EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 25(12), 132–146
https://doi.org/10.12912/27197050/193866
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.09.13
Accepted: 2024.10.15
Published: 2024.11.01

Performance of a Vortex Turbine With Modifications to Flow Angle, Blade Inclination, and Flow Velocity for a Cylindrical Basin

Imanuel Sinuraya[1], Tulus Burhanuddin Sitorus[1*], Idham Kamil[3], Bakhrul Ilmi[1]

[1] Department of Mechanical Engineering, Universitas Sumatera Utara, Dr. T. Mansur Street No. 9, Padang Bulan, Medan Baru District, Medan City, North Sumatra, 20155, Indonesia

[2] Department of Mechanical Engineering, Politeknik Negeri Medan, Jl. Dr. T. Mansur No.9, Padang Bulan, Medan Baru District, Medan City, North Sumatra, 20155, Indonesia

* Corresponding author's e-mail: tulus.burhanuddin@usu.ac.id

ABSTRACT

The aim of this research was to improve the performance of vortex turbines by testing the performance of vortex turbines using experimental methods, with test variables including blade tilt, flow speed, and vortex turbine impeller material using PLA (polylactic acid). Tests were conducted on a laboratory-scale gravitational water vortex turbine (GWVT) with a pool diameter of 1 meter and a height of 0.8 meters. The test results showed that the turbine with 5 blades produced a maximum torque of 5.89 Nm and an efficiency of 51.10%. The turbine with 7 blades produced a maximum torque of 7.85 Nm and an efficiency of 58.51%. The highest efficiency, 64.69%, was achieved by the 9-bladed turbine, which also had a maximum torque of 8.83 Nm. Experimental tests showed that this laboratory-scale vortex turbine achieved a maximum power output of 87.28 watts, with an efficiency of 56.66% and a torque of 9.81 Nm, using a 9-bladed turbine at a water velocity of 2.5 m/s. These results certainly show an improvement compared to previous reference studies, where the use of materials with lower density, higher blade angle, and larger blade geometry can improve the performance of vortex turbines.

Keywords: microhydro, performance, vortex-turbine.

INTRODUCTION

The UN's 2030 Agenda for Sustainable Development Goals (SDGs) addresses global sustainability and human development challenges. SDG-7 focuses on affordable, clean, and sustainable energy, making renewable energy research increasingly important. Transitioning to renewable energy is crucial for reducing greenhouse gas emissions and mitigating climate change. Indonesia, a major coal exporter with 3% of global reserves, faces significant challenges in reducing coal dependency, especially in electricity generation dominated by PLN (Silalahi *et al.*, 2022). In Indonesia, four types of coal-fired power plants (CFPPs) are used, with subcritical plants being the most common. The ASEAN Centre for Energy projects that the CO_2 emissions from these plants will rise to 8623 million tons by 2040 due to increasing electricity demand. These plants significantly contribute to CO_2 emissions and air pollution, adversely affecting public health (Sanchez and Luan, 2018). The air quality data from September 2023 revealed the highest pollution levels in Jakarta, followed by West Kalimantan and South Sumatra (Fadhlurrahman, 2023). Indonesian regulations set air pollution standards to address the emissions from fossil fuel-based industries (Figure 1). The UN has set greenhouse gas reduction targets to combat global climate change, emphasizing the urgency of switching to renewable energy. Rising global energy consumption underscores the need for further research and development in renewable energy to address the growing energy crisis. Diversifying energy sources is crucial for future human energy needs. As a potential alternative, hydropower highlights the need to explore other sustainable energy sources.

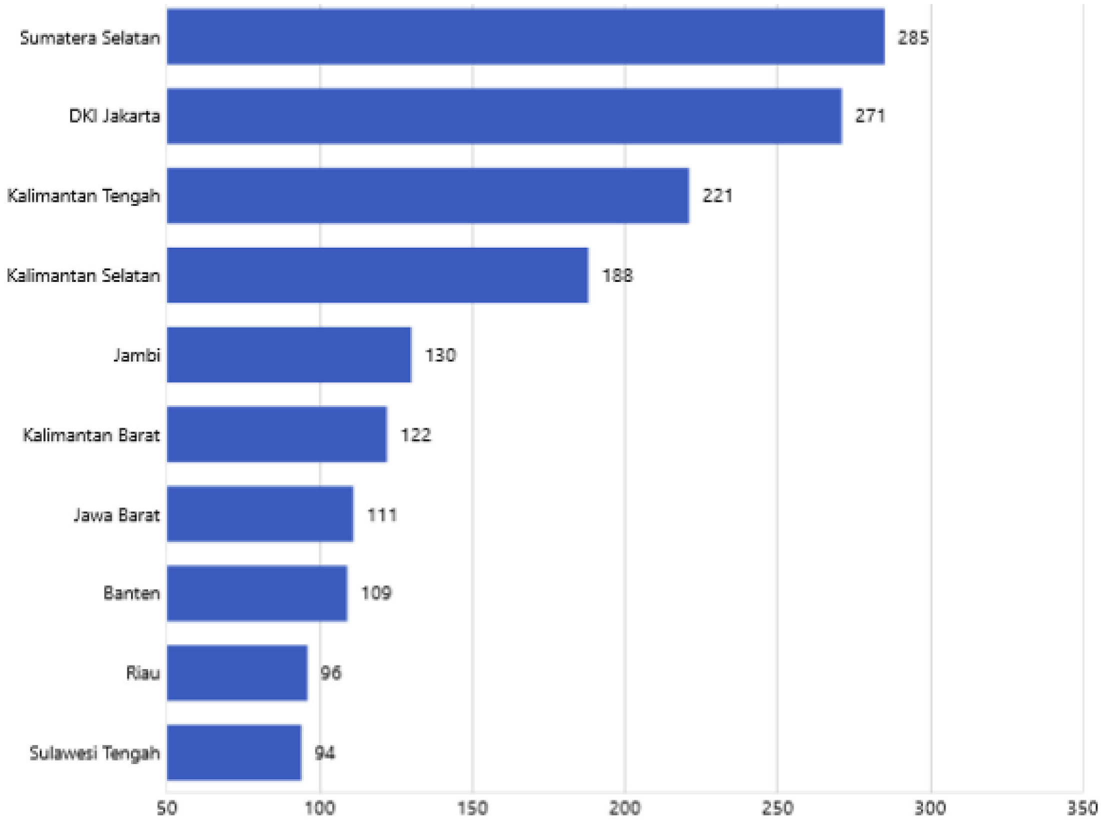

Figure 1. The 10 regions in Indonesia with the highest air pollution (Fadhlurrahman, 2023)

Despite renewable energy like hydropower comprising less than 20% of global energy consumption (Dhakal *et al.*, 2015), gravitational water vortex power plants offer environmentally friendly solutions for utilizing low-flow water with minimal impact of emissions and potential water quality improvement (Rahman *et al.*, 2017).

Transitioning away from fossil fuel power plants, which are still major emitters until 2030, poses significant challenges for Indonesia. The country's unique geographic structure leads to substantial disparities in electricity generation costs between regions, particularly with higher costs in eastern Indonesia compared to Java, despite its growth potential. Pressure from international institutions and NGOs to reduce global emissions has influenced public opinion and urged the government to reassess and revoke mining permits (Anderl, 2018). Uneven electricity cost distribution underscores why renewable energy is vital for Indonesia's power generation. As of mid-2020, share of renewable energy in Indonesia's electricity generation was under 15% (IESR Institute for Essential Services Reform, 2021). PLN, a key player in the energy industry, needs proactive measures to reduce carbon emissions, aligning with government goals to lower its carbon footprint. Research by UNESCAP using the levelized cost of electricity (LCOE) method demonstrates that renewable power plants like solar photovoltaic, geothermal, hydro, and wind are more cost-effective than coal-fired plants. The LCOE approach integrates a system's lifetime costs with energy generation costs, bridging high initial capital costs with low operational expenses or vice versa. The gravitational water vortex power plant (GWVP) offers the potential for renewable energy generation using cylindrical water flow containers. This study evaluated how container geometry and turbine design influence the GWVP performance. Despite the previous efforts to enhance GWVP designs, a deeper understanding of water flow-turbine interactions within conical containers is needed. Hence, this research employed experimental approaches to investigate the impacts of turbine power enhancements on the GWVP efficiency and performance. The study aimed to provide new insights into developing the GWVP technology as a more effective and sustainable renewable energy source (Edirisinghe *et al.*, 2022). Previous studies explored vortex turbine designs using cylindrical basins with dimensions such as 100 cm diameter and 80 cm height, featuring inclined blades with a head diameter of 20 cm, outer diameter of 60 cm, curvature radius (R) of 500, and a 60-degree tilt angle. Experimental tests achieved a peak power of 47.43 watts with 43.11% turbine efficiency and 10.8 Nm torque using 9-blade acrylic on a steel holder (Kamil *et al.*, 2023). Another study utilized a steel impeller with R140 curvature, yielding a flow rate of 0.06 m^3/s, 25 watts load, and 43.83% turbine efficiency, later modifying to aluminum, resulting in reduced efficiency to 8.06% (Suntivarakorn and Suntivarakorn, 2019) (Timilsina *et al.*, 2018).

