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Design of Archimedes Screw Turbine by Multi-step Selections on Parameter Pitch Distance, Blade Number, and Blade Angle

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Abstract
One of the water turbines called an Archimedes screw turbine (ASTs) is appropriate to run in a low head of just less than 5 m and works at a wide range of discharge operations. The performance of the turbine is influenced by some aspect that requires optimization. The research aims to characterize turbine performance by selecting the pitch distance of the blade, the number of blades, and the angle of the blade. Initiated by developing Archimedes screw turbine of 500 mm length and blade diameter of 100 mm, using screw blades at different distances of 50, 70, 100, 200, and 300 mm. Then continue to select blade numbers of 1, 2, and 3 respectively, while kept constant optimum distance of blade. Once the optimum number of blades and blade distance were achieved, followed by selecting blade angles of 23^o, 28^o, and 33^o, the optimum blade distance and number were kept constant. Acquisition data developed covers turbine speed (rpm), voltage (V), current (A), and power (W) measurements. The result of the research was optimum blade achieved at blade distance of 100 mm, blade number of 1 and optimal blade angle of 28^o, its produce debit of 0.0034 m^3/sec at turbine speed of 410.77 rpm, voltage generator of 79.82V with current of 0.0067A, and power of 0.55 Watt in efficiency of 33%, coefficient of performance (C_p) of 0.33, as well as tip speed ratio (TSR) of 2.56.

Keywords- ASTs, Optimization, Efficiency, C_p, Tip seed ratio.

1. Introduction

Electrical energy has an important role in everyday life. The community's need for electrical energy is very high and the distribution of electrical energy is uneven, especially for remote areas, so the supply of electrical energy has not fully met the community's needs. In Indonesia and other developing countries, there are still huge potential energy sources that can be converted into electrical energy, one of which is water. One of its uses is for Micro Hydro Power Plants (MHPP) (Bustomi et al., 2021). MHPP is a power plant that uses hydropower as a driving force by utilizing the height and discharge of water on a small scale such as in irrigation, rivers, or waterfalls. MHPP is very suitable for application in Indonesia because of its abundant water resources and is an environmentally friendly technology (Elbatran et al., 2015; Doost and Lubitz, 2020; Triasdian et al., 2020).

Various types of turbines are commonly used in MHPP, one of which is the Archimedes Screw Turbine (ASTs). Archimedes screw turbines have the advantage of not destroying the ecosystem and are suitable for use at low heads, making them suitable for use in rural areas or remote areas. However, the design of screw turbines is highly site dependent and there is currently no general standard for optimal design (Waters and Aggidis, 2015; Piper et al., 2018; Abdillah et al., 2022). Ubando et al. (2022) reported on the manufacturing process using modern technology namely 3D printer's model.

Center for Micro-Hydro Power Plants with Low Heads, researchers modeled micro-hydro power plants using Archimedes Screw Turbine with variations in the angle of the blades on screw turbines starting from 24^o, 26^o, 28^o, and 32^o. The specifications for screw turbines are with a blade spacing of 21 cm, a screw width of 10 cm, a turbine diameter of 26 cm, a turbine shaft diameter of 6 cm, and a turbine shaft length of 150 cm. The best blade angle was stated, as well as the rotation turbine and output work. In this study, there is no detailed explanation of the optimal distance and the number of blades (Lisicki et al., 2016; Songin, 2017).

Another micro-hydro power plant uses an Archimedes screw turbine (Archimedes Screw Turbine) carried out by (Bustomi et al., 2021; Misbah et al., 2021).

The turbine is made with a thread length of 1 m, an outer diameter of 30 cm, many blades of 15, and a pitch distance of 13 cm, and the angle of the turbine is 30°, 35°, and 40°. This research was conducted by measuring the water discharge by modeling a micro-hydro power plant, namely by dividing the volume of the vessel per time to fill the vessel. To achieve a better water discharge, the water discharge is dammed, so that the resulting discharge is more optimal. Then by using the first two designs without a deflector and the second with a deflector each variation of the turbine tilt is 30°, 35°, 40°. The first test run is carried out with the deflector positioned between the screw and the shaft on the same side along the screw sleeve. A deflector was employed to get optimal performance. After the first trial was completed, the second trial was carried out without a deflector with the same turbine tilt variation. The results showed that the addition of a deflector reduces the resulting screw turbine rotation. Again, in this study, there is no detailed explanation of the optimal spacing, number of blades, and thread angle (Shahverdi et al., 2019; Shahverdi et al., 2021). A separate study was carried out by Nurdin et al. (2020), in this study, there was no explanation of the detailed measurement methods regarding Arduino or digital.

