Original Research Article

Assessing the Feasibility of Gravitational Vortex Turbines for Sustainable Energy Production in Remote Hilly Areas of Bangladesh

ABSTRACT

This research paper presents a comprehensive study of the design, optimization, and performance analysis of a gravitational vortex water turbine for small-scale hydropower applications in the Chittagong Hill Tracts of Bangladesh. The urgent need for cleaner and more efficient energy sources to address global energy challenges drives the development of innovative renewable energy solutions. The proposed turbine harnesses the power of gravity-induced water flow to efficiently convert rotational energy from a water vortex into electrical energy. The research employs advanced computational fluid dynamics (CFD) analysis using ANSYS Fluent to investigate the intricate flow behavior and velocity distribution within the turbine. Through detailed CFD calculations, the study provides valuable insights into the turbine's performance, allowing for optimization of its design parameters. The influence of blade numbers on turbine efficiency is explored, contributing to a better understanding of the turbine's operational characteristics. The paper discusses the advantages of decentralized energy systems and emphasizes the potential of gravitational vortex turbines for small-scale hydropower projects. It highlights the importance of mathematical analysis and performance results, which are further supported by the CFD analysis, demonstrating the turbine's capabilities. The power outputs achieved by the turbine align with or surpass the potential power capacities of identified small hydro sites, reinforcing its viability as a clean and reliable energy solution. While the research findings showcase the turbine's potential, it emphasizes the need for further feasibility studies and site-specific assessments to ensure successful real-life implementation. The study underscores the significance of utilizing advanced computational techniques in the development of efficient and environmentally friendly hydropower solutions. The findings offer valuable insights for researchers, engineers, and policymakers in their pursuit of cleaner and more sustainable energy sources.

Keywords: Vortex turbine; CFD; Chittagong Hill Tracks; Decentralized System; Environment Friendly; Reliable Source of Energy.

1. INTRODUCTION

The modern world faces an urgent need for cleaner, more efficient energy sources to mitigate the declining days of fossil-fuel-based electricity and address environmental concerns. As global energy demands are projected to rise by 30% by 2040, coupled with a growing population, the transition towards sustainable and renewable energy solutions becomes imperative [1]. Hydropower, harnessing the power of water, emerges as a promising alternative due to its clean, abundant, and cost-effective nature. While large-scale hydropower projects have limitations, small hydropower offers significant potential, particularly in hilly regions and areas near rivers and lakes worldwide [2]. This research paper focuses on the design and optimization of a gravitational vortex water turbine, specifically tailored for the Chittagong Hill Tracts of Bangladesh, which possess substantial hydro-potential. A gravitational vortex water turbine is an impulse turbine that uses gravity to create a water vortex. The turbine collects the rotational energy from the vortex and converts it into electrical energy [3]. By utilizing gravity-induced water flow downstream, the turbine efficiently converts rotational energy from a water vortex into electrical energy. The implementation of a smart vortex turbine aligns with the goal of generating clean, cost-effective, and renewable electricity, particularly in remote areas. This technology not only reduces the environmental impact but also enhances the sustainability and health of rivers and water bodies. Innovative features, such as a sealed generator assembly integrated within the water flow, minimize energy losses and optimize overall efficiency. The research paper aims to contribute to the field of sustainable energy by presenting the design and optimization of a gravitational vortex water turbine [4]. By harnessing the hydro-potential of the Chittagong Hill Tracts in Bangladesh, this innovative small hydropower solution addresses the increasing demand for clean and reliable electricity. Through the integration of advanced manufacturing techniques, such as 3D printing environmentally friendly systems can pave the way for a more sustainable future.

2. LITERATURE REVIEW

2.1 Decentralized Energy Systems

Decentralized systems, characterized by localized energy production and distribution on a smaller scale, offer a multitude of benefits. These systems enhance energy resilience by reducing reliance on centralized grids, ensuring an uninterrupted energy supply, particularly in remote areas. By diversifying energy sources and reducing dependence on a single infrastructure, decentralized systems enhance energy security and stability [5]. They localize energy production, minimizing transmission and distribution losses and increasing overall system efficiency. Decentralized systems are well-suited for integrating renewable energy sources, contributing to a cleaner energy mix.

