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Performance Testing and Analysis of Gravitational Water Vortex Turbine: A Modified Experimental Study on Blade Arc and Inclination Angle

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ABSTRACT

Dams' systems were constructed to create higher water levels as high as head for generating renewable power. However, the construction process has impacted environmental changes such as land dredging and displacement of population settlements. Therefore, using a micro hydro power plant is the one of the solutions because this power plant is environmentally friendly and could help to facilitate the balance of the environmental ecosystem. This study aims to investigate the performance of a Gravitational Water Vortex Turbine (GWVT) with the blade arc and inclination angles. A Gravitational Water Vortex Turbine (GWVT) is a form of micro hydro turbine that does not require a large dam for its use, as well as a simple design model that can reduce maintenance and installation costs. This study conducted a laboratory-scale experimental study on GWVT turbines using a low-speed water canal and considered the varied shape and angle of inclination of the turbine blade profile. A conical basin and three different discharge variations were considered in this study. The discharge variations are 7.5×10^{-3} m^3/s, 8.5×10^{-3} m^3/s, and 9.5×10^{-3} m^3/s. This study designed and tested a prototype L-type runner with three inclination angles: 60°, 70°, and 80°. Based on the data, the runner with 60° blade inclination with 90° blade arc angle produced the highest turbine efficiency, followed by 75° and 105° blade arc angles.

1. Introduction

In response to maintain the number of sources for future generations, we need to concern about long-term sustainable development action that provides a renewable energy source. Hydropower offers enormous potential to produce clean, affordable, and environmentally friendly energy, which is critical for a sustainable future and in response to energy concerns [1,2]. Small-scale hydropower generation without dams has been one of the most economical and environmentally friendly technological investments in recent years [3,4]. Conventional dam construction impacts ecological and environmental changes, river flow disruption, and even population relocation.

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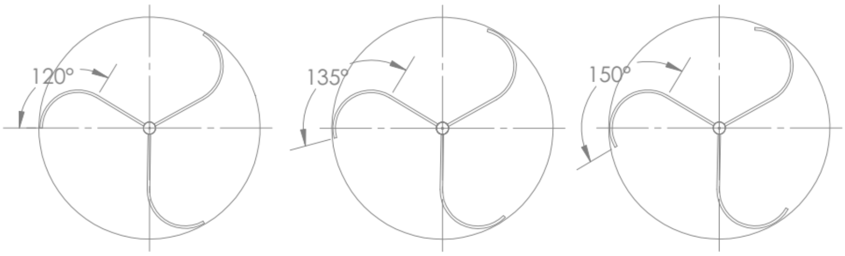
In remote places, rivers and lakes that continuously flow throughout the year have the potential as a place for installing micro-hydro power plants [5,6]. Hydropower potentials were categorized based on the capacities, such as pico (<0.005 MW), micro (<0.1 MW), mini (<1 MW), small (<10 MW), and large (> 10 MW). According to the world's gross hydropower potential usage, hydropower generations provide 10% of supplied energy from the world's total (10.74 million) energy consumption [7]. Gravitational Water Vortex Turbine (GWVT) is an example of a micro-hydro power turbine, as the highest power generated by GWVT is less than 100 kW. This turbine absorbs the vortex energy caused by gravity, which operates with a low head of 0.7 meters to 3 meters [8,9]. GWVT is an ultra-low head turbine with operational conditions ranging from 0.7 m - 2 m [7]. In the process of the invention of the GWVT, Franz Zotloterer was also looking for an efficient method to form a free surface vortex. Vortex is the basis for developing hydrodynamic turbines previously required to convert water energy. The Vortex turbine extracts the momentum of water from the vortex to drive the turbines. Else from the result of pressure differences, the turbine works due to the dynamic motion of the vortex [10]. The water flow enters the basin tangentially, rotates through the basin, and then flows to the output hole at the bottom [1]. The lower pressure on the orifice than the inlet basin causes the water flow forms a free surface vortex with a certain centre of gravity. Compared to most types of water turbines which only expose a portion of the blade, in the case of GWVT, water hits all of the blades so that the active turbine area is considerably greater [11]. The generated vortex will turn the turbine attached to the generator [1].

Various variations have been investigated to produce maximum turbine performance. A basin design that creates a free vortex surface facilitates the improvement of vortex turbine performance. Dhakal, *et al.,* [1] examined the structure of various basins using the ANSYS Fluent for computational fluids dynamic (CFD) simulation approach. Based on the simulation results, conical basins produce greater power output and production efficiency than cylindrical basins under the same inlet conditions and turbine position. The study of Srihari, *et al.,* [12] found that intensification of the vortex in a conical basin impacted the vortex power and increased the turbine efficiency. This study used Five configurations experimentally. The torque, power, and efficiency of the vortex turbine with a higher nozzle height of 200 mm had higher performance than the others. In addition, Chattha, *et al.,* [11] also found other factors affecting the generation of air vortices and the power generated by the turbine Inflow velocity, basin and orifice diameters, and basin aspect ratio are some of the parameters that have been studied. Moreover, the flow rate into the basin increases the head and vortex velocity [8].