In a study by modeling an Archimedes screw turbine with two blades made of stainless steel with a pitch size specification of 2Ro, an inner radius of 0.077 m, an outer radius of 0.1435 m, and a turbine length of 2 m. And for the variables tested are turbine rotation, torque, and flow rate.

The research method was explained in detail, and the study's results stated that to obtain maximum torque and power, the flow conditions must be maintained at the highest water discharge conditions, even though the efficiency values obtained are not optimal. The maximum power and efficiency obtained occurs at a flow rate of 0.02 m^3/s, proved in a slope angle of 30°. The turbine explains that the higher the distance the water falls from the tip of the v-notch, the greater the resulting flow discharge. In this study, there is no detailed explanation of the optimal spacing, number of blades, and screw angles as well as Arduino or digital measurement methods (Maulana et al., 2019; Supriyono and Siswanto, 2019).

Research on the design of Archimedes single-screw turbine construction based on the effect of flow rate on rotation, torque, power, and efficiency. Then this research can determine the right and good turbine design and performance in the manufacturing process. In this study, the Archimedes screw turbine is made of stainless steel 201 which has specifications N = 1 blade (Ro = 130 mm, Ri = 70 mm) with a pitch of 2Ro, turbine length (L = 2 m), head = 1 m, Angle = 30 the variables measured and observed were turbine rotation, torque, and flow rate. In conducting the research carried out at 3 variations of flow rate, namely 0.02 m^3/s, 0.009 m^3/s, and 0.003 m^3/s. From the test results, the highest turbine rotation and power occur at a discharge of 0.002 m^3/s at 236.40 rpm with a power of 116.10 watts and the resulting efficiency is 57%. Thus, the turbine with the maximum power and efficiency obtained occurs at a flow rate of 0.02 m^3/s. Proving that with a 30° slope angle on the turbine, it explains that the higher the distance the water falls from the v-notch tip, the greater the resulting flow discharge. In this study, there is no detailed explanation about the optimal distance, number of blades, and screw angle, nor about the variable measuring system used (Lashofer et al., 2012; Lyons and Lubitz, 2013; Lyons et al., 2014; Syam et al., 2019; Sari et al., 2021).

In a study investigating the effect of angle on the effect on performance of the Archimedes screw turbine, it was carried out with a discharge flow of 0.00106 m3/s at an angle of 36° to 44° and three different loads. Based on the results of the experiments conducted, the higher the angle, the more power is produced, but the efficiency produced is less, because the effective head value increases, proving that the angle does not affect the amount of power produced. In addition, that overflow event causes losses. When the angle increases in this case it is not accurate because it is more influenced by the load value of α or the angle value. Thus, the angle value does not significantly affect turbine performance. Considering some of the research above and considering the experiments of team members who have studied the optimal pitch distance and other teams optimizing the optimal number of blades in this study this experiment will be focused on optimizing the optimal pitch distance to get turbine performance (Lubitz et al., 2014; Siswantara et al., 2019).

Related context of study to evaluate the analysis of the effect of changes in the number of blades and the angle of blade inclination of Archimedes screw turbines in pico-hydro power plants, power calculations related to the number and inclination of turbines with the conclusion that the peak when the turbine is tilted 30° on a generator with 1 blade gets the greatest power of 14,407 watts, and on a turbine generator with 2 blades get the greatest power of 13,661 watts. The use of screw turbines by utilizing low water flow energy and converting it into a permanent magnet generator driving power to generate electricity. The output from the generator is in the form of AC voltage until it is rectified later with the rectifier and capacitor (Kastawan et al., 2022).

Another study has been done in finding best performance of ASTs by changing pitch, length and blade elevation. The study was also carried computationally. There is not clear conclusion than that is a Archimedes turbine is potential to use. Meanwhile, in the interest of optimization of ASTs there have been undertaken in specific mean that performance of coefficient was evaluated. The response method was used to determine coefficient of performance. The numerical meant was used in investigating parameter on the

effect of turbine performance. Some parameter was used in validating between CFD and experimental, prediction value was derivate from a validity in reduce second order regression model. Other context was study by optimizing size of screw turbine discussed, simulation model was made to determine mechanic efficiency related with geometry parameter, study was emphasizing on finding best turbine efficiency. All study was due to their consent in finding alternative energy using Archimedes screw turbine hydropower (Rohmer et al., 2016; Shahverdi et al., 2019; Abdullah et al., 2020; Bouvant et al., 2021).

In finding and developing the renewable energy sector responding to emission increase, non-renewable fuel endless, and fulfill the requirement for electricity in front areas. Water turbines are well known to have a high potential in generating electricity source. The objective of this working paper is to address a new floating turbine concept and analyze it using Computational Fluid Dynamics (CFD). The CFD was used and A grid freedom study and boundary sensitivity study were undertaken to convince the validity of the result. The sliding mesh model measured the work of the turbine. It seems that the aim turbine has significantly more work than common Savonius turbines, from 0.1 to 0.42 and 0.8 to 1.3 Cp (Turbine work) and TSR (Tip Speed Ratio), respectively (Al-Quraishi et al., 2021).

