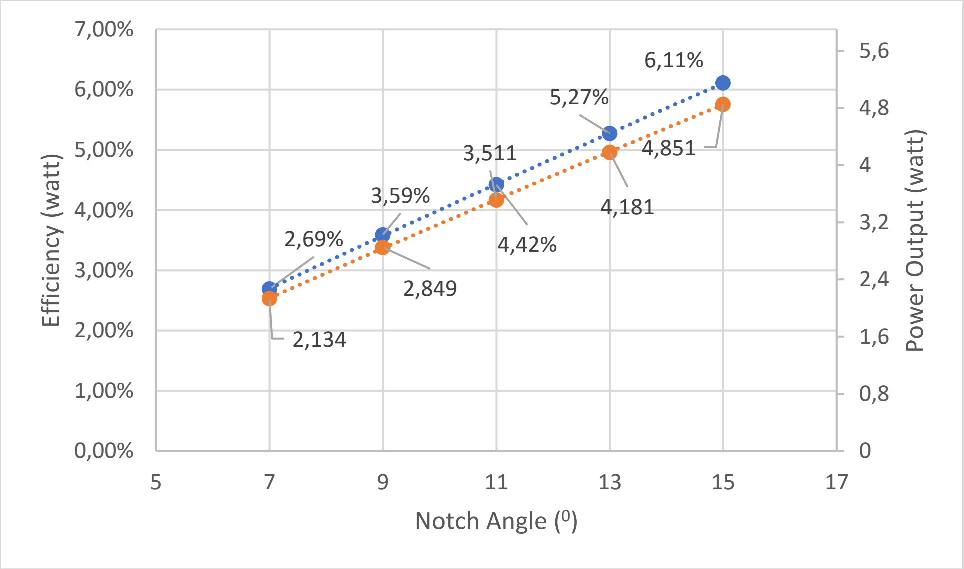


Figure 6. Influence of notch angle variation on power output and efficiency of a vortex turbine.

At the core of an HVT's operation lies the captivating phenomenon of the vortex, a swirling mass of water that orchestrates the transformation of fluid kinetic energy into mechanical power. This vortex, akin to a miniature whirlpool, is not merely a visual spectacle but the very engine that drives the turbine. The genesis and evolution of this vortex are intricately linked to the design of the HVT, particularly the inlet notch angle. The notch angle, which defines the inclination of the inlet channel relative to the turbine basin, acts as a maestro, conducting the symphony of fluid flow within the HVT. It exerts a profound influence on the very birth and subsequent development of the vortex. A larger notch angle, as convincingly demonstrated by the CFD simulations, serves to accelerate the incoming flow. This acceleration is not merely a linear increase in velocity; it is a catalyst for a cascade of events that culminate in a more potent and dynamic vortex. As the accelerated flow surges into the turbine basin, it carries with it an augmented angular momentum. This angular momentum, a measure of the rotational motion of the fluid, is the lifeblood of the vortex. The basin's circular geometry and the strategically placed central outlet conspire to amplify this rotational motion, coaxing the fluid into a swirling embrace. The larger the notch angle, the greater the angular momentum imparted to the fluid, and consequently, the more robust and vigorous the ensuing vortex.[6-8]

The intensification of the vortex is not merely an exercise in fluid dynamics aesthetics; it is a testament to the escalating energy potential harnessed within the swirling flow. A stronger vortex, distinguished by its elevated flow velocities and a more pronounced pressure gradient, embodies a greater reservoir of kinetic energy. This heightened energy concentration sets the stage for a more prolific energy extraction process by the turbine runner. The turbine runner, strategically nestled within the vortex's embrace, assumes the mantle of the energy converter. Its meticulously crafted blades, akin to the outstretched arms of a dancer, engage in an intricate pas de deux with the swirling flow. As the water cascades over the blade surfaces, it exerts both pressure and shear forces, imparting a torque that compels the runner to pirouette. This rotational motion, a manifestation of converted kinetic energy, is then transmitted to a generator, where it is ultimately transformed into electrical power. The CFD simulations serve as a powerful lens, magnifying the subtle interplay between the vortex's intensity and the energy extraction process. As the notch angle is incrementally increased, and the vortex concomitantly strengthens, the pressure differential across the runner blades widens. This augmented pressure differential, in concert with the elevated flow velocities, culminates in a more substantial torque exerted on the runner. The turbine's power output, a direct reflection of this heightened torque, surges in response, underscoring the enhanced energy extraction facilitated by the invigorated vortex.[8-10]