Commonly, the configuration of the Vortex turbine affects the vortex turbine performance. Sritram and Suntivarakorn [2] investigated the effect of the number of blades and the additional baffle plates. Their study shows that the turbine performance depends on the number of blades, and the presence shows baffle plates. Wichian and Suntivarakorn [13] confirmed that additional baffle plates improve vortex turbine performance. Using the CFD approach, their study created a baffle plate with a 45 cm diameter and a 32 cm height. The results showed that five blades produced the highest torque with 50% baffle plates. Dhakal and Khanal [14] conducted an experimental investigation by adjusting the radius of curvature of the blade with the hub between 15°-25° with 1° intervals. They discovered that the optimal outcome is at 19° angle between the hub, and the blade, which generates 80% of efficiency. Saleem, *et al.,* [15] also investigated the impact of blade orientation on a vortex with a 90° configuration and a 68.5° inclination. The fundamental concept behind this improvement was to enhance the turbine performance to capture the power that was already present in the axial vortex velocity. The results showed the mechanical efficiency increased up to 10% with the 68.5° inclined angle. Nadhief, *et al.,* [16] conducted the research in designing and testing L-type Savonius turbine blades (Figure 1) with three blade angle variations of 120°, 135°, and

150°. The results showed that the L-type Savonius turbine with a blade angle variation of 135° produced the highest power coefficient of 27% at TSR 1.32 than the others. Therefore, this study investigated the improvement of vortex turbine performance with the blade arc angle [16] and blade inclination angle modification, as an earlier study has investigated the performance improvement of inclination angle with only two variations.



(a) (b) (c)

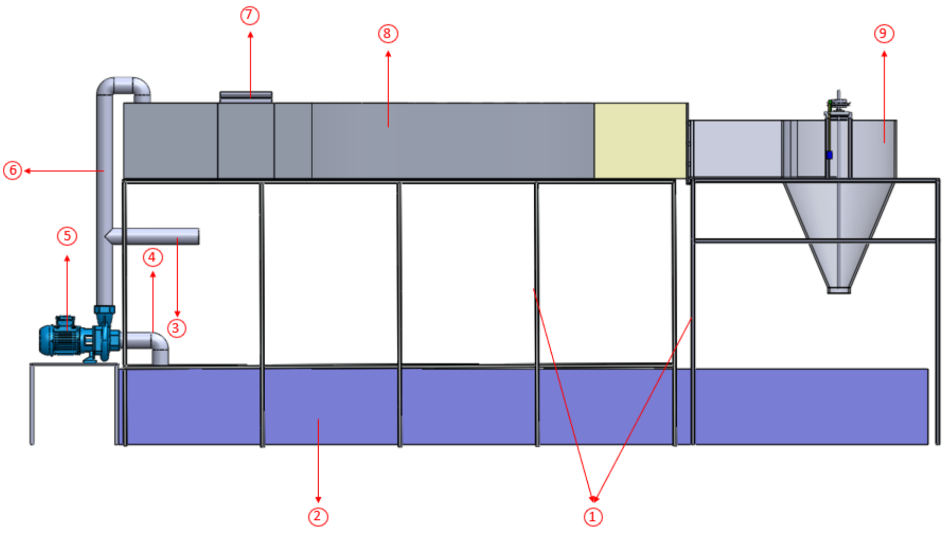
Fig. 1. Rotors Variation (a) Blade arc angle120° (b) Blade arc angle135° (c) Blade arc angle 150° [16]

2. Methods

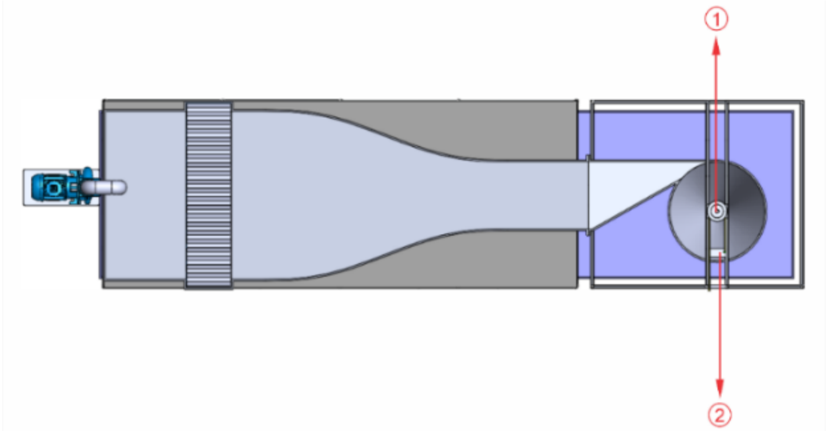
2.1 Experimental Set-up

This study analyses the performance of the vortex turbine runner using experimental methods to determine the turbine's optimal power and efficiency. The experiment uses a low-speed water canal with a concept resembling the flow conditions in a river. The water canal can accommodate 4,75 ×10-^{3}m^{3}/s of water. Figure 2 shows the settings for the test equipment to be utilized on a low-speed water canal.

Two centrifugal pumps are used to pump water into the canal. Basin design is made based on previous studies (Figure 3). The basin used in this study is a conical basin in which the basin produces a higher power output and efficiency compared to a cylindrical basin under the same conditions [14]. The water flow rate is controlled using a bypass channel that is installed on the outlet pipe to the lower reservoir. A honeycomb is installed near the pump outlet in the water canal. Turbine rotational speed is measured using a tachometer (KRISBOW KW0600563, Accuracy 0.05% + 1 digit), while the turbine torque uses a prony brake system [17]. This mechanism involves a pulley system with a diameter of 72 mm and a rope diameter of 2 mm. The water enters the conical basin and creates a free surface vortex after passing the honeycomb. The height of the water vortex (Hv) is measured directly using the measuring line on the basin wall [15]. The water flow rate is measured using the volumetric method, whereby the orifice hole is closed. We also measured how long the water would fill the canal with a known volume. The turbine is installed on the holder, which positions above the basin.