Considering much previous research, it is challenging to conduct to optimize screw angle, pitch distance, and number of blades comprehensively on Archimedes screw turbines. The problem is that there is no reference or proper information on how to determine the configuration of the Archimedes screw turbine for good efficiency. This research offers the determination of the working efficiency of the Archimedes screw turbine through a multi-step selection process in stages, determining the pitch distance, selecting the number of blades, and determining the size of the blade slope simultaneously and sequentially.

2. Research Methodology

This research tries to find the optimum performance of the Archimedes screw turbine in terms of optimum pitch distance, the best number of blades, and the optimum blade angle from the horizontal axis. The research was initiated with the first step by designing a five-blade turbine at different pitch distances of 50, 70, 100, 200, and 300 mm. as shown in **Figure 1**.

Figure 1 shows the front and side view of 5 type blade model with pitch distance of 50 mm (1), pitch distance of 70 mm (2), pitch distance of 100 mm (3), pitch distance of 200 mm (4) and pitch distance of 300 mm (5). The outer and inner blade diameters are 100 mm and 30 mm respectively. All blade angle is set as 28^{o}. From five models then optimum performance was selected as a reference to the forthcoming experiment.

Once the first design was tested and the optimum pitch distance was found, the next three model blades were produced in different numbers of blades and tested to get the optimum performance of the turbine. **Figure 2(a)** shows three different numbers of blades, whilst the optimum pitch distance was kept constant at 100 mm, the blade angle remained constant at 28^{o}. Further specimens were produced of three blade models in different angles of the blade from the horizontal axis of 23^{o}, 28^{o} and 33^{o} shown in **Figure 2(b).**

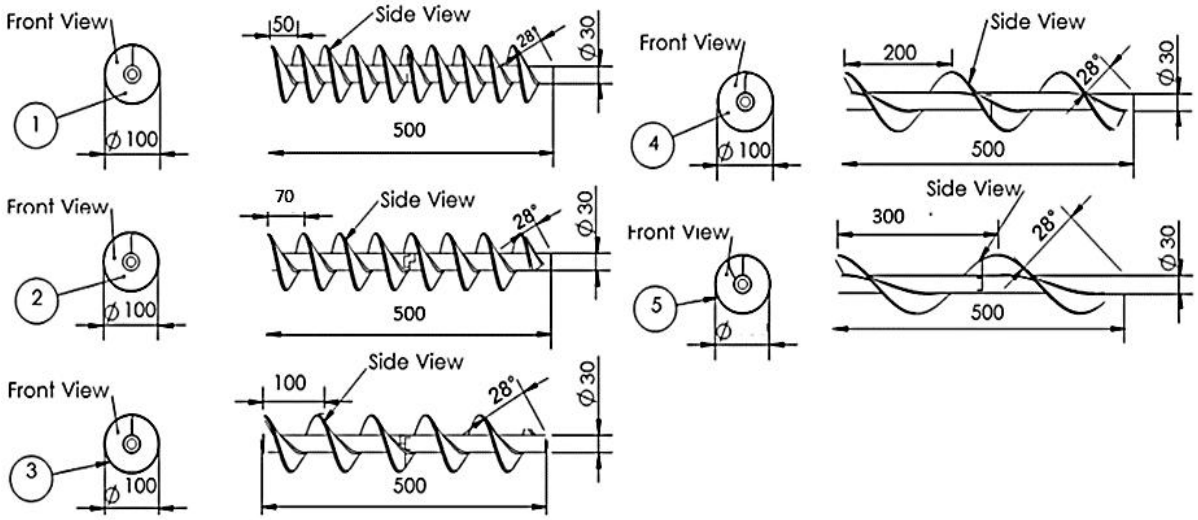
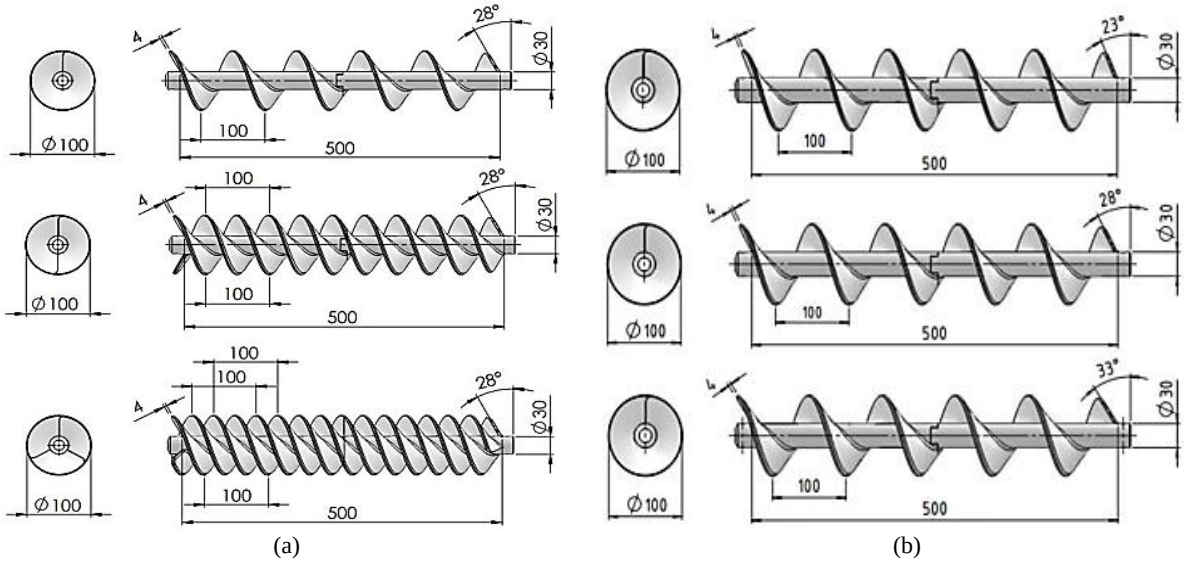