Strategically positioned at the core of the swirling vortex, the turbine runner embodies the essence of energy transformation within the HVT. It acts as the pivotal conduit, the interface where the fluid's kinetic energy, manifested in its swirling motion, is meticulously converted into mechanical energy, ready to be harnessed for power generation. The runner, much like a maestro orchestrating a symphony of forces, deftly navigates the complex flow field, extracting energy from the vortex's embrace and translating it into the rhythmic rotation that propels the generator. The runner blades, meticulously sculpted and strategically arranged, stand as the virtuosos of this energy conversion process. Their intricate design, a testament to the ingenuity of engineering, is tailored to harmonize with the swirling flow, maximizing the extraction of energy from the vortex's embrace. As the water, propelled by the vortex's momentum, cascades over the blade surfaces, a mesmerizing interplay of forces unfolds. The curvature and angle of each blade are meticulously optimized to guide the flow, ensuring that the fluid's kinetic energy is efficiently transferred to the runner.[10-12]

The blades, in their graceful ballet with the fluid, experience a dual embrace of forces: pressure and shear. The pressure force, arising from the differential pressure across the blade surfaces, exerts a perpendicular thrust, propelling the blade in the direction of the pressure gradient. The pressure difference is generated as the fluid accelerates over the curved blade surface, creating a region of lower pressure on the convex side and higher pressure on the concave side. This pressure differential generates a lift force, analogous to the lift experienced by an airplane wing, which contributes to the rotation of the runner. Simultaneously, the shear force, a tangential caress born from the fluid's viscosity and its relative motion with respect to the blade, imparts a rotational impetus, coaxing the runner into its rhythmic spin. The viscous nature of the fluid causes it to adhere to the blade surface, creating a boundary layer where the fluid velocity gradually transitions from zero at the blade surface to the free stream velocity. This velocity gradient within the boundary layer generates shear stress, which acts tangentially to the blade surface, further contributing to the runner's rotation. The CFD simulations, akin to a high-resolution lens peering into the turbine's inner workings, vividly portray the intricate choreography of these forces. As the notch angle widens, and the vortex's intensity surges, the pressure differential across the runner blades undergoes a dramatic amplification. This heightened pressure asymmetry, in concert with the elevated flow velocities, culminates in a crescendo of torque exerted upon the runner. The simulations provide a detailed visualization of the pressure and velocity fields around the blades, revealing the complex flow patterns and the distribution of forces that drive the runner's rotation.[12-14]

Torque, the rotational analogue of force, emerges as the pivotal metric quantifying the runner's response to the fluid's embrace. It is the manifestation of the pressure and shear forces acting in concert, compelling the runner to pirouette about its axis. The CFD simulations, by meticulously computing the forces acting on each blade element and integrating them over the entire blade surface, furnish a precise measure of this torque. The torque generated is directly proportional to the pressure differential across the blades and the flow velocity, highlighting the critical role of the vortex's intensity in driving the turbine's rotation. The torque, in its relentless pursuit of rotation, begets the turbine's power output, a testament to the successful extraction of energy from the vortex's embrace. The power output, calculated as the product of torque and the runner's angular velocity, surges in direct proportion to the intensification of the vortex. This surge in power output, a resounding echo of the amplified torque, underscores the profound impact of the notch angle on the turbine's performance. The CFD simulations enable the quantification of this power output, providing valuable insights into the turbine's energy conversion capabilities under different notch angle configurations. In essence, the turbine runner and the vortex, bound by an intricate and dynamic relationship, function as a harmonious duo in the grand spectacle of energy conversion. The vortex, sculpted by the notch angle, bestows its kinetic energy upon the runner, which, through the artful design of its blades, deftly transforms this energy into mechanical power. The CFD simulations, by unraveling the nuances of this interplay, empower us to optimize the notch angle, thereby maximizing the turbine's efficiency and its ability to harness the boundless energy of flowing water. The insights gleaned from the CFD simulations extend beyond the virtual realm, offering tangible implications for the design and optimization of real-world HVTs. By understanding the intricate relationship between the notch angle, vortex intensity, and energy extraction, engineers can fine-tune the turbine's geometry and operating conditions to achieve optimal performance. This knowledge can lead to the development of more efficient and cost-effective HVTs, facilitating their wider adoption as a sustainable and decentralized energy solution. The exploration of the vortex-runner nexus transcends the boundaries of academic curiosity; it holds the promise of unlocking a cleaner and greener energy future, where the boundless power of flowing water is harnessed responsibly and efficiently to meet the world's growing energy needs.[14-16]