(a) Side view



(b) Top view

(c) Prony Brake System

Fig. 2. Low-speed water canal (a) Side view, (b) Top view, and (c) Prony brake system [17]

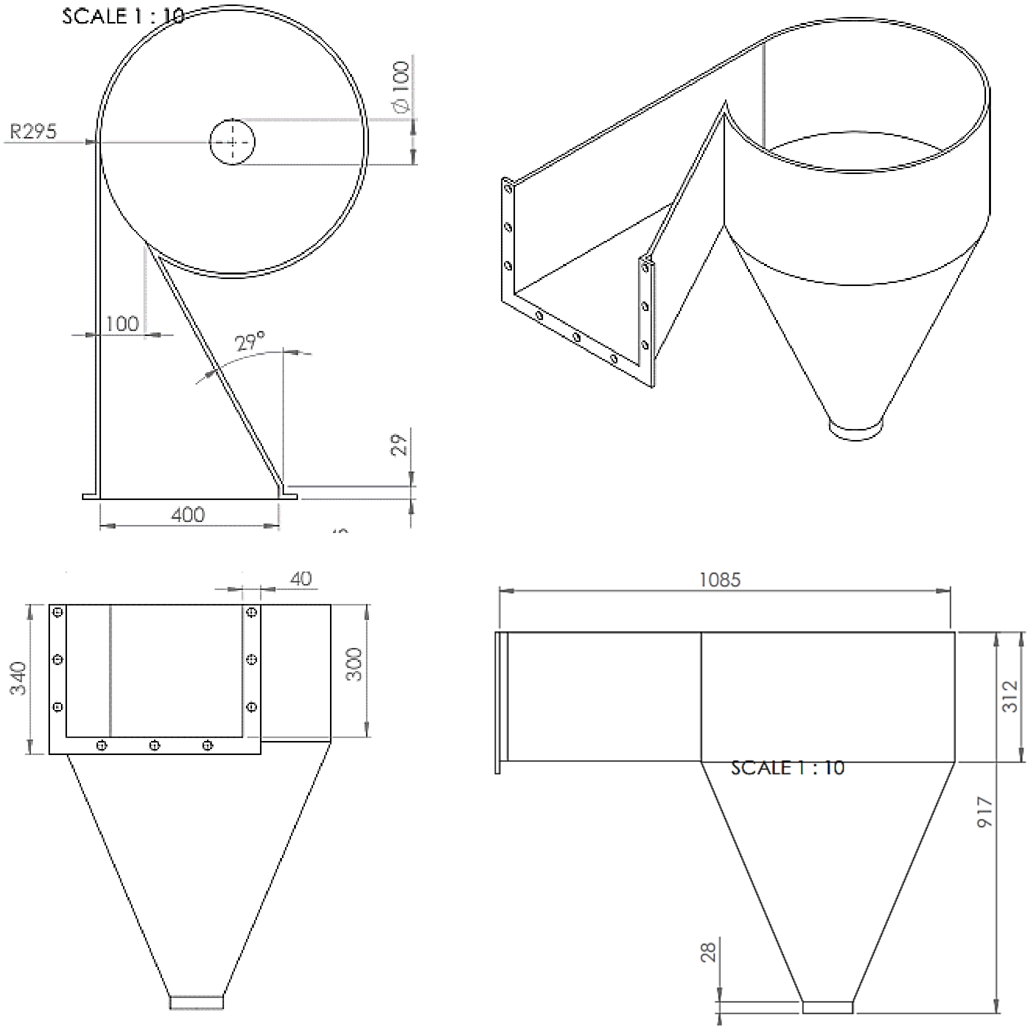


Fig. 3. Conical basin dimensions

Loads Measurement received by the turbine used a load cell installed on the Prony brake mechanism seen in Figure 2(c). Data were collected in this study using calibrated measuring instruments. Data was collected for three times in each variation to minimize the deviation error that occurred.

Table 1
Caption of Low-speed water canal

Side View	Top View
1. Frame	1. Pulley
2. Water Tank	2. Prony Brake Mechanism
3. Bypass Channel	
4. Inlet Pump	
5. Centrifugal Pump	
6. Outlet Pump	
7. Honeycomb	
8. Water Canal	
9. Conical Basin	