Further research analyzed single-stage gravitational water vortex power plants with cylindrical basin types, exploring mathematical and experimental approaches on factors like vortex height, blade position, submerged percentage, blade tilt, and impact of shape on turbine performance (Ullah *et al.*, 2020). Studies highlighted increased water inflow enhancing vortex height and turbine shaft rotation, noting higher blade submergence enhancing rotation speed. Different blade shapes affected torque and mechanical efficiency, with conical blades enhancing rotation but reducing torque, while straight blades achieved optimal efficiency when fully submerged in water vortices. Additionally, studies analyzed axial flow in hydraulic turbines within open channels, characterizing flow and slipstream dynamics via particle image velocimetry (PIV) and Ansys CFX 15.0 simulations (Nishi *et al.*, 2019). Findings indicated downstream vorticity due to runner rotation, water displacement, and depth differences inside and outside turbines, affecting the vortex turbine performance. Another study used CFD simulations and experiments to vary the number of blades in concave cylindrical vortex turbines (Ambarita *et al.*, 2023). Results showed that increasing the blade count enhanced torque and power production, with simulations validating the highest torque at 14.6 Nm for 7-blade turbines and peak efficiency at 43.5%, contrasting with 40.4% for 5-blade turbines. Analytical analysis affirmed that increased blade count expanded water contact area, thereby enhancing water energy absorption by turbines. Previous research has explored the performance of vortex turbines by testing various variables such as blade inclination of 60 degrees, flow speed, and impeller material used (Kamil *et al.*, 2023). In that study, the researchers conducted detailed tests to evaluate how the blade inclination angle affects the water flow rate in the basin, efficiency and performance of the vortex turbine. Variable water flow velocities were also tested to determine their effect on turbine performance, with the aim of finding out how changes in water flow velocity affect the results of the tests conducted. Previous research used vortex turbine impeller material, namely iron combined with acrylic. Previous research has underlined the importance of understanding the gravity flow field in vortex turbines to improve their performance. The difference between this research and previous research lies in the use of different impeller materials. Therefore, this study aimed to modify the blade inclination by 70 degrees, flow velocity, flow angle, and impeller material using PLA (polylactic acid).

THEORETICAL FOUNDATION

Microhydro power plant

Using micro hydro turbines as a source of power generation is an efficient and economical alternative to addressing the current energy crisis. One type of micro hydro turbine, the GWVT, offers a decentralized solution that can tackle the challenges of providing electricity in remote areas. The GWVT operates by utilizing water flow that forms a vortex on the free surface, generating mechanical power that is converted into electrical energy through a rotor and generator. This process allows for energy extraction from the vortex flow without disrupting the main flow of the river or canal, making it an environmentally friendly and sustainable solution (Li *et al.*, 2008). GWVT is known for its ability to operate at low flow rates and low heads, distinguishing it from other conventional technologies (Rahman *et al.*, 2017). Installing these turbines along watercourses provides easy access for local communities to generate sustainable electricity. With GWVT contribution to power generation, renewable energy becomes more affordable and reliable. Environmental benefits, including zero greenhouse gas emissions, make it an attractive choice. Furthermore, the increased water surface area produced by GWVT enhances aeration and overall water quality, providing a better environment for aquatic life (Nishi and Inagaki, 2017). All these features indirectly support a more efficient energy framework than conventional energy technologies (Ciupageanu, 2018).

Water vortex power plant

GWVT is an adaptable solution for generating energy from industrial wastewater, demonstrating its flexibility in resource recovery. Its simple design distinguishes it from other water energy extraction methods, offering lower installation and maintenance costs (Vivekananda, 2019). Another advantage is its capability to operate across various flow rates, even under very low head conditions.

Illustrations in Figures 2 and 3 depict the design and installation of GWVT, which is the focus of this study. The water vortex is generated by the flow driven gravitationally into a circular container with tangential inlet channels and a central bottom outlet channel. A turbine with a vertical axis is positioned at the center of the vortex where the strongest rotational force occurs. This turbine rotates with the vortex flow, driving the generator. Additionally, the surface vortex plays a role in the aeration process (Kim and Kim, 2021), aiding in air mixing and enhancing dissolved oxygen concentrations in the water. Thus, vortex hydroelectric power plants can also contribute to natural water purification through interactions with microorganisms. The concept of energy contained in natural water vortices was initially explored by Viktor Schauberger, an Austrian forest expert and naturalist (Harding, 1984). Later, Austrian engineer Franz Zotloterer utilized this principle to generate rotational energy by placing a vertical axis rotor in the center of the vortex (Warjito *et al.*, 2020).

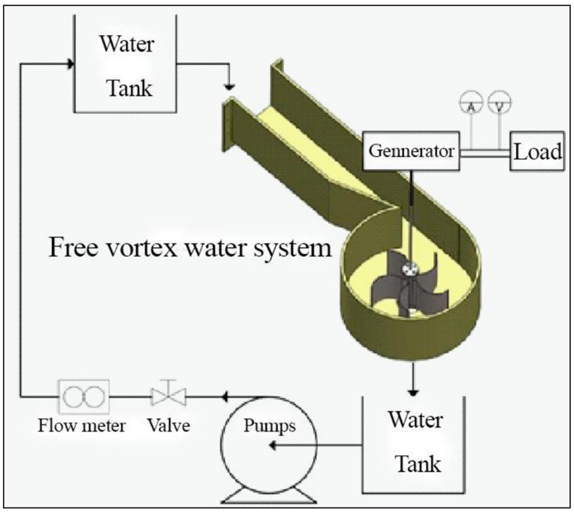

Figure 2. Illustration of GWVT design (Suntivarakorn and Suntivarakorn, 2019)

However, vortex hydroelectric power technology is still relatively new compared to other micro-hydropower generation methods, and currently, there are few operational vortex hydroelectric power plants worldwide. Due to its compelling advantages, many researchers have been interested in further developing this technology. Development efforts are primarily focused on optimizing the design of vortex pool configurations and turbines. Despite numerous discoveries related to various geometric parameters, there is still no standardized design procedure available for vortex hydroelectric power plants. Therefore, the design of vortex hydroelectric power plants for each location remains highly dependent on the specific needs and characteristics of that site.