2.2 Exploration of Gravitational Vortex Turbines

A promising renewable energy technology, that harnesses the power of falling or flowing water to efficiently generate electricity. These turbines take advantage of the natural force of gravity to create swirling vortexes, converting the kinetic energy of the water into mechanical and electrical energy. With their scalability, gravitational vortex turbines can be implemented in various water sources, making them suitable for both small-scale and large-scale applications. This system focuses on the following advantages:

- Access clean energy from untapped river or canal sources
- Provide electricity for communities and villages with 50 to 500 households

- Generate annual energy output ranging from 120,000 to 560,000 kWh per turbine
- Simple civil works required for installation
- Reliable and consistent energy source, unlike intermittent renewables such as wind or solar power
- Continuous energy supply 24 hours a day and 365 days a year
- Focus on developing a comprehensive ecosystem that prioritizes biodiversity preservation and maximizes positive impacts on the surrounding area.
- Incorporate fish-friendly design features, such as a slow RPM impeller with low shear stress, ensuring the safe passage of fish and aquatic life.
- Foster local development by empowering and transferring sustainable energy to the local communities [6].

3. METHODOLOGY

3.1 Design Parameters and Operating Conditions

The HFLH (High Flow Low Head) vortex turbine blades are precision-optimized for peak performance within specific flow and head ranges. The open flow design requires careful selection of the head-flow combination to ensure optimal performance at each site. Standard turbine impeller dimensions range from 1.3 to 1.9 meters, enabling efficient energy extraction. The standard electrical power outputs range from 15 to 70 kW. To address higher power demands, multiple standard turbine models can be combined and installed in clusters

Table 1. Performance parameters of HFLH turbine system [7]

Parameters	Minimum	Maximum	Units
Flow	1.5	4.7	m^3/s
Head (Inflow channel to tailwater level)	1.4	2.7	m
Hydraulic efficiency at BEP	0.65	0.75	-
Inflow channel water depth	1.3	2.3	m
Impeller diameter	1.3	1.9	m
Impeller rotational speed	40	100	rpm

Table 2.Turbine specifications and performance for standard power output range [7]

Impeller Diameter	1.3 m	1.5 m	1.7 m	1.9 m
Hydraulic output (kW)	17	34	56	78
Electrical output (kW)	15	30	50	70
Maximal energy generation (per year) (kWh)	130k	260k	440k	610k
Design flow (m^3/s)	1.6	2.5	3.4	4.3
Design head (m)	1.7	2.2	2.4	2.6
Rotational speed (rpm)	75	95	75	75
Dimensions core unit (L×W×H) (m^3)	1.8	3.5	5.4	7.9
Impeller and Support weight	240	380	590	870
(kg)	310	470	700	1070
Generator and gearbox weight (kg)	550	850	1290	1940
Core unit total weight (kg)				

3.2 Measurement Process

The initial step in assessing the hydropower potential of a site involves measuring or estimating the head and flow parameters.

Flow: This refers to the minimum volume of water that remains consistently available for at least nine months of the year. It pertains to the amount of water that descends the stream.

Head: It represents the vertical distance or variation in height between the upper and lower levels of water and refers to the vertical separation between the intake and the outflow of the turbine.
Both head and flow are frequently exaggerated, and the flow rate can vary throughout the year. It is common to encounter incorrect data, making it highly recommended to verify the existing information.

Estimation of height: The method involves using a spirit level and a plank or string. This process entails measuring the height difference between the outflow water level and the upper water level (at the waterfall or inlet) in multiple sections. The measurements are taken over a distance, with each section separated by the length of the plank or string. By adding up all the height differences using a specific formula, the total head (Hg) can be determined.

$$H_g = h_1 + h_2 + h_3 + \ldots\ldots + h_n$$

Estimation of flow:

- Locating an area with consistent water flow, extending for a specified length, denoted as L in meters.
- Determining the cross-sectional area of the identified region by measuring the width, represented by B in meters, and the height, denoted as H in meters. Area (A) can be calculated as the product of B and H: A = B x H.
- Measuring the time, denoted as T in seconds, it takes for a float to traverse the determined length L. Ensure that the float has sufficient time to accelerate before the measurement starts.
- Calculating the velocity (V) by dividing the length L by the time T: V = L / T, expressed in meters per second.
- Computing the flow rate (Q) by multiplying the velocity V by the cross-sectional area A: Q = V x A. The flow rate is measured in cubic meters per second.

Fish survival: The turbine’s design differs from conventional turbines, lacking inlet guide vanes and leading to a swirling flow pattern. Computational fluid dynamics (CFD) calculations provide insights into the velocity distribution within the turbine, and the average Euler head is determined. The research follows the NEN 8775 standard, which outlines fish safety guidelines, and employs a blade strike model to estimate the likelihood of collisions between the runner blades and fish [8].