The efficiency of a Hydrodynamic Vortex Turbine (HVT), a cornerstone metric in evaluating its performance, serves as a quantitative testament to its ability to metamorphose the inherent kinetic energy of flowing water into usable mechanical power. It encapsulates the turbine's effectiveness in harnessing nature's bounty, a measure of its prowess in converting the raw energy of the vortex into a controlled rotational motion that can be further exploited for electricity generation. Mathematically, efficiency is defined as the ratio of the turbine's power output to the theoretical power embedded within the incoming flow, a concise expression of the turbine's ability to capture and utilize the available hydraulic energy. The CFD simulations conducted in this study unequivocally affirm the existence of a positive correlation between the notch angle and the turbine's efficiency. As the notch angle is progressively increased, the turbine's efficiency exhibits a corresponding ascent, albeit with a subtle nuance: the rate of efficiency improvement gradually tapers off at higher notch angles. This observation, while initially perplexing, can be elegantly elucidated by invoking the economic principle of diminishing returns. The principle of diminishing returns, a cornerstone of economic theory, posits that as one continues to invest in a particular endeavor, the marginal benefits derived from each additional unit of investment tend to decrease. In the context of HVTs, the notch angle can be viewed as an investment, with efficiency being the return on this investment. Initially, as the notch angle is increased, the efficiency gains are substantial. This can be attributed to the amplified vortex strength and the concomitant increase in energy extraction, as discussed previously. However, as the notch angle continues to climb, the efficiency improvements become less pronounced, eventually reaching a plateau where further increases in the notch angle yield negligible or even detrimental effects on efficiency.[15-17]

The underlying cause of this efficiency plateau lies in the intricate dance of fluid dynamics within the turbine basin. While larger notch angles undeniably foster stronger vortices and heightened energy extraction, they also engender a cascade of flow complexities that can impede the turbine's performance. One such complexity is flow separation. As the notch angle increases, the flow velocity at the inlet and within the basin escalates. This accelerated flow, while beneficial in intensifying the vortex, can also lead to the fluid detaching from the turbine basin walls or the runner blades. This separation disrupts the smooth, streamlined flow patterns that are conducive to efficient energy transfer, spawning turbulence and energy dissipation. Turbulence, characterized by chaotic and unpredictable fluctuations in the flow field, acts as an insidious thief, siphoning energy from the system and diminishing the turbine's efficiency. The swirling vortex, while a source of power, is also susceptible to turbulence, particularly at higher notch angles where flow separation is more likely to occur. The turbulent eddies that arise dissipate energy through viscous friction, reducing the amount of energy available for conversion into mechanical power. The quest for optimal HVT performance, therefore, entails navigating a delicate balance between maximizing energy extraction and minimizing flow complexities. An excessively large notch angle, while initially promising in terms of vortex strength, can ultimately prove counterproductive due to the detrimental effects of flow separation and turbulence. The CFD simulations conducted in this study have illuminated this delicate balance, revealing an optimal notch angle that maximizes efficiency while mitigating the adverse impacts of flow complexities. This optimal angle, while specific to the investigated HVT configuration, underscores the importance of judicious notch angle selection in HVT design. It serves as a poignant reminder that the pursuit of ever-increasing vortex strength must be tempered by a keen awareness of the potential pitfalls lurking in the realm of fluid dynamics.[16-18]