Figure 1. Dimension of the turbine in a variety of pitch distances.



(a) (b)

Figure 2. Turbine dimension in (a) different blade numbers of 1, 2, and 3 and (b) three different blade angles.

Three scenario models were designed and then realized with the production of a three-dimensional model using three-D printing. One of which is five models in different pitch distances the other is three models in different blade number models and then three models in different blade angles from the horizontal axis as follows:

(a). 5 model blades in different pitches (b). 3 models of blades in different numbers (c). 3 models of the blade at different angles

Figure 3. Screw blade model resulted from three-D printing.

The investigation was conducted experimentally at the mechanical engineering laboratory Universitas Muhammadiyah Surakarta Indonesia. The suction apparatus was constructed as the following **Figure 4**.

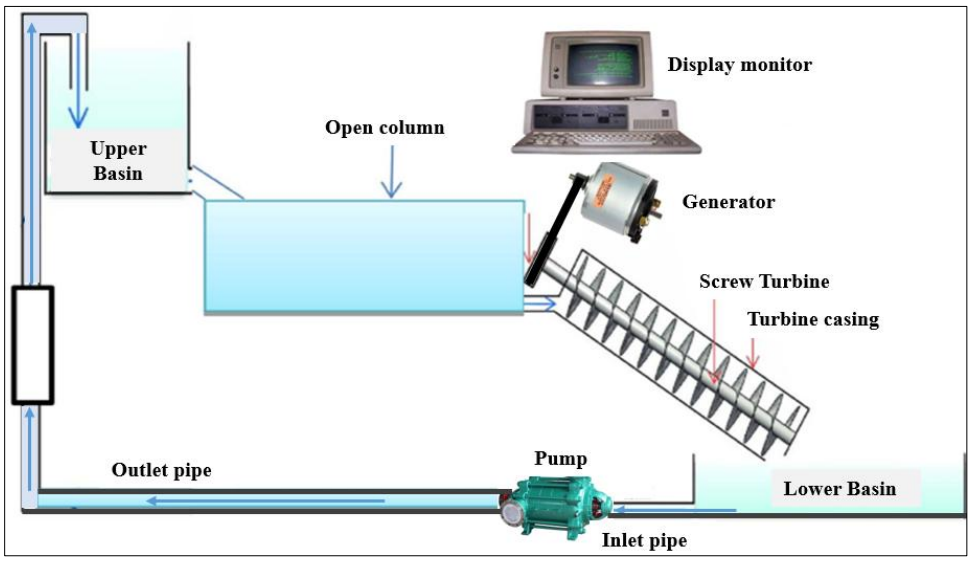


Figure 4. Section apparatus.

Measurement of selected variables in experiments such as turbine rotation, current, and voltage is done by developing Arduino-based data acquisition and then the reading is viewed on the computer monitor screen. While the water discharge is measured through a V-notch weir model, by measuring the height of the overflow at the V-notch, using the formula as follows:

$$Q = \frac{8}{15} \cdot Cd \cdot \sqrt{2 \cdot g} \cdot \tan\frac{\theta}{2} \cdot H^{2.5} \quad (1)$$

where, Water volume flow rate, Q (m^3/s), Coefficient discharge, Cd (0.6), gravitational force, g ($9.81 m/s^2$), angle of V-notch weir meter, θ (90^o) and height of V-notch water level, H (mm).