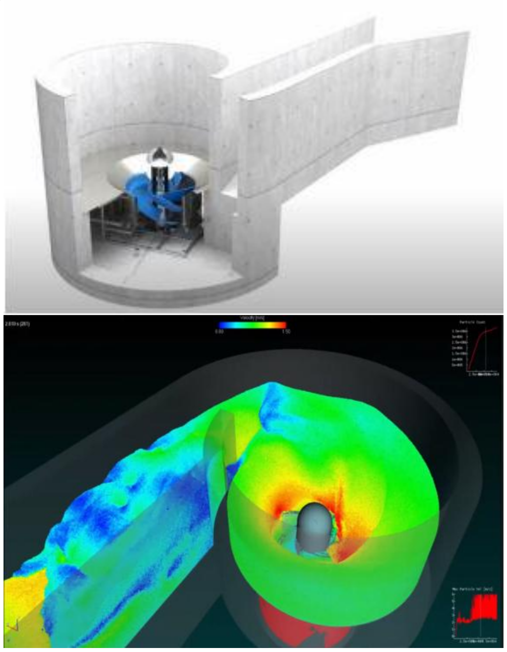

Figure. 1. Installation of a runner in the scroll casing showing the flow path through the turbine

The CFD calculations indicate that the swirl velocity near the runner entrance changes from around 2.5 m/s at the hub to 3.8 m/s at the blade tip, suggesting a rotational flow resembling the speed of the blades. The circumferential velocity along the leading edge of the blade remains below 0.7 m/s. Figure 1 (down) displays the CFD illustrates the free surface of the vortical flow within the scroll and presents the distribution of swirl velocity in a cross-section of the turbine. These results correspond to a flow rate of 1.1 m3/s, a system head of 1.1 m, and a rotational speed of 52 rpm.

3.3 Potential Hydro Sites

BPDB, BWDB, and IFRD of BCSIR have conducted a comprehensive study to identify potential sites for small-scale hydroelectric power generation in Bangladesh. The study has revealed that due to the predominantly flat topography of the country, the Chittagong Hill Tracts region holds the majority of the hydroelectric potential. This region is characterized by hilly terrain and a higher elevation, making it suitable for harnessing the power of flowing water to generate renewable energy through small hydropower projects

Table 3. Potential small hydro sites identified by BPDB and BWDB [9]

District	Name	Potential Power (KW)
Khagrachari	Nunchari Tholipara	3
Bandarban	Bangchari	25
Bandarban	Liragaon	20
Rangamati	Kamalchar	20
Rangamati	Thang Khrue	30
Bandarban	Monjaipara	7.5
Chittagong	Foy's Lake	4
Chittagong Hill Tracks	Sealock	81
Chittagong	Lungi chara	10
Chittagong	Budia Chara	10
Sylhet	Nikhari Chara	26
Sylhet	Ranga Pani Gung	61
Bandarban	Taracha Khal	20

3.4 Feasibility Assessment

In the computational model, the stationary domain was assigned an inlet velocity of 0.3 m/s and an outlet static pressure of 1 atm. The boundary conditions for water and air were adjusted accordingly at the interface. The rotating domain was configured to rotate in an anticlockwise direction with angular velocities ranging from 40 to 100 rpm. The boundary conditions are depicted in Figure 2 (up). The observed flow behavior and velocity distribution, as illustrated in Figure 2 (down), indicate that the rotating blade will encounter a vortex pool with an approximate velocity of 1.3 m/sec within the radial range of 60mm to 120mm. This velocity value is significant for the torque generation on the shaft through the blade. Additionally, based on the streamlines, it is anticipated that the blade with a curved profile will likely experience the maximum water stream impact area.

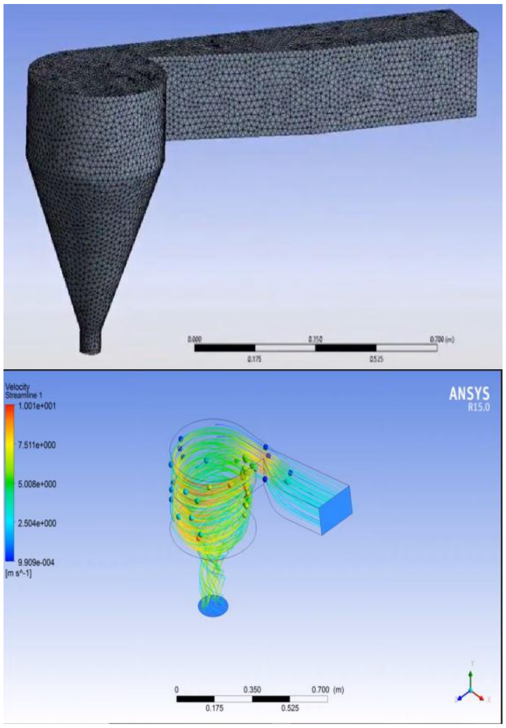

Figure. 2. Optimized meshing for streamlining flow in the stationary domain considering the ideal runner position