The turbines used in GWVT do not rely on pressure differentials but instead harness the dynamic force of the water vortex (Rahman *et al.*, 2017). The turbine blades play a crucial role in

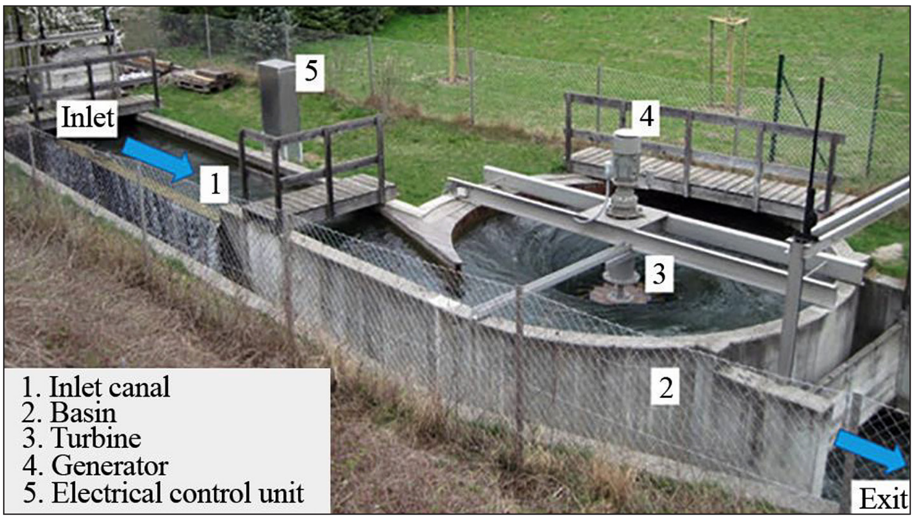

Figure 3. Installation at Obergrafendorf, Austria (reproduced with permission from Zotlöterer (Bajracharya *et al.*, 2020)

converting the tangential velocity of the vortex by absorbing power, reducing tangential speed, and increasing axial speed.

MATERIALS AND METHODS

The research was conducted at the Laboratory of Fluid Mechanics in the Department of Mechanical Engineering, Universitas Sumatera Utara. This research study utilized various tools and materials, with the primary equipment being an inclined-blades turbine (Figure 4) and a cylindrical basin intake tunnel (Figure 5). The turbine blades had specific specifications: inclined type, with a shaft hole diameter of 20 mm, outer diameter of 717 mm, blade curvature radius R200, and inclination angle of 70°. The basin used was cylindrical.

Figure 4 shows the design of the inclined blade type vortex turbine with 5, 7, and 9 blades, where the 3D model was designed using Solidworks 2020. Manufacturing the vortex turbine through 3D-printing technology with PLA filament resulted in turbine impellers weighing 4.2 kg, 4.9 kg, and 6 kg.

The 3D printed results seen in Figure 5 illustrate the physical details of the applied design. The use of 3D-printing technology with PLA filament ensured the manufacture of turbine impellers with

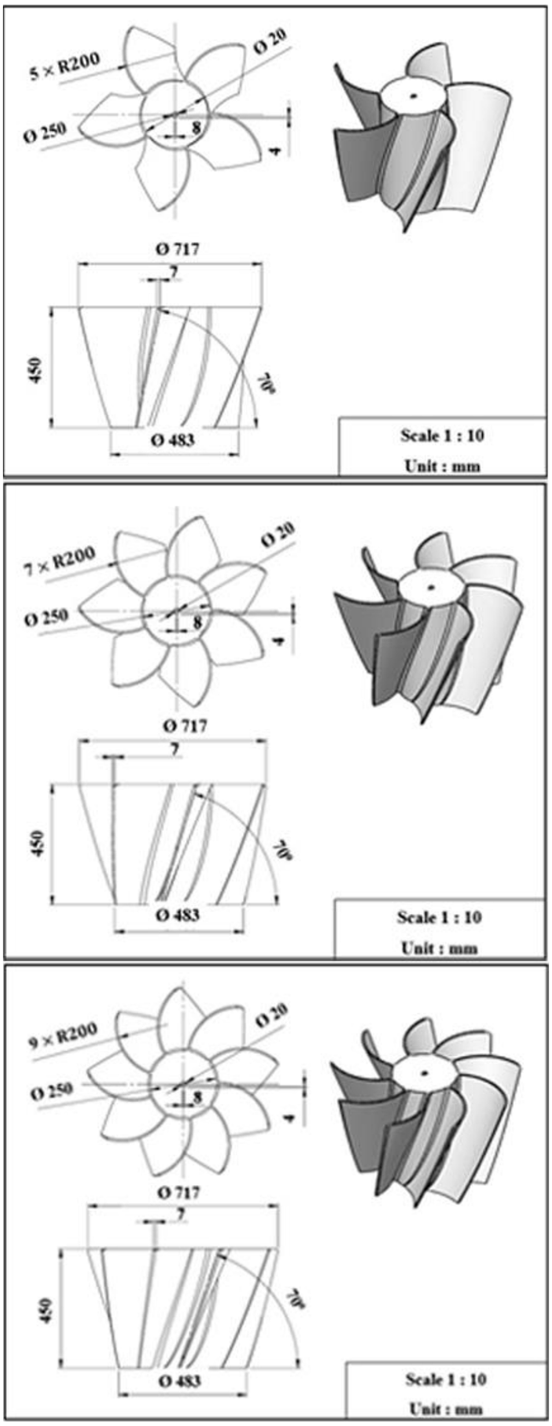

Figure 4. Design of the 9, 7, and 5-blade vortex turbine impeller

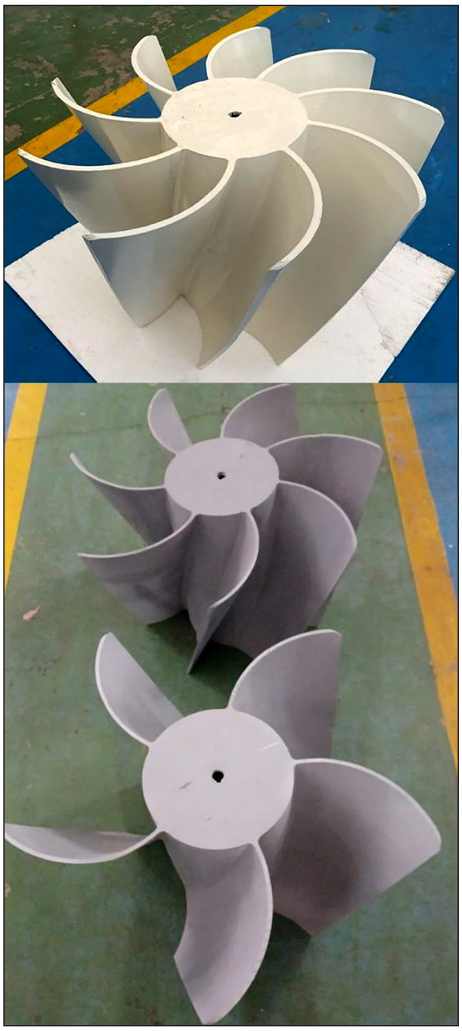

Figure 5. Images of turbines with 9 blades, 7 blades, and 5 blades

a high degree of precision, in accordance with the designs developed using SolidWorks 2020.

Figure 6 depicts flow patterns with blade variations of 5, 7, and 9. The flow pattern in turbine is influenced by the number of blades used, with variations of 5, 7, and 9 blades showing different characteristics. A turbine with 5 blades tend to produce smooth and stable water flow, with each blade efficiently capturing and channeling water energy. Meanwhile, a turbine with 7 blades offer more uniform and efficient flow, capable of effectively capturing kinetic energy from the water flow. On the other hand, turbines with 9 blades provide very smooth and stable flow, demonstrating high efficiency in converting water energy due to a larger surface area involved in the process. The decision to choose the number of blades considers flow efficiency and stability (Figure 7).

This experimental layout was designed to test the electric power generation system using GWVT, as illustrated in Figure 8 (Kamil *et al.*, 2023).