The Coefficient of Performance (Cp) is the ratio of the power generated to the available air power.

$$Cp = \frac{P_{out}}{P_{in}} \quad (2)$$

where, Coefficient of Performance, C_p, Power generated, P_{out} (W) and Hydraulic power, P_{in} (W)

Tip Speed Ratio (TSR) is the ratio of the turbine blade tip speed to the incoming water flow speed.

$$\omega = \frac{2 \,.\, \pi \,.\, N}{60} \quad (3)$$

$$\lambda = \frac{\omega \,.r}{v} \quad (4)$$

where, Angular velocity, ω (rad/s), velocity flow, v (m/s), turbine speed, N (rpm), tip speed ratio, λ (TSR) and turbine gyration, r (mm).

The experiment steps can be seen as a flow chart diagram in **Figure 5** as follows:

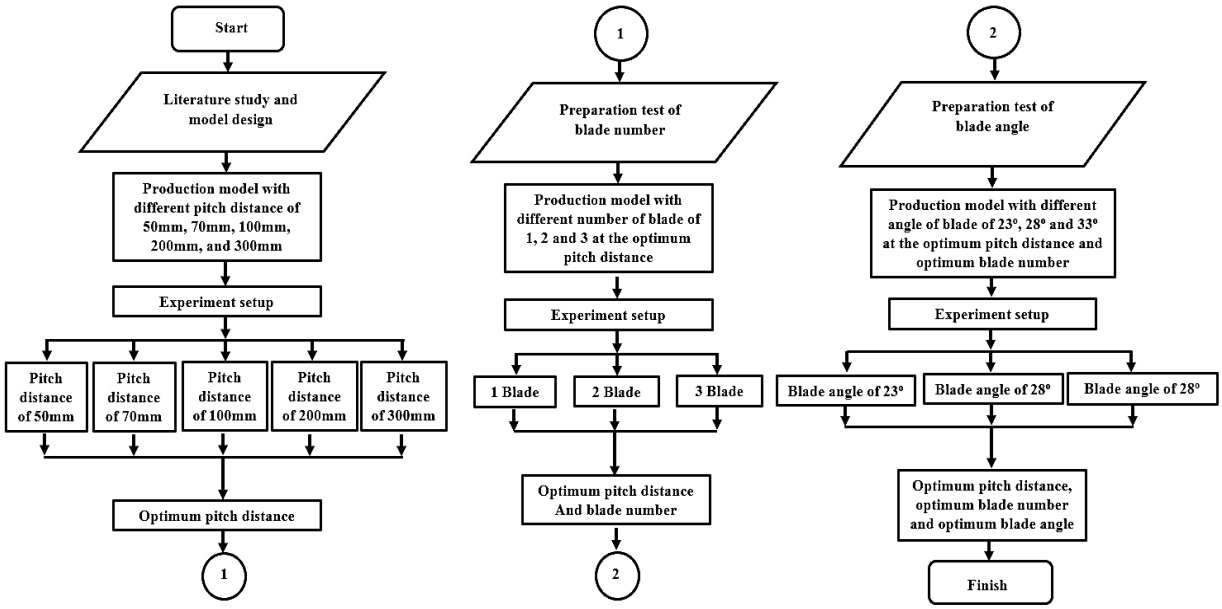


Figure 5. The experimental steps.

3. Results and Discussions

In this study, the performance of the turbine was derived using a series of correlations. First was the test to investigate the best performance of the turbine in different pitch distances. Following to initial step then work was continued to get the best correlation of blade number, and finally, ended with investigating the best blade angle from the horizontal axis.

3.1 Correlation of Pitch Distance and Rotation of the Turbine

The experiment results in data that is not shown in this section covering turbine revolution versus pitch distance in various water volume flow rates, Q of 0.0012, 0.0018, 0.0025, and 0.0035 m^3/sec, in different

pitch distances provided. The corresponding chart for the whole volume flow rate investigated in conjunction with the data collected versus generator speed can be expressed as the following **Figure 6**.