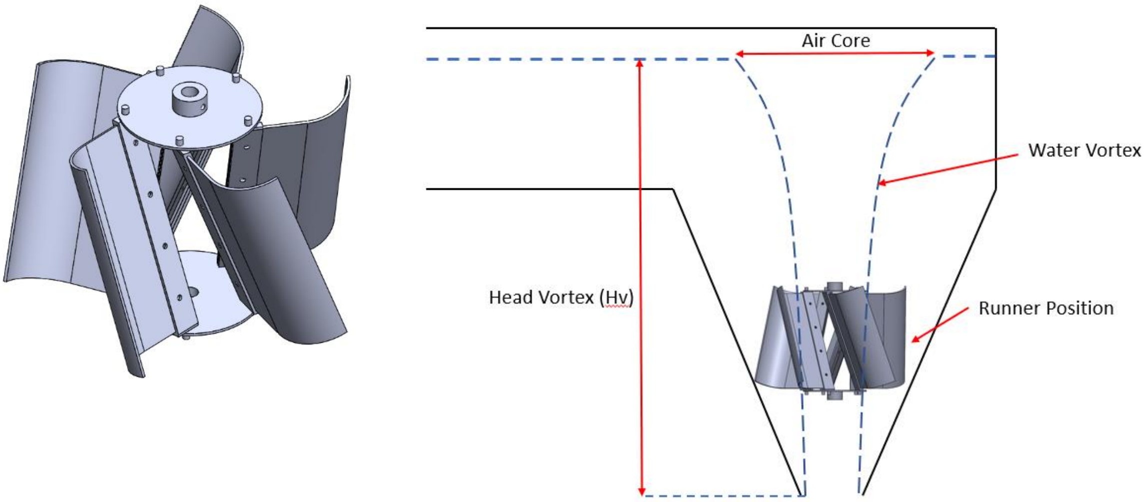
2.2 Runner Design

The researchers designed and customized the runner using several references considering the laboratory basin conditions. To assist in the design process, we used SolidWorks. When the design of one blade is adopted in Sritram and Suntivarakorn [2], the five blades reach the highest torque value [18]. The runner has an aspect ratio of W/H=0.5 with a value of W=80mm and H=160mm. (Table 2)

Table 2
Runner Geometry

Parameters	Value
Blade width	80 mm
Blade height	160 mm
Hub diameter	100 mm
Number of blades	5
Shaft diameter	12 mm
Blade inclination	60°, 70°, 80°
Blade arc angle	75°, 90°, 105°
Turbine material	Aluminium
Thickness	2 mm

Visualization design, position of runner, and runner geometry are attached in Figure 4 below [14].



(a) (b)

Fig. 4. (a) Vortex runner design (b) Schematic of GWVT

2.2.1 Variations of inclined angle blade

According to the literature, the blade's position and shape, especially its inclination angle, significantly extract more energy from fluids in the form of the water's tangential, relative, and axial velocities. Therefore, this study uses three different angles in the experiment: 60°, 70°, and 80°. The schematic of the inclined angle used for the experiment is shown in the following Figure 5.

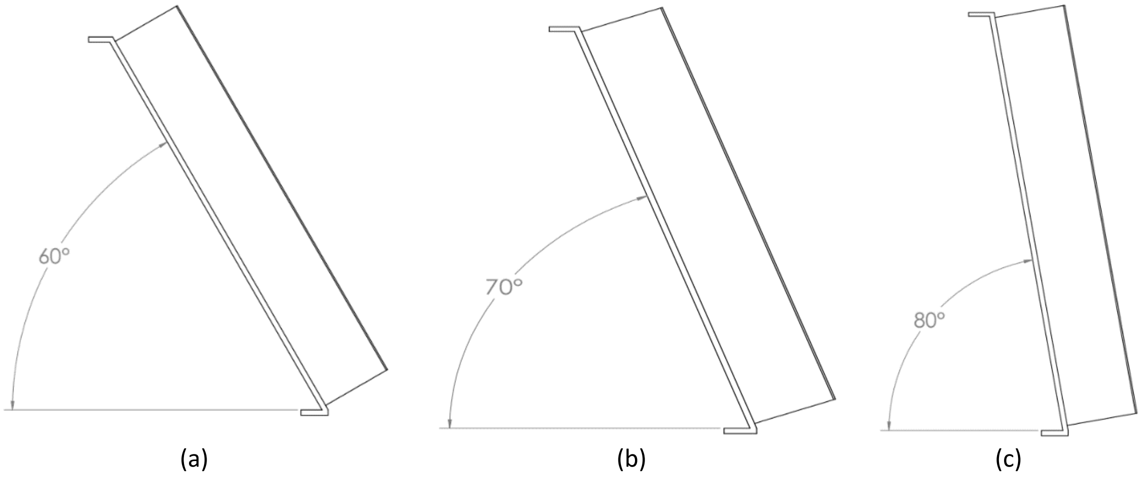


Fig. 5. Variation of inclined angle: (a) 60°, (b) 70°, and (c) 80° of blade

2.2.2 Variations of arc angle blade

This study investigated the blade form from the second variation during the experiment. The blade arc angle was defined by the shape of the blade, as shown by the information and visualizations in the following Figure 6. We used three different arc angles that were used as the same with the variations in inclinations angle. The difference between each value is 15°.

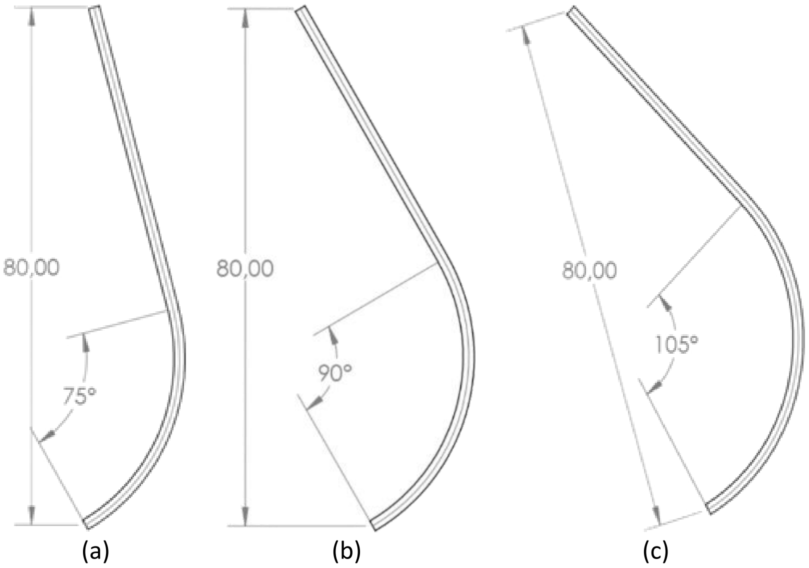


Fig. 6. Variations in arc angle (a) 75°, (b) 90°, (c) 105°

2.3 General Equations

Power input stored in the water canal and then rotated on the basin was calculated using Eq. (1), given equation as follows:

$$P_{in} = \rho\ g\ Q\ H_v \tag{1}$$

To determine the potential power, there are two parameters, which are water discharge and vortex head. The water discharge measurement in this study uses an ultrasonic flowmeter mounted on the pump output pipe. Meanwhile, the head measurement on the vortex turbine is done by measuring the height of the whirlpool with the orifice output hole [15]. The amount of power input depends on the vortex head (Hv) and how much the discharges ($m^{3/}s$) flow through the basin as well as the acceleration gravity (9.81 m/s^2) and the density of water (Kg/m^3) influence the forms of the free surface vortex forming. After that, energy from the rotating water was extracted using a runner to generate power output. The performance power output during the process is calculated using Eq. (2).

$$P_{exp} = T_{exp}\omega_{exp} \tag{2}$$

A pulley-belt transmission connects the rotating shaft to the Prony brake mechanism. By using this mechanism, the generated torque (Nm) is measured using a load cell and then calculated by Eq. (3). The angular velocity is transformed from rpm to rad/s using Eq. (4).

$$T_{exp} = r \times F \tag{3}$$

$$\omega = \frac{2\pi N}{60} \tag{4}$$

The runner does not entirely extract all the energy stored in the water. This issue frequently occurs because of energy loss during the processes as the pulley-belt transmission and the head cannot maintain a constant value. The percentage of efficiency was produced during the experiment according to Eq. (5).

$$\eta_{exp} = \frac{P_{exp}}{P_{in}} \times 100\% \tag{5}$$

3. Result and Discussion

3.1 Power Input

This study uses Eq. (1) to determine the power input available on a low-speed water canal. The three variations of discharges used in this study are $7.5\times10^{-3}m^3/s$, $8.5\times10^{-3}m^3/s$, and $9.5\times10^{-3}m^3/s$, which flow to the inlet water canal and enter the basin. We used an ultrasonic flow meter to measure the flowing discharges on the exit side. We also installed a valve that regulated the streams. We found that the different discharges, ordered from the lowest, produced different values on the head that reached 0.90 m, 0.97 m, and 1 m. Figure 7 shows a linear relationship between the discharge and head changes during increasing discharges.

The generated power input has directly proportional to increasing discharges (see Figure 8). Along with increasing discharge, the generated power inputs are 65.22 watts, 79.32 watts, and 92.93 watts. Therefore, the power input and head value depend on the discharges, correspondingly with Eq. (1).