The experimental procedure for this research includes: 1) Providing a vortex turbine blade with nine blades 2) Providing a turbine shaft 3) Installing the shaft into the vortex turbine blade 4) Assembling the vortex turbine blade into a cylindrical basin 5) assembling the turbine shaft on the bearing, after which the bearing key with the L

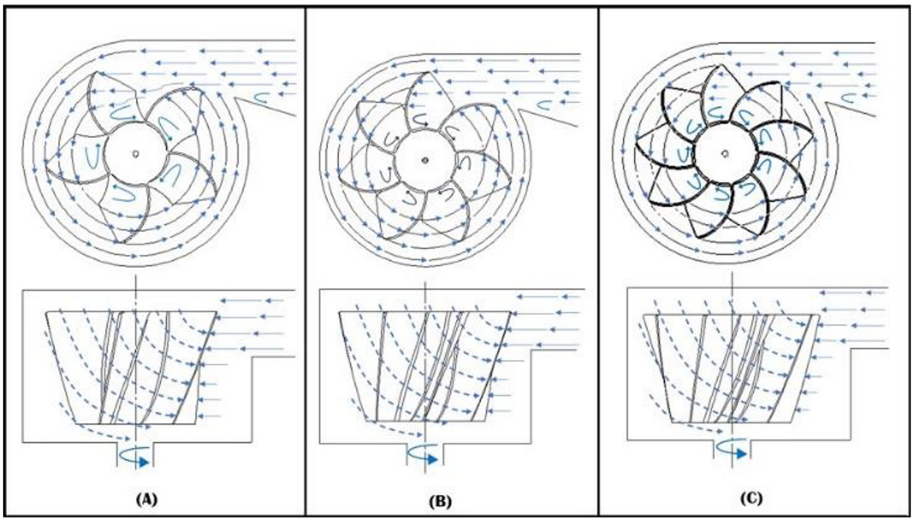

Figure 6. Sketch of water flow impacting turbine blades

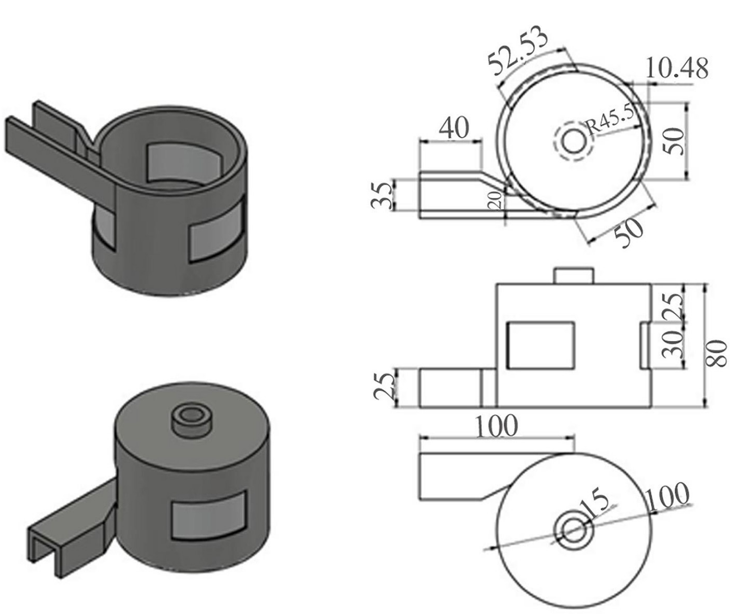

Figure 7. Basin and intake tunnel

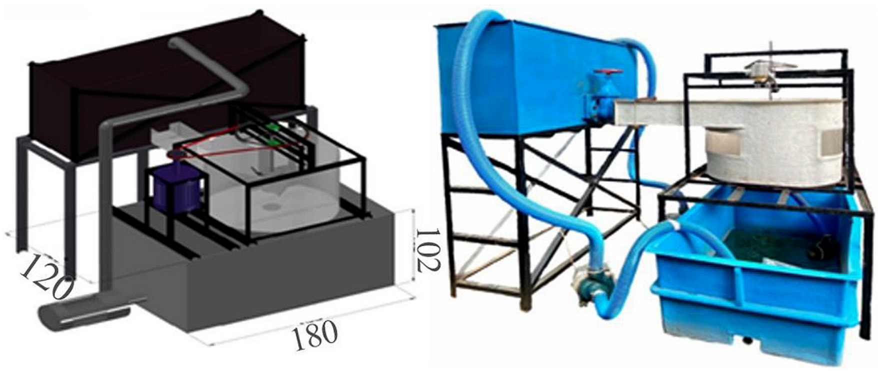

Figure 8. Experimental design and layout (Kamil *et al.*, 2023)

key 6) Turning on the centrifugal pump to fill the upper water tank 7) Filling the lower tank with water to maintain water stability during testing 8) Testing and conducting the data retrieval process 9) Opening the valve by seven turns to achievee a water speed of 2 m/s 10) Opening the valve by 13 turns to achieve a water speed of 2.2 m/s 11) Opening the valve by 26 turns to achieve a water speed of 2.5 m/s 12) Measuring the rotation speed on the turbine shaft using a tachometer 13) Taking data with variations in head height with values of 0.4, 0.5, 0.7, and 0.8 m. 14) Observing and analyzing the gravitational force of the vortex rotation on the 9-blades 15) Taking data for torque testing on the 9-blades 16) Connecting the belt to the pulley on the turbine shaft and generator pulley 17) Installing lights that have been arranged in parallel to determine the maximum power output 18) Taking data at each water speed and height variable to determine the resulting power 19) Repeating the test for 5 and 7 blades 20) Observing the results of the five and 7-blade tests and preparing testing tables.

To assess the turbine effectiveness, it is essential to consider torque and shaft rotation. Gathering data for calculation and analysis is crucial in evaluating the performance of the vortex turbine, as referenced by a researcher who conducted experiments on gravity-driven whirlpool turbines. These parameters are pivotal for determining the operational performance of a turbine. Torque and shaft rotation speed significantly influence the power output of turbines, necessitating data for calculation and analysis. Abdul Samad Saleem researched gravitational water vortex turbines, utilizing the following formulas to process data (Saleem *et al.*, 2020):

Water power (P_{water}) is the power generated by water per unit area and is defined as:

$$P_{water} = \rho \cdot g \cdot v \cdot H \quad (1)$$

Turbine power ($P_{turbine}$) is the power generated by the turbine rotor after extracting energy from the water flow, adjusted for the power coefficient:

$$P_{turbine} = \tau \cdot \omega \quad (2)$$

Torque (τ) represents the rotational force generated by the turbine shaft or the ability of a turbine to perform work.

$$\tau = F \cdot r_p \quad (3)$$

Angular velocity (ω) refers to the magnitude of the angle formed by the path of a point moving in a circle per unit time.

$$\omega = \frac{\Delta\theta\ (2 \cdot \pi \cdot r)}{\Delta t} \quad (4)$$

Turbine efficiency (η) measures the ability of a turbine to convert potential energy in water into mechanical energy to drive a generator.

$$\eta = \eta_T = \frac{P_{water}}{P_{turbine}} \times 100\% \quad (5)$$

RESULT AND DISCUSSIONS

This study analyzed various performance parameters including speed, blade rotation, torque, and power generated by the system. One of the main focuses of this research was to investigate the effect of blade number and valve opening variations on the overall performance. Various blade configurations were tested under three different valve opening conditions, while maintaining a constant flow rate at 0.0225 m³/s, 0.0154 m³/s, and 0.0140 m³/s, respectively. The water level in the reservoir was maintained at 1 meter to ensure consistent flow during the test. In addition, this study also analyzed the experimental data at a water level of 0.7 meters, as at that height the flow exhibited a steady or 'steady step' velocity. This condition allows for more accurate and consistent measurements, especially when it comes to evaluating torque and blade rotation. With the flow velocity under control, the influence of blade number and valve opening on performance parameters can be analyzed in greater depth. The results of these tests are expected to provide greater insight into the optimal design for improving the efficiency of hydraulic and mechanical-related systems.

Figure 9 illustrates the relationship between water height and RPM for three different water velocities: 2 m/s, 2.2 m/s, and 2.5 m/s. At all three water velocities, the RPM remains stable between 60 and 70 RPM as the height increases from 0.4 to 0.7 meters. This indicates that the changes in height within this range do not have a significant impact on RPM. At a water velocity of 2.5 m/s, the RPM shows slightly higher values than water velocities of 2.2 m/s and 2 m/s. This suggests that increasing water velocity tends to increase RPM, although the increase is insignificant.