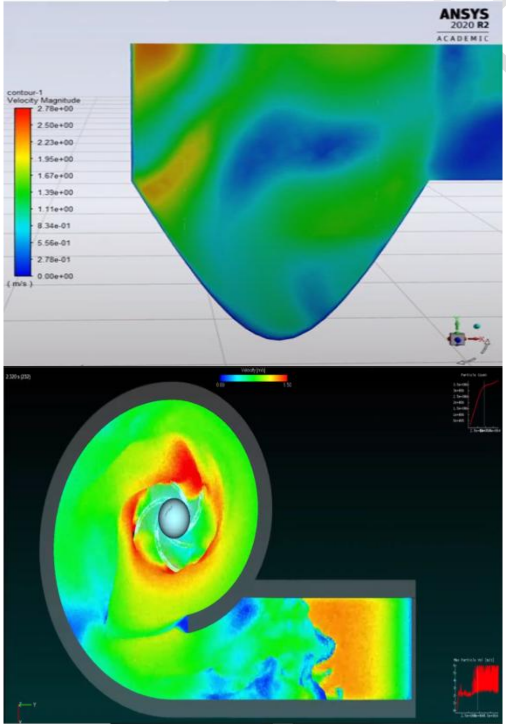

Figure. 3. Velocity vectors and potential energy conversion at the free surface

Figure 3 illustrates the velocity vectors at the free surface, showcasing a gradual increase in velocity in the radial direction due to rotational swirling and the conversion of potential energy. The use of the homogeneous multiphase Eulerian fluid approach reveals the interface between air and water where the presence of an air-filled vortex core contributes to the beneficial aeration of water, positively impacting the environment [10].

Figure. 4. Vortex turbine - generator system

Figure 4 illustrates the integration of the vortex turbine, which captures energy from a fluid flow, with the generator, which converts the mechanical energy into electrical energy. The blades in a vortex turbine generator system play a crucial role in the conversion of fluid flow energy into mechanical energy that drives the generator. The blade profile, shape, and angle of attack are important factors that determine the efficiency of energy conversion [11]. The design aims to maximize the extraction of energy from the fluid flow while minimizing losses due to turbulence and friction.

4. MATHEMATICAL ANALYSIS

The mathematical analysis was conducted using a theoretical approach, and a mathematical model was formulated in a Google spreadsheet.

4.1 Formulas Considered

The equations presented in the book "Basic Fluid Mechanics and Hydraulic Machines" are given below [12]:

1. Actual velocity, $v = \frac{Q}{A} = \frac{4Q}{\pi d^2}$
   Q = Experimental flow rate, d = Diametre of the nozzle
2. Peripheral velocity, $U = \frac{\pi DN}{60}$
   U = Peripheral velocity, D = Outer diameter of the turbine, N = Rotational speed
3. Inlet hydraulic power, $P_i = \delta QH$
   Q = Experimental flow rate, H = Head available at the nozzle, δ = Specific weight of water
4. Turbine output power, $P_o = \eta_\tau QHg\rho$
   η_τ = Hydraulic efficiency, ρ = Density of water
5. Hydraulic efficiency, $\eta_\tau = \frac{2U(V_1 - U)(1 + \cos\beta)}{V^2{}_1}$
   U = Peripheral velocity of the turbine, V_1 = Absolute velocity of the jet before striking the blades, β = Turbine blade angle

5. RESULTS

Table 4. Calculated performance analysis of gravitational low-head vortex turbine (Using the values of Table 1 and Table 2)

Flow Rate (m^3/s)	Height (m)	Power Output (KW)
1.5	1.4	11
2	1.6	16
2.5	1.8	23
3	2	30
3.5	2.2	35
4	2.4	48
4.5	2.6	59
4.7	2.7	63

Table 5. Efficiencies with blade number

Blade-Number	Efficiencies	Blade Angle
2	14.15	20
3	20.10	25
5	28.15	30
8	26.41	35
10	24.66	40

The study aims to investigate the influence of different blade numbers on the efficiency of vortex turbines in Table 5 and Figure 6. Through the experiments, we tested turbine configurations with 2, 3, 5, 8, and 10 blades while keeping all other parameters constant [13]. The findings of the study revealed interesting insights. The turbine with 5 blades exhibited the highest efficiency among all the configurations, achieving a remarkable percentage of 28.15%. This suggests that the design with 5 blades was most effective in harnessing the energy from the water vortex. Furthermore, we observed a notable increase of 4% in the power coefficient when the blade number was increased from 4 to 5.