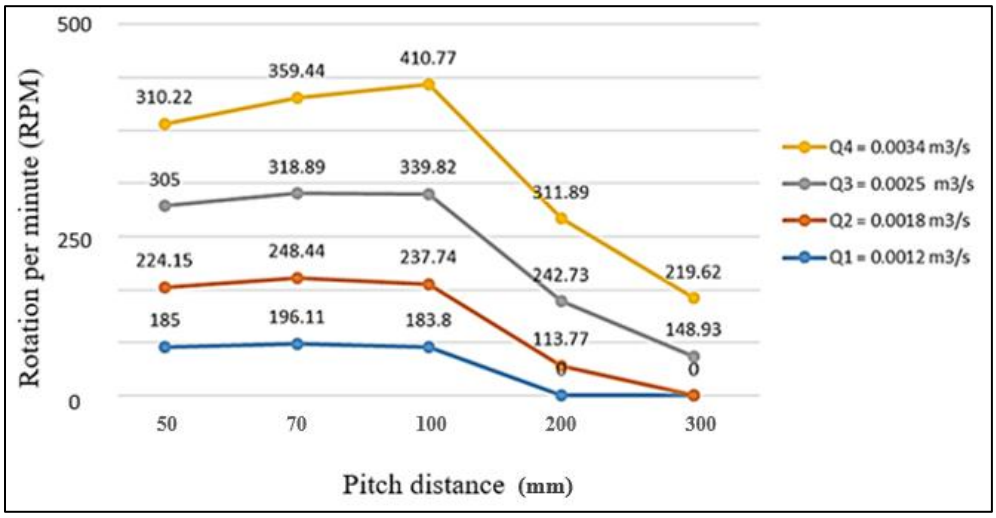


Figure 6. Correlation of pitch distance versus turbine rotation per minute.

In volume flow rate (Q1) of 0.0012 m^3/s at a pitch distance of 50, 70, and 100 mm, a rotation speed turbine was slightly increased from 185, 196.11, and 183.80 revealed. Meanwhile, it does not produce rotation speed at 200 and 300-mm pitch distances. In the volume flow rate (Q2) of 0.0018 m^3/s at a pitch distance of 50, 70, 100, and 200 mm were produced rotation speeds of 224.15, 248.44, 237.74, and 113.77 rpm are revealed. At a pitch distance of 300 mm, it does not produce rotation speed. It is predicted that a bigger pitch distance causes the screw not able to catch water in an optimal quantity so that the force is low. On the other hand, there is a loss of water momentum when water is moving through the screw, because Archimedes's turbine works by changing potential energy to kinetic energy of water then converted to rotation energy, that way momentum loos will reduce the energy transferred to the turbine. Other than that, Archimedes turbine is less effective on low water flow, since long pitch distance will be influencing flow energy is not utilized completely. It is ideally, pitch distance needs to be designed as the water flow condition, in order turbine to produce optimal power. While in volume flow rate (Q3) of 0.0025 m^3/s at a pitch distance of 50, 70, 100, 200, and 300 rpm, resulting in a rotational speed of 305, 318.89, 339.82, 242.73, and 148.93 rpm consecutively. In the volume flow rate (Q4) of 0.0034 m^3/s at a pitch distance of 50, 70, 100, 200, and 300 cm, the production of rotation speeds of 310.22, 359.44, 410.77, 311.89, and 219.62 rpm is evidenced. From the results obtained, it can be summarized that every time there is an increase in water discharge, there is also an increase in the speed of the turbine rotation and when in each variation of water discharge. The most optimal turbine pitch distance is obtained at a pitch distance of 100 mm.

3.2 Correlation of Blade Number and Rotation of the Turbine

Following the best correlation found of pitch distance and rotation of the turbine in a various volume flow rate, then the best-fit distance was kept as a reference to continue further study of the best blade number studied. The corresponding chart of different volume flow rate investigations using 1, 2, and 3 blades correlated with the data collected is shown as the following **Figure 7**.

Based on the graph in **Figure 7**, it shows that in volume flow rate (Q1) the water discharge was 0.0012 m^3/s on a turbine with several blades of 1, 2, and 3, the rotational speed is obtained to be 183.80, 197.31, and 209.38 rpm respectively. It seems that the more blades added the rotation of the turbine increased. It also occurred at a volume flow rate (Q2) of 0.0018 m^3/s. In contrast for the volume flow rate (Q3 and Q4) with a water discharge of 0.0026 m^3/s and 0.0034 m^3/s, the greater number of blades added caused the turbine rotation to decrease accordingly. It is summarized that in the low volume flow rate, the torque of the turbine was increased due to the additional blade given. However, in the high-volume flow rate, the additional blade was less effective revealed. It is supposed that water flowing along the turbine blade is forming significant back pressure (hydraulic load) causing faster turbine speed and faster, when the mass flow is increased, back pressure and its resistive force increase, and then the turbine should be working harder to defend that force, as a result, it reduces the rotation. Other than that, most possibly there is the slippage or loose phenomenon encountered, where on higher flow some water might be unstrapped effectively between the turbine blade and free slippage, which causes energy efficiency reduced. Overall Archimedes turbines tend to be more efficient on a certain mass flow rate range and possibly reduce turbine speed at very low debit or too high debit depending on design and flow condition.