Figure 10 displays the relationship between RPM and $P_{turbine}$ for three different speeds: 2 m/s, 2.2 m/s, and 2.5 m/s. At a water speed of 2 m/s, the turbine power experienced a gradual increase from about 45 watts at RPM 65 to reach 52 watts at RPM 78. Meanwhile, at a water speed of 2.2 m/s, the turbine power ranged from 50 to 58 watts, as the RPM increased from 68 to 74. On the other hand, at a water speed of 2.5 m/s, the turbine power experienced a larger increase, from about 55 watts at RPM 66 to about 85 watts at RPM 78. On the basis of this graph, it can be seen that the turbine power tends to increase as the RPM and water speed increase. The propeller working at higher water velocity can produce more power at each RPM. This shows that water speed has a significant impact on the increase in turbine power, where higher speeds produce more power.

Figure 11 shows the relationship between turbine power and efficiency at different water speeds, namely 2 m/s, 2.2 m/s, and 2.5 m/s. At a water velocity of 2 m/s, the turbine efficiency

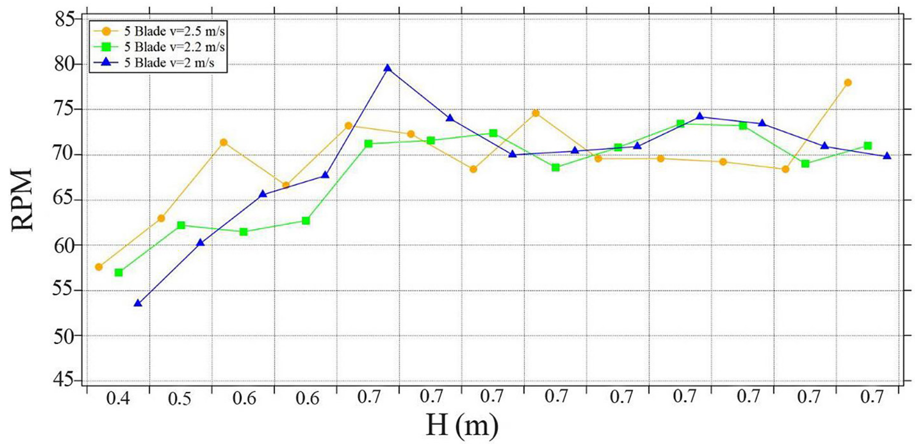

Figure 9. Comparison of RPM and water height with 5 blades

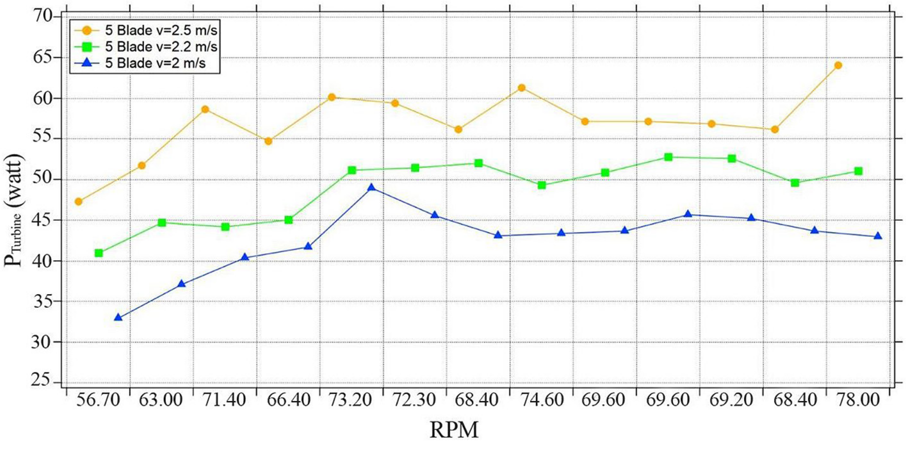

Figure 10. Comparison chart of Turbine Power ($P_{turbine}$) and Rotation (RPM) with 5 blades

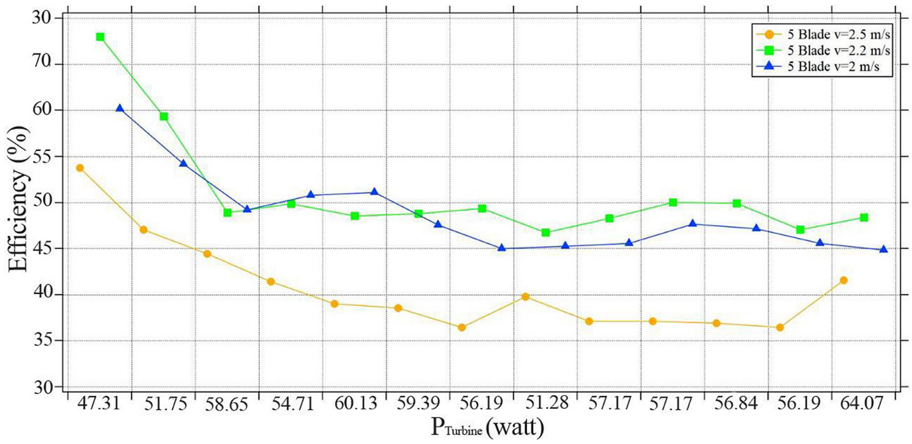

Figure 11. Comparison of efficiency (ηt) and turbine power ($P_{turbine}$) with 5 blades

increases from about 45% at 44 watts to about 48% at 48 watts. At a water velocity of 2.2 m/s, the turbine efficiency is in the range of 50% to 52% with an increase in power from 50 to 54 watts. At a water speed of 2.5 m/s, the turbine efficiency shows an increase from about 34% at 52 watts of power to reach about 38% at 64 watts of power. This graph shows that an increase in turbine power is generally accompanied by an increase in efficiency, but the pattern of increase varies depending on the water velocity. At lower water velocities of 2 m/s and 2.2 m/s, the efficiency is higher than at a water velocity of 2.5 m/s at the same power. This shows that at higher water velocities, the efficiency of the turbine decreases, despite the greater power generated.

Figure 12 shows the relationship between water height and RPM for three different water velocities: 2 m/s, 2.2 m/s, and 2.5 m/s. Analysis of the graph shows a general pattern where the RPM increases as the water level increases. At a water speed of 2.5 m/s, it shows an increase in RPM from around 60 to a peak of 85 RPM before decreasing to around 70 RPM at a water height of 0.7 meters. The water speed of 2.5 has the highest RPM among the three speeds which shows that a higher water speed produces a faster RPM. At a water speed of 2.2 m/s the RPM rises from around 60 to a peak of 75 RPM at a height of 0.6 meters, then decreases at a water height of 0.7 meters. This indicates a water speed of 2 m/s, having a slower increase in RPM. Overall, this graph shows that higher flow rates result in higher RPM.

Figure 13 displays the relationship between the RPM variable and turbine power ($P_{turbine}$) for three different speeds: 2 m/s, 2.2 m/s, and 2.5 m/s. Analysis of this graph shows that variation in water velocity has a direct effect on the power generated by the turbine at various RPM levels. At 2 m/s water velocity, the turbine power increases gradually from about 45 watts at RPM 68 to reach 55 watts at RPM 76. This shows a positive relationship between the increase in turbine rotation speed and the power generated at that water