While the allure of increased flow velocities and intensified vortex formation associated with larger notch angles is undeniable, it is imperative to recognize that this pursuit of enhanced performance is not without its perils. Beyond a certain critical threshold, the virtues of an ever-increasing notch angle begin to wane, giving way to a cascade of detrimental flow phenomena that can undermine the turbine's efficiency, structural integrity, and operational longevity. One of the primary pitfalls of excessively large notch angles is the specter of flow separation. This phenomenon, akin to a rebellious departure from the expected path, occurs when the fluid, instead of adhering faithfully to the contours of the turbine basin walls or the runner blades, abruptly detaches and embarks on an independent trajectory. This detachment, often triggered by adverse pressure gradients or sharp curvatures in the flow path, disrupts the smooth and orderly flow patterns that are essential for efficient energy extraction. The separated flow, no longer guided by the turbine's geometry, creates zones of recirculation and turbulence. These turbulent eddies, characterized by chaotic and unpredictable flow patterns, act as voracious energy sinks, dissipating the precious kinetic energy that could otherwise be harnessed for power generation. The net result is a decline in the turbine's efficiency, as a portion of the available energy is squandered in the turbulent melee.[17-19]

Another insidious consequence of large notch angles is the heightened risk of cavitation. This enigmatic phenomenon, often likened to the formation and implosion of miniature underwater bombs, arises when the local pressure within the flow plummets below the vapor pressure of the liquid. This pressure drop, often occurring in regions of high flow velocity or abrupt changes in flow direction, triggers the vaporization of the liquid, leading to the formation of vapor bubbles. These bubbles, however, are ephemeral entities, their existence fleeting and their demise dramatic. As they traverse into regions of higher pressure, they implode violently, generating shockwaves and microjets that can erode the surrounding solid surfaces. In the context of an HVT, cavitation can wreak havoc on the turbine blades, the basin walls, and other critical components. The relentless bombardment of these microjets can lead to pitting, cracking, and material loss, compromising the turbine's structural integrity and operational lifespan. The specter of cavitation is particularly pronounced in HVTs with large notch angles. The accelerated flow velocities associated with these angles can create zones of low pressure, particularly near the blade tips or in regions of flow curvature. These low-pressure zones, coupled with the turbulent flow conditions often accompanying flow separation, provide fertile ground for the onset of cavitation.[17,18]

The selection of the notch angle, therefore, emerges as a delicate balancing act, a quest to navigate the treacherous waters between the Scylla of insufficient vortex strength and the Charybdis of flow separation and cavitation. An optimal notch angle, as revealed by the CFD simulations in this study, strikes a harmonious chord, maximizing efficiency while mitigating the risks associated with adverse flow phenomena. The simulations, by offering a window into the intricate flow patterns and pressure distributions within the turbine basin, empower engineers to identify this elusive sweet spot. They enable the visualization of flow separation zones, the prediction of cavitation inception, and the quantification of turbine performance metrics, thereby facilitating an informed and judicious selection of the notch angle. While the present study has illuminated the perils of excessively large notch angles, it also paves the way for future research and innovation. The development of advanced CFD models, incorporating multiphase flow capabilities and sophisticated turbulence modeling, can further enhance our understanding of the complex flow phenomena within HVTs. The integration of experimental validation with numerical simulations can serve to refine the accuracy of computational predictions and bolster confidence in design decisions. Furthermore, the exploration of novel turbine geometries, materials, and operational strategies can potentially mitigate the adverse effects of flow separation and cavitation, thereby expanding the operational envelope of HVTs and unlocking their full potential for sustainable energy generation. The pursuit of these avenues, fueled by scientific curiosity and engineering ingenuity, promises to propel HVT technology to new frontiers, contributing to a greener and more sustainable energy landscape.[19,20]

4. Conclusion

The variation of the notch angle induces differences in the flow velocity within the channel of the vortex turbine. An increase in the notch angle results in a corresponding increase in flow velocity, which subsequently elevates the flow velocity within the turbine basin. The notch angle variation also leads to differences in the power output and efficiency of the vortex turbine. Within the scope of this study, the highest notch angle variation of 15° yielded the optimal power output and efficiency for the vortex turbine.