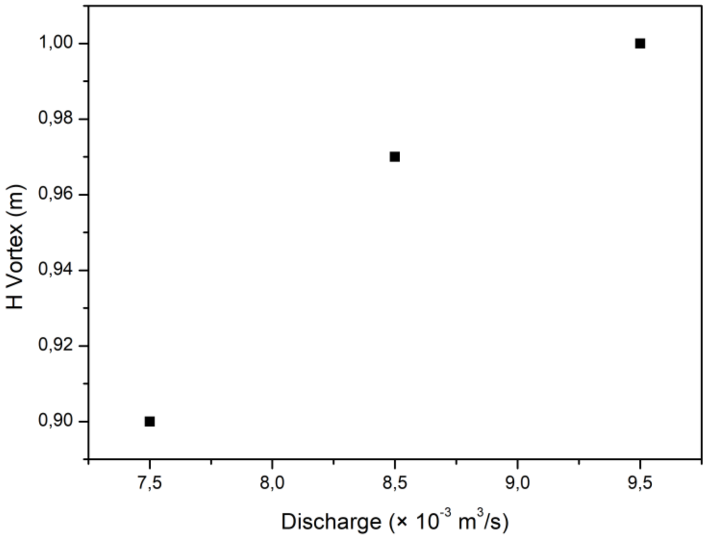


Fig. 7. The relations between the discharges and head

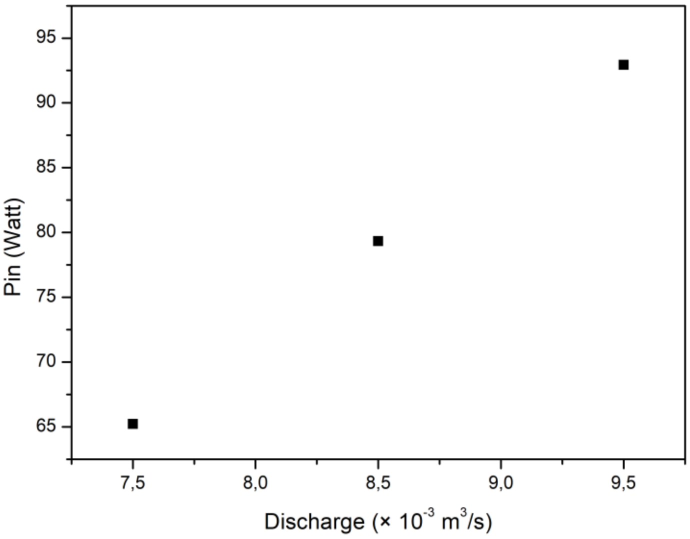


Fig. 8. Resulting power input each discharge

3.2 Performance Analysis Under 7.5×10^{-3}m^{3}/s of Discharge

The torque generated during the experiment was connected to the rotating shaft through a pulley-belt transmission and was measured using the Prony braking mechanism. This study proved that modified blades influence torque results. Figure 9 below shows the torque test result using 7.5×10^{-3} m^{3}/s of discharges. Compared to other turbines, the model with a 70°/90° (inclination/arc angle) produced the highest torque. The turbine should be inclined at the proper angle against the rotating water to catch the maximum energy before flowing out to the orifice hole.

The turbine should have an appropriate shape and arc angle to maintain the water flow before hitting the blade. The data shows that the maximum torque performance was 0.82 Nm, and the minimum was 0.75 Nm at 60°/105°. In addition, the 70°/90° blade was suitable for extracting maximum energy under 7.5×10^{-3}m^{3}/s discharges.

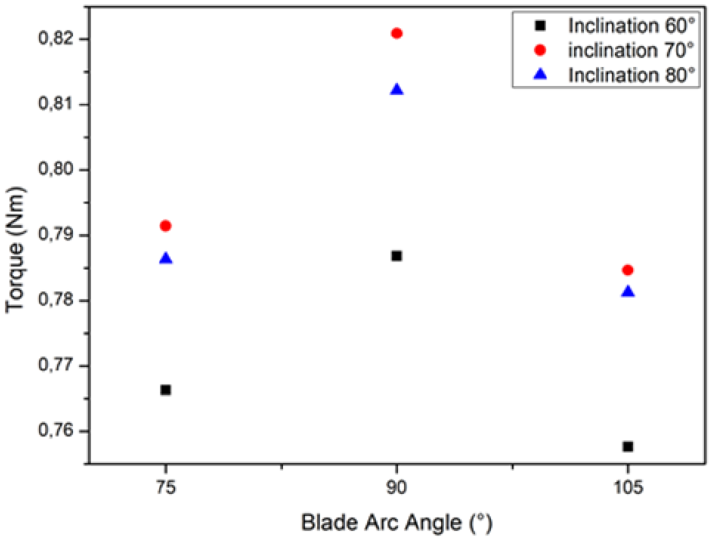


Fig. 9. Results on torque to inclination and arc angle variations under 7.5×10^{-3}m^3/s

The outputs or mechanical power was the main factor in determining the vortex turbine's generated performance. It was calculated using Eq. (2). Figure 9 shows the result of turbine mechanical power with variations in blade arc and inclination under 7.5×10^{-3}m^3/s testing discharge. Generally, the turbine shape or profile plays an essential factor in the performance turbine because the flow direction that hits the turbine depends on the configuration. Therefore, we should be concerned about the discharges and head available on location when considering turbines. Figure 10 below presents the highest mechanical power, which is always dominated by the blade profile arc 90° with an inclination of 60°. There are increasing number of power outputs on 75° to 90° arc angle, then drops from 90°to 105°. The highest power output generated is 16.02 watts. Meanwhile, the lowest production mechanical power reached 80°/75° blade profile with the generated power of 14.37 watts.

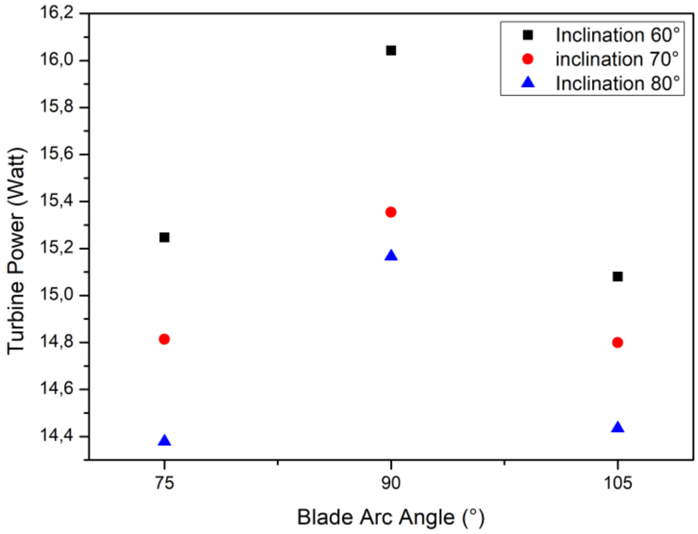


Fig. 10. Results on turbine power to arc and inclination blade 7.5×10^{-3}m^3/s

3.3 Performance Analysis Under 8.5×10^{-3}m^3/s of Discharge

The braking force that rushes up under the Prony brake usage was determined as the load received by the turbine. Figure 11 shows the torque graph with arc and inclination blade variations under 8.5×10^{-3}m^3/s. The 70°/90° profile produced the highest torque compared to others (see Figure 11), with a generated value of 0.98 Nm, while the lowest was produced by 60°/105° with a generated value of 0.91 Nm.