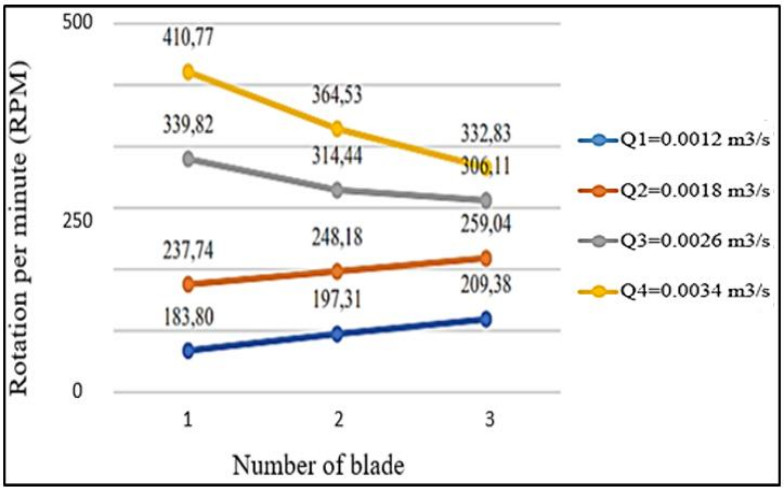


Figure 7. Correlation of blade number versus turbine rotation per minute.

3.3 Correlation of Blade Angle and Rotation of the Turbine

In conjunction with this, the third purpose of the study is to determine the optimal blade angle on the turbine within various water discharges, after the optimum pitch distance and number of blades found. A discussion of the relationship between the turbine blade angle and the rotational speed of the turbine is carried out to obtain the optimum blade angle. The test resulting a series of data not seen in this section and expressed on **Figure 8** as follows. The corresponding chart at different volume flow rates and investigation using turbine with blade angles of 23º, 28º and 33º is seen in the following **Figure 8**.

Based on the graph in **Figure 8** above, shows that in the volume flow rate (Q1) of 0.0012 m^3/s at a blade angle of 23º, 28º and 33º, the rotational speed was 172.64, 183.80, and 164.72 rpm. In volume flow rate (Q2) of 0.0018 m^3/s at a thread angle of 23º, 28º, and 33º, the rotational speed was 230.94, 237.74, and 224.72 rpm respectively. Meanwhile in water flow (Q3) of 0.0026 m^3/s at a thread angle of 23º, 28º and 33º, the rotational speed was 331.67, 339.82, and 334.30 rpm respectively. Whereas in volume water flow

rate (Q4) of 0.0034 m^3/s at a thread angle of 23°, 28° and 33°, the rotational turbine speed was 406.42, 410.77, 386.04 rpm consecutively. From the data obtained, the highest turbine rotation speed is steadily obtained at a blade angle of 28°. From Q1 to Q4 with turbine rotation speeds of 183.80 rpm, 237.74 rpm, 339.82 rpm, and 410.77 rpm respectively. From the results, it was found that each time there was an increase in the water discharge, there was also an increase in the speed of the turbine rotation, and for each variation of the water discharge, the most optimal turbine thread angle was found at the blade with angle of 28°.

Most possibly with the small angle of the blade (flat) water flow is good throughout the blade, and increases the rotation of the turbine, at a low flow rate of water that is not suspended by the blade. However, the very small angle of the blade probably causes water not enough chaptered by the blade hence reducing efficiency at a higher water flow rate. On the other hand, a bigger blade angle turbine will be better in caching the volume flow rate of water, then force is increased, at an optimal angle, Archimedes turbine achieves best efficiency in changing potential energy of water to be the turbine speed. Overall, the optimal angle depends on the hoped flow rate. At a low flow rate, the smaller angle may help, meanwhile at a higher flow rate, the higher angle is much more efficient to run the turbine.