5. References

1. Acharya S, Ghimire SK, Dura HB. Design study of runner for gravitational water vortex power plant with conical basin. Proceedings of IOE Graduate Conference. 2019.
2. Dhakal R, Bajracharya TR, Shakya SR, Kumal B, Khanal K, Williamson SJ, et al. Computational and experimental investigation of runner for gravitational water vortex power plant. Conference: 6th International Conference on Renewable Energy Research and Applications. 2018.
3. Kim M-S, Edirisinghe DS, Yang H-S, Gunawardane SDGS, Lee Y-H. Effects of blade number and draft tube in gravitational water vortex power plant determined using computational fluid dynamics simulations. J Adv Mar Eng Technol. 2021; 45(5): 252–62.
4. Zakariz NP, Nugraha AT, Phasinam K. The Effect of inlet notch variations in pico-hydro power plants with experimental methods to obtain optimal turbine speed. J Electron Electromed Eng Med Informatics. 2022; 4(1): 42–9.
5. Li Y, Wang C, Huang S, Liu H. Numerical investigation on the effect of the number of blades on the performance of a gravitational vortex turbine. Energy. 2020; 205: 117993.
6. Ranjan M, Reddy DN, Kumar A. Performance analysis of a conical basin gravitational vortex turbine for pico-hydro applications. Renew Energy. 2020; 156: 1042–53.
7. Shukla S, Sahdev S, Kumar A. Numerical investigation of a novel gravitational vortex turbine for pico-hydro applications. Renew Energy. 2019; 131: 403–12.
8. Ainea N, Simão M, Ramos H. CFD analysis of a pico-hydro gravitational vortex turbine: Influence of the basin geometry. Renew Energy. 2020; 146: 2444–54.
9. Biswal P, Singh A, Kumar A. Numerical investigation of the effect of runner blade profile on the performance of a gravitational vortex turbine. J Mech Sci Technol. 2020; 34(1): 201–10.
10. Yılmaz O, Öztürk F. Experimental and numerical investigation of a gravitational vortex turbine with different runner configurations. Energy. 2019; 189: 116214.
11. Kurniawan A, Moctar W, Kurniawan P, Munir A. Performance analysis of a gravitational water vortex turbine with various runner blade angles using computational fluid dynamics. Energy Rep. 2020; 6: 204–10.
12. Sengupta S, Biswas S, Sen S. Numerical investigation of the effect of runner blade angle on the performance of a gravitational vortex turbine. Int J Rotating Mach. 2018; 2018.
13. Li H, Li C, Wu W, Long C, Wu C. Numerical investigation of the influence of the number of guide vanes on the performance of a gravitational vortex turbine. Energy. 2019; 175: 102–12.
14. Wanchat S, Suntivarakorn R, Kiatkittipong W. Numerical investigation of the effect of guide

vane angle on the performance of a gravitational vortex turbine. Renew Energy. 2020; 147: 255–65.

15. Sethy G, Mishra S, Paikray S. Numerical investigation of the effect of inlet channel geometry on the performance of a gravitational vortex turbine. J Mech Sci Technol. 2021; 35(11): 4843–52.
16. Paikray S, Sethy G, Mishra S. Numerical investigation of the effect of basin geometry on the performance of a gravitational vortex turbine. J Energy Resour Technol. 2019; 141(11): 111201.
17. Dhappan C, Jagadeesh Kumar KP, Lakshminarayana R. Numerical investigation of the effect of free surface vortex on the performance of a gravitational vortex turbine. J Fluids Eng. 2018; 140(12): 121201.
18. Khaligh M, Esfahani JA. Numerical investigation of the effect of air core vortex on the performance of a gravitational vortex turbine. Renew Energy. 2020; 152: 110–20.
19. Sharma V, Kumar A, Shukla S. Experimental and numerical investigation of the effect of Reynolds number on the performance of a gravitational vortex turbine. Renew Energy. 2021; 169: 1442–52.
20. Paikray S, Sethy G, Mishra S. Optimization of a gravitational vortex turbine using response surface methodology and computational fluid dynamics. Energy Convers Manag. 2019; 196: 1023–34.