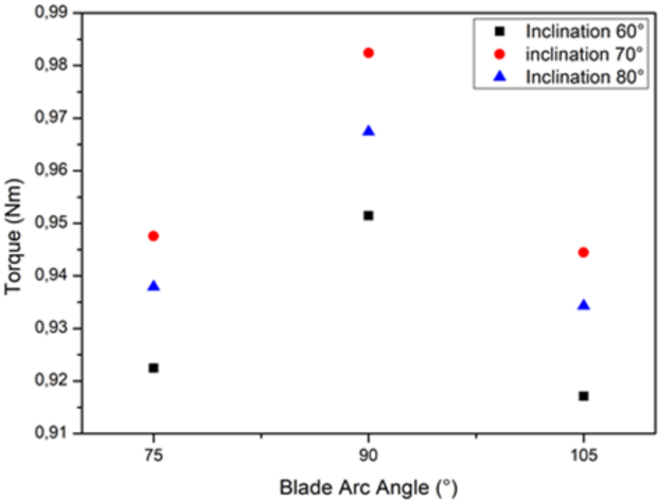


Fig. 11. Results on torque to arc and inclination blade under 8.5×10^{-3}m^3/s

When we applied the same discharge, we found that the resulting turbine power reached the highest value of 21.56 watts and the minimum generated power of 18.57 watts. The investigation turbine profiles under 8.5×10^{-3}m^3/s was proven to influence the turbine performance, with the profile 90°/60° reaching the highest generated turbine power. On the other hand, the 80°/75° profile generated the lowest turbine power because this turbine did not match the tangential flow direction when discharges changed. The resulting turbine power generated under 8.5×10^{-3}m^3/s shown in the following (see Figure 12).

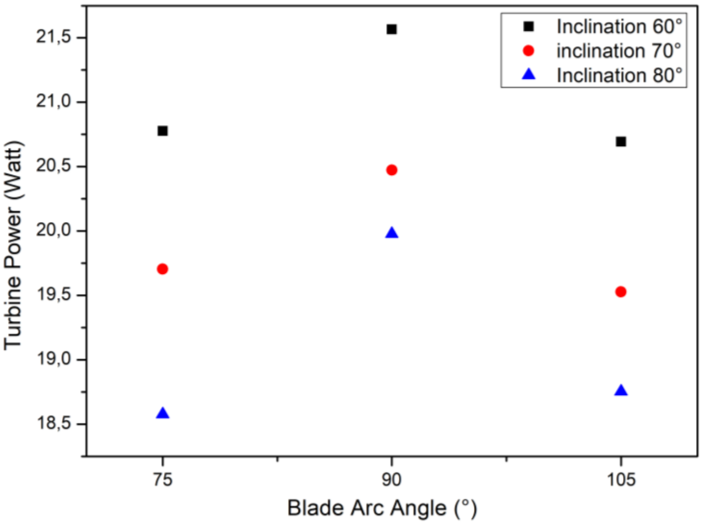


Fig. 12. Results on turbine power to arc and inclination blade under 8.5×10^{-3}m^3/s

3.4 Performance Analysis Under $9.5\times10^{-3}m^3/s$ of Discharge

The discharges produced the highest torque and mechanical power compared to others under $9.5\times10^{-3}m^3/s$. Based on Eq. (2), we confirmed that the available power input stored in the water canal depends on the number of discharges. The power input has a linear relation to the generated turbine power and torque, which can be inferred that the increased power input raises the value of torque and turbine power. The relations between produced torque and blade profile are presented in Figure 13.

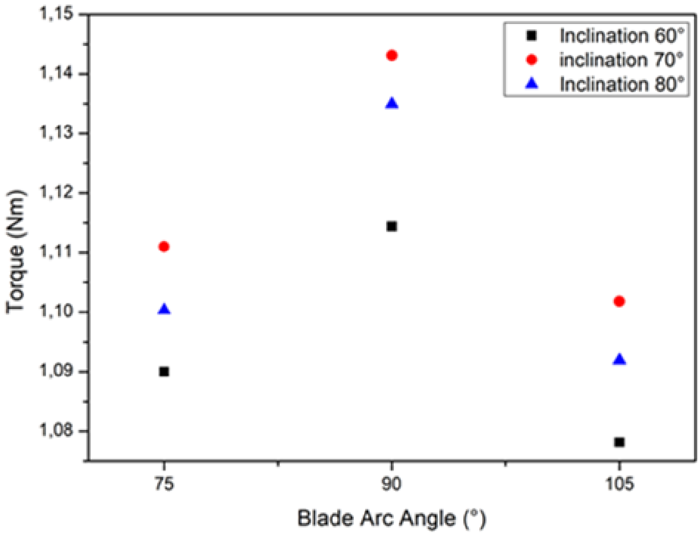


Fig. 13. Results on torque depending arc and inclination blade under $9.5\times10^{-3}m^3/s$

Profile 70°/90° was the torque result with a value of 1.14 Nm. It consistently performed better in extracting the energy stored in water. Its profile changed in the tangential flow direction under maximum discharges. This great reversing performance was produced by a 60°/90° profile with only 1.07 Nm of torque. Generally, the turbine power has the same algorithm with resulting torque under maximum discharge. The torque generated by all inclination blades rose at 90° of blade arc angle with 2.01 Nm as the highest torque, and then down to 105° of blade arc angle. The turbine power depends on the shape or profile, significantly affecting the performance [7].