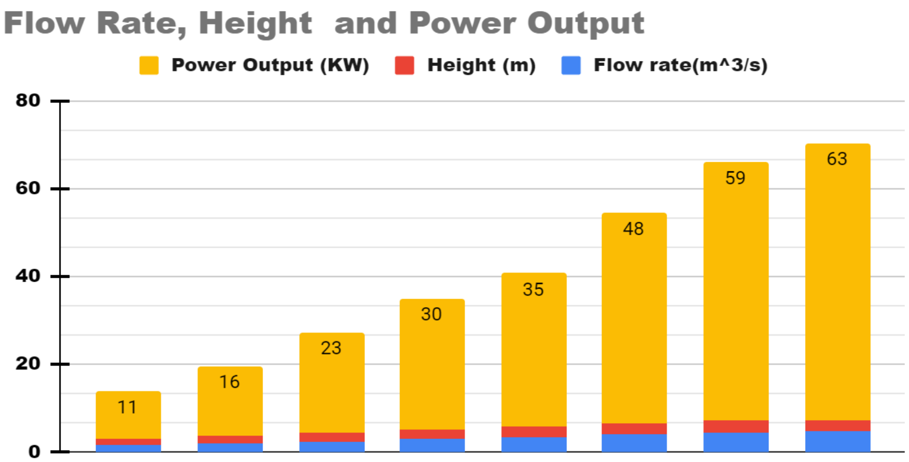

Figure 5: Representation of performance analysis

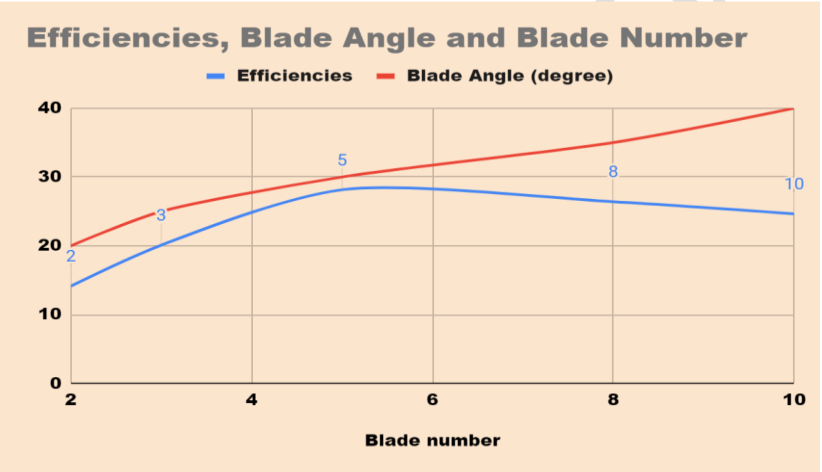

Figure 6: Efficiency and blade angle of gravitational vortex turbine with different blade numbers

5. DISCUSSIONS

The comparison between the potential small hydro sites identified by BPDB and BWDB in Table 3 and the performance analysis of our designed gravitational low-head vortex turbine in Table 4 provides valuable insights into the applicability and effectiveness of our turbine in real-life scenarios. Table 3 highlights several potential small hydro sites with varying power capacities, ranging from 3 KW to 30 KW. Analyzing Table 4, we observe that our turbine can effectively match and even exceed these Power outputs. For example, at a flow rate of 2.5 m^3/s and a head height of 1.8 m, our turbine generates a power output of 23 KW, which aligns well with the potential power of 20 KW identified in Bandarban. Additionally, Table 5 shows the efficiencies achieved with different blade numbers. Our turbine exhibits high efficiency, with a peak efficiency of 28.15% obtained with a blade number of 5. This indicates the turbine's ability to efficiently convert a significant portion of the water’s kinetic energy into electrical power.

6. CONCLUSIONS

The findings underscore the adaptability and performance of our designed gravitational vortex turbine. It demonstrates the capability to effectively utilize the available flow rates and head heights, thereby generating electricity at or above the power levels identified in the potential small hydro sites. While these results demonstrate the turbine's capabilities, it is essential to conduct further feasibility studies and site-specific assessments to validate its performance under actual operating conditions. Factors such as local topography, environmental considerations, and other site-specific variables should be taken into account to ensure successful implementation and optimal performance.

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