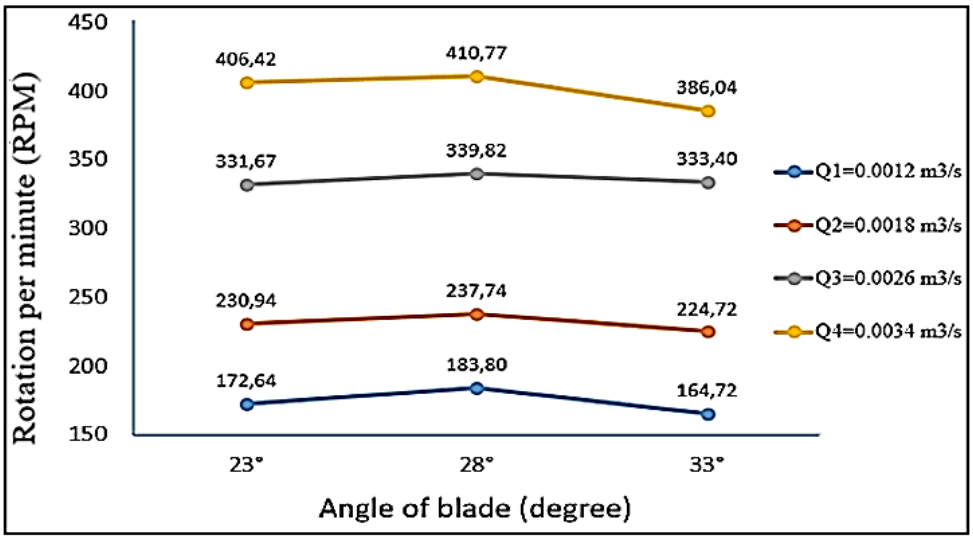


Figure 8. Correlation of blade number versus turbine rotation per minute.

3.4 Power, Efficiency, Coefficient of Performance, and Tip Speed Ratio (TSR)

Following to optimum pitch distance, number of blades, and blade angle, further investigation was intended to analyze experimental results to measure generator power with acquisition data and without acquisition data. Both data showed as much as 0.55 watts without data acquisition and using data acquisition found to be 0.53 watts. As the final objective of the experiment in water volume flow rate of Q1 to Q4, efficiency (η), coefficient of performance, and tip speed ratio (TSR) were found to be 33%, 0.33, and 2.56 and all achieved in blade angle 28°. This work is compared with the published data by Bouvant et al. (2021) in the following **Figure 9**.

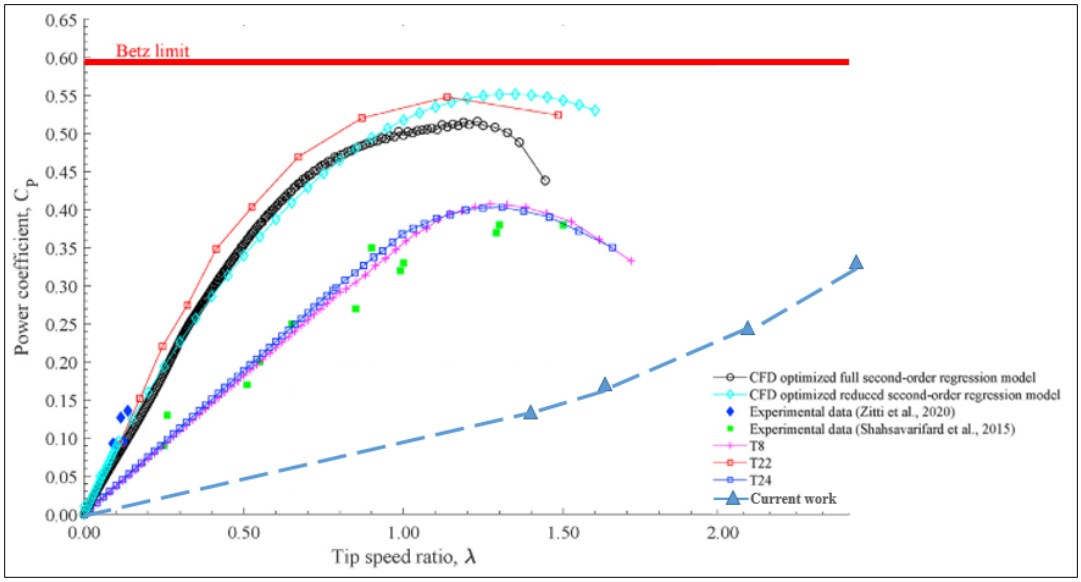


Figure 9. Current work, numerical and experiment comparison of Cp vs. tip speed ratio (λ) curves. (Bouvant et al., 2021, with permission from Elsevier, license no. 5833001203974).

Good agreement between the trends in the published data and experimental results is evident, with the experienced power coefficient, C_p consistently slightly lower and data scattered in the same range area as the values obtained from the best-fit published data correlation. A smooth scatter in the experimental data is evident. Exponential and polynomial trend is predicted due to the not-perfect calibration process of acquisition data corrected and customized manually.

4. Conclusions

A series of works have been carried out to achieve the specific objective of this work was to prove the optimal performance and effectiveness design of the Archimedes screw turbine. Initial experiment results produced data for turbine rotation speed versus pitch distance. The experiment analysis indicated the optimum pitch distance was found to be 100 mm. Investigation of blade number indicates that the most effective blade number from 1 to 3 changed the effective torque of the Archimedes screw turbine was increased due to the additional angle. But, in the high-volume flow rate, the additional angle of the blade was less effective are evident. The difference in blade angle in various volume flow rate resulting reliable performance in blade angle of 28°. Generating power, efficiency, coefficient of performance as well as tip speed ratio were described briefly.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

AI Disclosure

The author(s) declare that no assistance is taken from generative AI to write this article.

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