The efficiency is demonstrated by comparing the vortex turbine's extraction power to the available power input stored in a low-speed water canal. Generally, the generated efficiency has linear relations with the increasing discharges (see Figure 15). According to the processed and analysed data, maximum turbine efficiency was reached by a maximum discharge of $9.5\times10^{-3}m^3/s$, which aligns with [12] and [19]. The profile modification blade was proven to influence the generated efficiency. Some minor cases were presented in Figure 15, and the 80°/75° and 80°/105° profiles resemble the trendline efficiency graph, followed by the 70°/75° and 70°/90° profiles. These cases indicated that arc angle variations have not significantly influenced the performance of vortex turbines. It depends on some conditions. However, compared to the other profile, a turbine with a 60°/90° profile has the highest dominant generated efficiency for each applied discharge condition. The 60°/90° profile generated the maximum efficiency, respectively 24.28 %, 26.77 %, and 28.01 %, from the minimum to maximum applied discharges. Figure 15 below presents information about the general data efficiency generated by each vortex turbine profile.

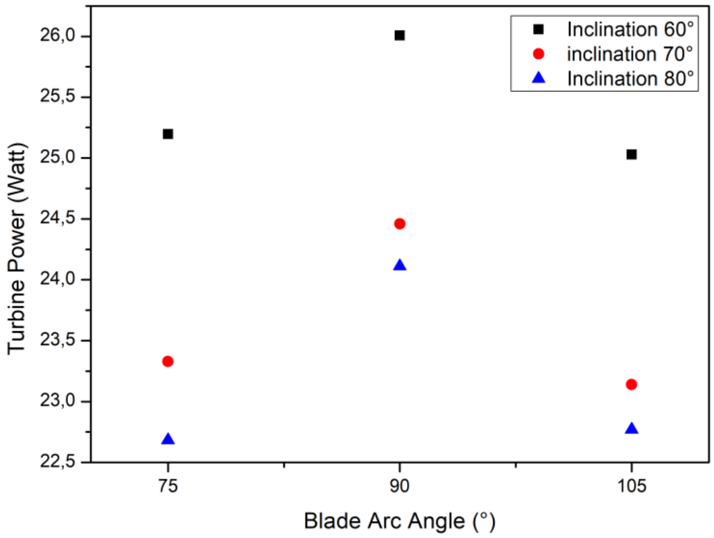


Fig. 14. Result on turbine powers on arc and inclined blades under $9.5\times10^{-3}m^3/s$

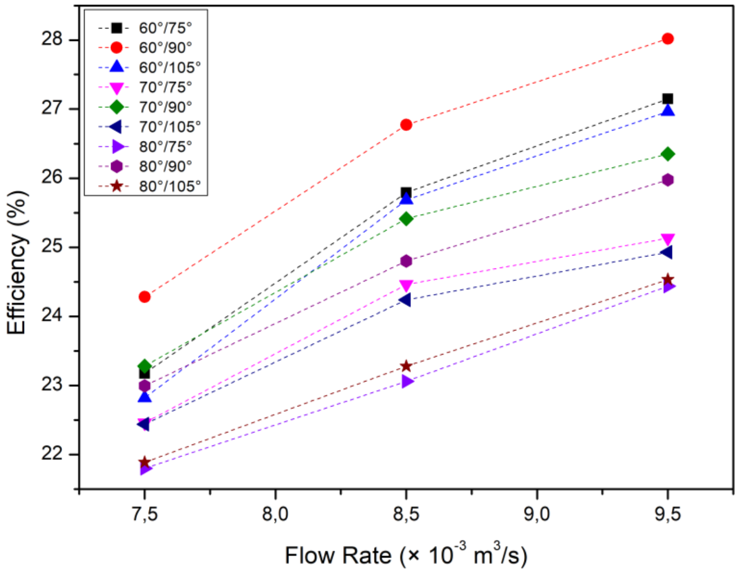


Fig. 15. Results on the efficiency of arc and inclined angle

4. Conclusions

We conducted this study to investigate the performance of a modified vortex turbine by considering its inclination and arc angle blade. The cumulative data were calculated and analysed using a commonly general equation and the measurement process. Based on experimental results, the modified runner using blade inclination and arc angle improves vortex turbine performance. This study measured the turbine's performance considering three aspects: torque, turbine power, and efficiency. Each variation turbine profile generated various values. There are differences within the modified runners while extracting energy.

The rotating water through the basin has different tangential velocities for each applied discharge. Turbines with profile shapes that match the tangential flow direction have generated maximum performance. Variation in the arc angle gives the turbine a different concave profile, as the concave side was assisted in holding some of the water mass and reducing the negative torque. The best turbine performance reached a profile of 60°/90° with 26.01 watts of turbine power and 1.14 Nm of the maximum generated torque. The highest turbine efficiency is obtained in the variation of blade inclination 60° blade arc angle 90° at a discharge of 9.5×10^{-3} m^3/s with a value of 28.02%. Generally, the maximum torque, turbine power, and efficiency performances are always generated at the maximum discharges of $9.5\times10^{-3} m^3/s$ as they have a maximum stored energy. The limitation of this research is further analysis of the vortex formed where there are three components of speed in the vortex that can be used to rotate the turbine runner. Researchers suggest further analysis of the whirlpool and measuring instruments used to calculate the speed of the whirlpool from its various speed components so that it can be used to design turbines with the most optimal design.

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