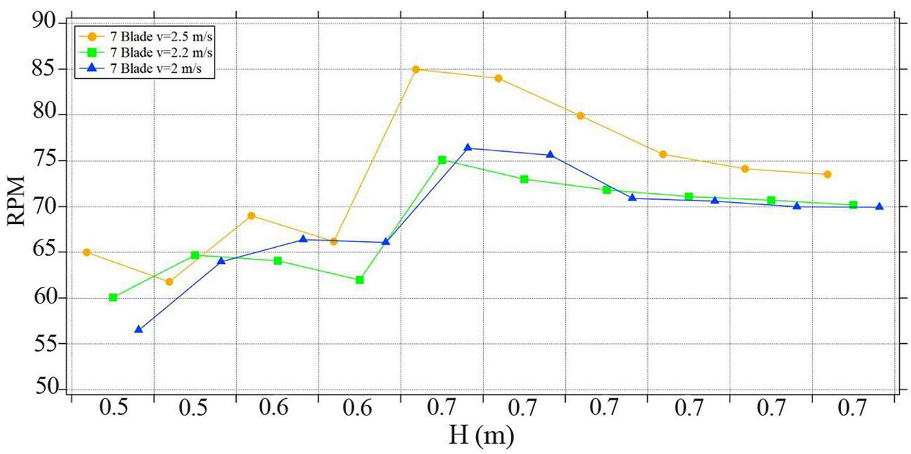

Figure 12. Comparison of RPM and water height with 7 Blades

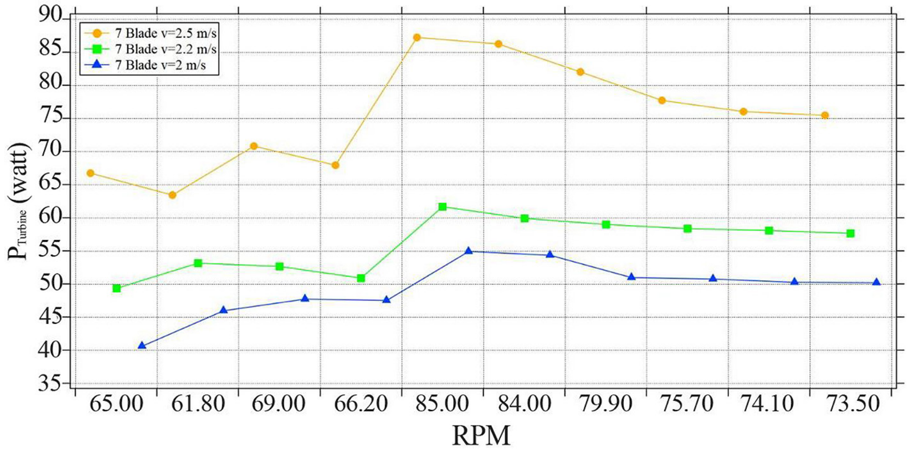

Figure 13. Comparison of Turbine Power ($P_{turbine}$) and Rotation (RPM) with 7 Blades

speed. When the water speed was increased to 2.2 m/s, the power generated by the turbine also increased more significantly, from about 50 watts at RPM 70 to reach 65 watts at RPM 77, showing an increase in efficiency as the water flow speed increased. At higher water velocities of 2.5 m/s, the increase in turbine power becomes much more significant, compared to lower water velocities. The turbine power increased from about 60 watts at RPM 74 to reach 85 watts at RPM 84. This increase confirms that higher water velocities have a significant impact on the power generated by the turbine at the same RPM.

Figure 14 shows the relationship between Turbine Power and Efficiency for three different water speeds of 2.5 m/s, 2.2 m/s, and 2 m/s. Overall, the graph trends show that as the power generated by the turbine increases, the efficiency also tends to increase, although there are differences in the range of power and efficiency at each water speed. At a water speed of 2 m/s, the turbine efficiency ranges from 50% to 58%, with the power generated increasing gradually from around 50 watts to 55 watts. Although this increase is relatively small, its consistency shows a positive relationship between water speed and power. When the water speed was increased to 2.2 m/s, the turbine efficiency showed a higher increase, ranging from 50% to almost 60%, with the power generated increasing from about 58 watts to 60 watts. The increase in efficiency at this speed indicates that at moderate flow rates, the turbine can perform more optimally. However, when the water velocity increased even higher to 2.5 m/s, although the turbine power increased significantly from about 75 watts to 85 watts, the efficiency remained in the range of 50% to almost 60%. This shows that an increase in water speed results in greater power, but is not necessarily accompanied by a significant increase in efficiency. Under these conditions, the 7-bladed turbine used in the tests showed that a moderate water speed of 2.2 m/s

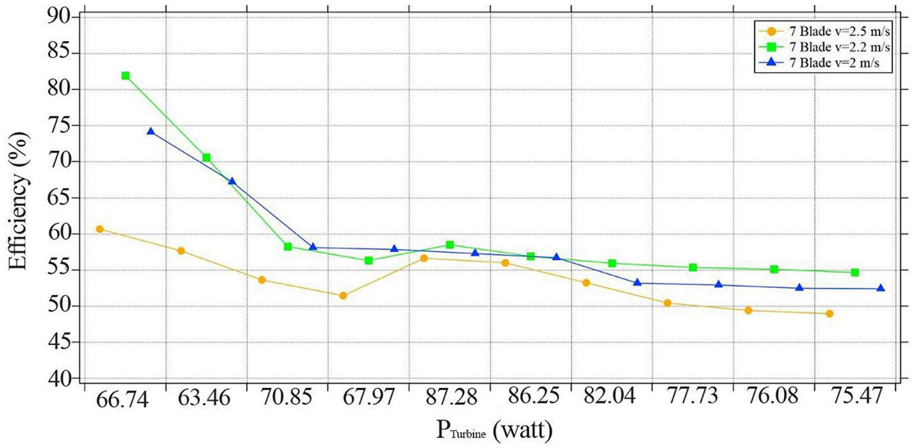

Figure 14. Comparison of efficiency (ηt) and Turbine Power ($P_{turbine}$) with 7 Blades

resulted in a more optimal efficiency, compared to the speeds that were too low or too high. From this analysis, it can be concluded that while higher water speeds are capable of producing more power, the efficiency of the turbine tends not to change significantly at a given speed level. Optimization of turbine performance can be achieved at a moderate range of water velocities, where efficiency and power generated are balanced.

Figure 15 shows the relationship between water height variables and RPM for three different water speeds: 2 m/s, 2.2 m/s, and 2.5 m/s on a turbine with 9 blades. At all water speeds, RPM increases along with water height up to about 0.60 m. At a water speed of 2.5 m/s, the RPM reaches a maximum value of around 70–75 at a water height of around 0.60 m. At a water speed of 2.2 m/s the RPM increases until it reaches a peak of around 70 RPM at a water height of 0.60–0.70 m. At a water speed of 2 m/s, the RPM also increases by about 70 RPM. Analysis of this data shows that there is a relationship between water speed, height, and RPM, where RPM tends to increase along with height. Fluctuations at 2 m/s may indicate greater variability at lower water velocities.

Figure 16 depicts the relationship between RPM and P parameters turbine for three different speeds: 2 m/s, 2.2 m/s, and 2.5 m/s. In general, the graphs show that the higher the RPM, the greater the turbine power generated. At a water speed of 2 m/s, the turbine power increases from about 60 watts to 64 watts as the RPM increases from 63 to 66. At a water velocity of 2.2 m/s, the power generated is greater, from about 65 watts to 74 watts, with an RPM range from 65 to 73. Meanwhile, at a water velocity of 2.5 m/s, the turbine power is highest, from about 75 watts to 82 watts with an RPM that is also higher, between 69 to 75. From this analysis, it can be seen that higher water velocities result in greater turbine power at higher RPMs. However, the increase in turbine power is not perfectly linear, especially at lower water speeds. A water speed of 2.5 m/s gives the most turbine power, followed by a speed of 2.2 m/s,

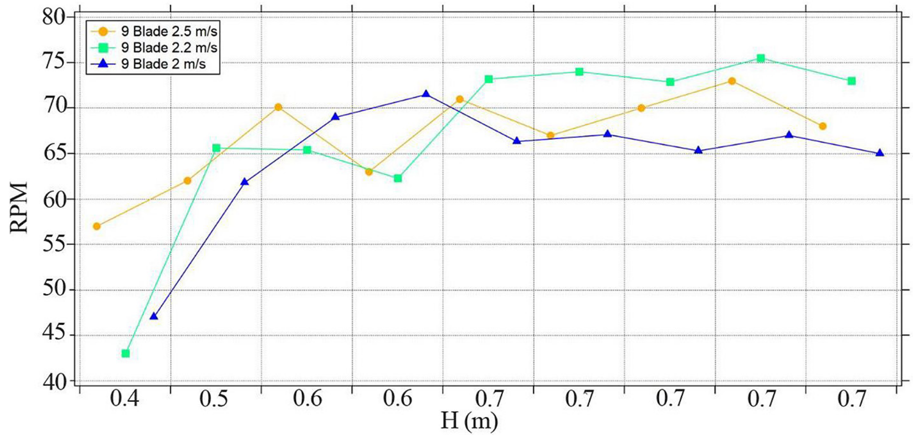

Figure 15. Comparison of RPM and water height with 9 Blades

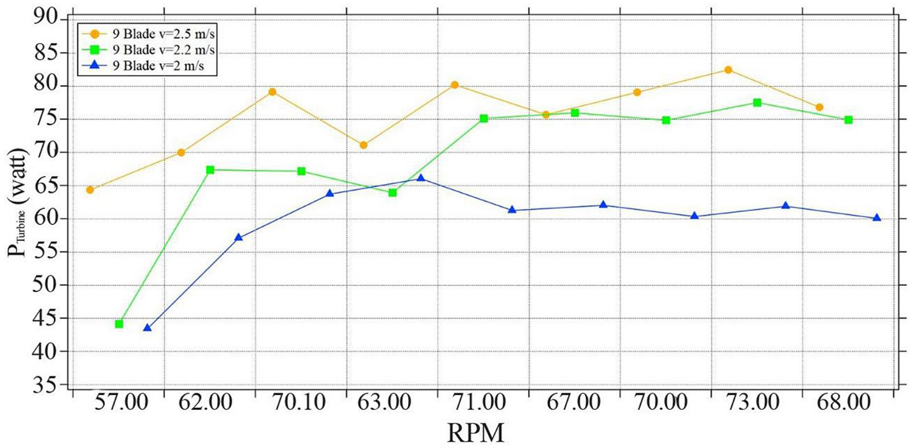

Figure 16. Comparison of turbine power ($P_{turbine}$) and rotation (RPM) with 9 Blades

and the least at a speed of 2 m/s. This relationship shows that at greater water speeds, the turbine spins faster and produces higher power.

Figure 17 shows the relationship between efficiency and turbine power for a 9-bladed turbine at three different water velocities of 2 m/s, 2.2 m/s and 2.5 m/s. At a water speed of 2 m/s, the efficiency ranged from 58% to almost 70%, with the turbine power increasing slowly from 61 watts to 63 watts. The increase in efficiency at this speed was relatively small but steady, indicating that at moderate water flows, the turbine was able to maintain good efficiency with fairly consistent power output. The 2 m/s water speed provides an optimal balance between efficiency and power, as the turbine is still able to produce high enough power without experiencing a significant drop in efficiency. When the water speed was increased to 2.2 m/s, the efficiency experienced a small drop initially, ranging from around 55% to almost 65%, with an increase in turbine power from 68 watts to 74 watts. Although the power generated was higher than at 2 m/s, the efficiency was not as high as expected, which may be due to the increased flow velocity not being fully utilized by this 9-bladed turbine design. On the other hand, at the higher water velocity of 2.5 m/s, the efficiency was even lower, starting from around 45% and increasing to around 55%. Although the turbine power increased from 76 watts to 81 watts, the decrease in efficiency at this speed shows that an increase in water speed does not always go hand in hand with an increase in efficiency. Overall, while higher water velocities can result in greater turbine power, efficiency tends to decrease at faster flows. A water speed of 2 m/s proved to provide the best balance between power generated and efficiency, as the turbine was able to achieve the highest efficiency without sacrificing power. In contrast, at 2.5 m/s, despite the greater turbine power, the efficiency decreased, indicating that the turbine was unable to fully utilize the faster flow. This suggests that the turbine design is most efficient when operating at lower to moderate water speeds, rather than at excessively high speeds, where power increases but efficiency decreases. The best efficiency is achieved at moderate water velocities, demonstrating the importance of a balance between water flow velocity and turbine design to maximize performance.

On the basis of the experiments that have been carried out using different numbers of blades, the following table and experimental data results are obtained (Table 1).

A clear approach to the influence of the number of blades on turbine performance is obtained based on the data presented. From the three variations in the number of blades above, the relationship between performance parameters goes in the same direction. The increasing speed of water entering the basin will increase the axillary water that can be maximized. However, in general, large water discharge will increase water performance very much. As shown in Figure 18, the turbine efficiency increases as the circulating water discharge increases.

A comparison of turbine efficiency can be seen in Figure 18, showing that with a blade number of 9, the turbine shows the highest efficiency among all variations in the number of blades. A water speed of 2.2 m/s achieves the highest efficiency of around 60%, followed by 2 m/s and 2.5 m/s which have almost the same efficiency values. This shows that a higher number of blades is very

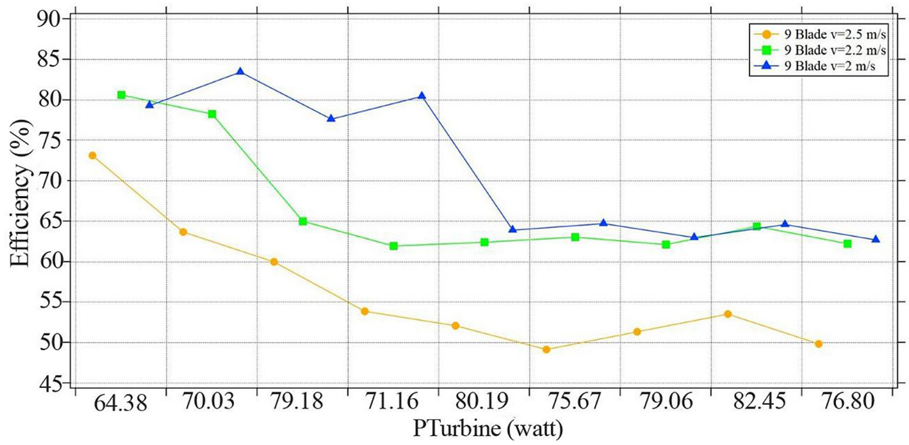

Figure 17. Comparison of efficiency (ηt) and turbine power ($P_{turbine}$) with 9 blades

Table 1. Experimental data

Number of blades	V_{air} (m/s)	m (kg)	F (N)	Torsi (N)	RPM	ω (rad/s)	H(m)	P_{turbin} (watt)	P_{air} (watt)	ηt (%)
5	2	3	29.43	5.89	79.5	8.32	0.7	48.98	95.85	51.10
	2.2	3.5	34.33	6.87	73.4	7.68	0.7	52.76	105.43	50.04
	2.5	4	39.24	7.85	78.0	8.16	0.7	64.07	154.04	41.59
7	2	3.5	34.43	6.87	76.4	8.00	0.7	54.91	95.85	57.29
	2.2	4	39.24	7.85	75.1	7.86	0.7	61.69	105.43	58.51
	2.5	5	49.05	9.81	85.0	8.90	0.7	87.28	154.04	56.66
9	2	4.5	44.14	8.83	67.1	7.02	0.7	62.01	95.85	64.69
	2.2	5	49.05	9.81	75.5	7.90	0.7	77.52	120.50	63.34
	2.5	5.5	53.95	10.79	73.0	7.64	0.7	82.45	154.04	53.32

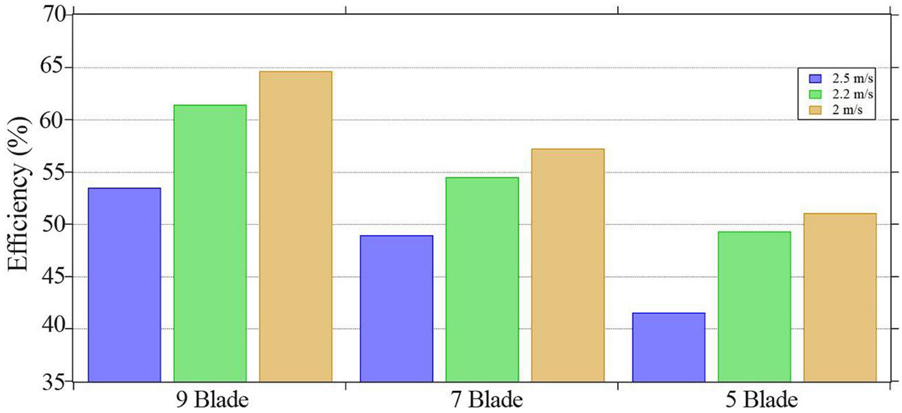

Figure 18. Graph of efficiency (%) of the turbine with varying number of blades (9, 7, and 5 blades) and three different wind speeds (2.5 m/s, 2.2 m/s, and 2 m/s)

effective in capturing water energy and converting it into power. With a blade number of 7, the turbine efficiency decreases slightly but is still around 50% for all water velocities. Water speeds of 2.2 m/s and 2.5 m/s have almost the same efficiency, while water speed of 2 m/s is slightly lower. This shows that despite reducing the number of blades, the turbine can still operate efficiently, although not as well as with 9 blades.

At 5 blades, the turbine efficiency decreases more significantly. A water speed of 2.2 m/s still has the highest efficiency at around 45%, followed by 2 m/s and 2.5 m/s with slightly lower values. This decrease in efficiency indicates that a smaller number of blades is less effective in capturing water energy, especially at higher water velocities. This graph shows that turbine efficiency is influenced by the number of blades and water speed. A higher number of blades (9 blades) provides the highest efficiency, especially at a water speed of 2.2 m/s. A decrease in the number of blades leads to a general decrease in efficiency, with lower efficiency at a water speed of 2.5 m/s when the number of blades is reduced to 5. This indicates that there is an optimal balance between the number of blades and water speed to achieve maximum turbine performance. The lower efficiency at a water speed of 2.5 m/s with a smaller number of blades shows that increasing water speed does not always increase efficiency if the number of blades is insufficient.

CONCLUSIONS

On the basis of the conducted research, the efficiency of the vortex turbine is 64.69%. In the previous research on the performance of the vortex turbine conducted by Kamil (2023), the efficiency was 43.11%, and by Ambarita (2023) was 45.1%. There was an increase in efficiency of around 19–21% by modifying the turbine blade.

The research gap that was bridged was the increased performance of the vortex turbine being tested. This research successfully bridged the gap regarding the impact of blade number and water flow velocity on the efficiency of gravity vortex turbines, providing experimental data that was previously limited, especially at the laboratory scale. In addition, the results of this study open up a variety of new prospects, including the development of turbines with optimal blade designs to maximize the balance between efficiency, torque, and production costs.

The research also hints at potential applications of gravity vortex turbines on a larger scale, such as micro-hydro power generation in remote areas with low water flow, as well as small-scale optimization of turbines that can be used as a renewable energy source for households or small communities. With these findings, this research contributes to developing gravity vortex turbine technology and its potential applications in the energy sector.

Acknowledgements

The author would like to thank the DRTPM of Higher Education, Ministry of Education and Culture of the Republic of Indonesia, for research funding assistance with contract number 95/UN5.4.10.S/PPM/KP-DRTPM/2024, and Research Institute of Universitas Sumatera Utara (Lembaga Penelitian USU).

REFERENCES

1. Ambarita, H., Hafid, B., Telaumbanua, I.T., Kamil, I., Napitupulu, F. 2023. Numerical and Experimental Study of Gravitational Water Vortex Turbine at Different Number of Blade, in Proceedings of the 1st International Conference on Sustainable Engineering Development and Technological Innovation. Tanjungpinang, Indonesia.
2. Bajracharya, T.R., Shakya, S.R., Timilsina, A.B., Dhakal, J., Neupane, S., Gautam, A., Sapkota, A. 2020. Effects of geometrical parameters in gravitational water vortex turbines with Conical Basin, Journal of Renewable Energy, 1–16.
3. Ciupageanu, D.-A. 2018. Variability assessment of renewable energy sources based on power generation recordings. 18th International Multidisciplinary Scientific GeoConference SGEM 2018. Albena, Bulgaria.
4. Dhakal, S., Timilsina, A.B., Dhakal, R., Fuyal, D., Bajracharya, T.R., Pandit, H.P., Amatya, N., Nakarmi, A.M. 2015. Comparison of cylindrical and conical basins with optimum position of runner: Gravitational water vortex power plant. Renewable and Sustainable Energy Reviews. 48, 662–669.
5. Edirisinghe, D.S., Yang, H., Gunawardane, P., Lee, Y-.H. 2022. Enhancing the performance of gravitational water vortex turbine by flow simulation analysis. Renewable Energy, 194, 163–180.
6. Fadhlurrahman, I. 2023. 10 daerah dengan Indeks Standar Pencemar Udara (ISPU) tertinggi di Indonesia per September. Jakarta.
7. Anderl, F. 2018. Rule and resistance beyond the nation state : contestation, escalation, exit. Edited by C.D.N.D.V.K.J.P. and P.W. Felix Anderl. Frankfurt: Published by Rowman & Littlefield International Ltd 6 Tinworth Street, London, SE11 5AL, UK.
8. Harding, D.M. 1984. Living water. Victor Schauberger and the secrets of natural energy', Forest Ecology and Management. 7(3), 238–239.
9. Institute for Essential Services Reform.2021. Indonesia Energy Transition Outlook 2022 IESR Institute for Essential Services Reform. Jakarta Selatan.
10. Kamil, I., Sitorus, T.B., Ambarita, H., Napitupulu, F.H., Abdullah, I., Sabri, M. 2023. Effect of variation in the number of inclined type blades and flow discharge on the performance of a vortex turbine using a cylindrical type basin. International Journal of Renewable Energy Research. 13(3), 1031–1038.
11. Kim, D.and Kim, D. 2021. Free-surface vortex formation and aeration by a submerged rotating disk. Chemical Engineering Science. 243, 116787.
12. Li, H.-F., Hong-xun, C., Zheng, M., Yi Z. 2008. Experimental and numerical investigation of free surface vortex. Journal of Hydrodynamics. 20(4), 485–491.
13. Nishi, Y., Sato, G., Shiohara, D., Inagaki, T., Kikuchi N. 2019. A study of the flow field of an axial flow hydraulic turbine with a collection device in an open channel. Renewable Energy. 130, 1036–1048.
14. Nishi, Y. and Inagaki, T. 2017. Performance and flow field of a gravitation vortex type water turbine. International Journal of Rotating Machinery. 1–11.
15. Rahman, M.M., Tan, J.H., Fadzlita, M.T. and A.R., Muzammil W.K. 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, 012007.
16. Saleem, A.S., Cheema, T.A., Ullah, R., Ahmad, S.M., Chattha, J.A., Akbar, B., Park, C.W. 2020. Parametric study of single-stage gravitational water vortex turbine with cylindrical basin. Energy. 200, 117464.
17. Sanchez, L. and Luan, B. 2018. The health cost of coal in Indonesia GSI REPORT.
18. Silalahi, D.F. et al. 2022. Indonesia post-pandemic outlook: strategy towards net-zero emissions by 2060 from the renewables and carbon-neutral energy perspectives, Indonesia Post-Pandemic Outlook: Strategy towards Net-Zero Emissions by 2060 from the Renewables and Carbon-Neutral Energy Perspectives. Penerbit BRIN.

19. Sritram, P. Suntivarakorn, R. and Suntivarakorn, R. 2019. The effects of blade number and turbine baffle plates on the efficiency of free-vortex water turbines. IOP Conference Series: Earth and Environmental Science. 257, 012040.
20. Vivekananda, S.V. 2019. Design and fabrication of gravitational vortex water turbine. International Journal for Research in Applied Science and Engineering Technology. 7(4), 331–342.
21. Timilsina, A.B., Mulligan, S. and 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.
22. Ullah, R., Cheema, T.A., Saleem, A.S., Ahmad, S.M., Chattha, J.A., Park, C.W. 2020. Preliminary experimental study on multi-stage gravitational water vortex turbine in a conical basin. Renewable Energy. 145, 2516–2529.
23. Warjito, Budiarso, Christopher, C.R. and Adanta, D. 2020. The effect of basin geometry on gravitational vortex hydropower. In: IOP Conference Series: Materials Science and Engineering. 788(1), 012081.