Design of Laboratory-Scale Archimedes Screw Turbine Prototype

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ABSTRACT

The number of blades and helix range in the helical turbine are considered as internal parameters, while the outer radius of the turbine, turbine length, and turbine shaft inclination are regarded as external parameters. Both of these parameters define the geometric characteristics of the helical turbine. The geometric configuration of the Archimedes turbine can be determined using the formulation by Chris Rorres. The designed prototype of the Archimedes turbine has the following specifications: a total of 3 blades (N), an inner diameter (Di) of 11.4 cm, an outer diameter (Do) of 21.28 cm, a turbine length (L) of 80 cm, a screw pitch (Λ) of 25.53 cm, a number of turns (Z) of 3, and a turbine weight of 10.80 kg, with a turbine shaft inclination angle of 30°. From the research findings, the highest turbine performance was achieved at a water discharge of 0.006 m³/s, resulting in a generated voltage of 41.02 V with a turbine rotation speed of 309.3 rpm. In this research, the experimental method was used, which involved testing the turbine performance by varying the water discharge under both unloaded and loaded conditions (load simulated using a lamp). Throughout the research process, each test data was recorded and analyzed using relevant formulas, and the results were presented in the form of graphs to facilitate drawing conclusions. From the research findings, the best turbine voltage regulation occurred at a water discharge of 0.0026 m³/s, resulting in a voltage regulation of 22.38%.

Keywords: Archimedes Screw Turbine, voltage, turbine speed, water discharge, prototype design

1. INTRODUCTION

The need for electrical energy is currently considered crucial, both for household and increasingly growing industrial needs. However, the existing power generation units have seen minimal significant improvements. Indonesia possesses abundant potential for renewable energy, one of which is water energy. West Kalimantan, in particular, is dubbed the "land of a thousand rivers" due to its vast potential of rivers, both small and large, that can be utilized as sources of power generation. However, this potential has not been optimally harnessed due to limitations in turbine technology to harness this energy. For medium to high heads and flows, turbines like Pelton, Francis, Kaplan, and Crossflow are relied upon. However, the development for low-head turbines is challenging, despite Indonesia having immense potential in this regard. This research is driven by the limited availability of electricity in remote areas, where there exists a sufficient water energy source, albeit with low heads. Therefore, the potential for power generation using low-head water energy needs to be explored. To convert this water energy, a specific turbine is required, namely the Archimedes Screw Turbine (AST).

The principle behind the AST is based on the Archimedes screw pump system, which functions to lift water from a river to the surface. The AST is essentially the reverse of the screw pump. Water with a certain head, even with a low flow rate, is capable of rotating the AST, which can be connected to a generator to produce electricity. This research discusses the design, implementation, and testing of a Laboratory-Scale AST as a power generator. This research will focus on the "Design of Laboratory-Scale Archimedes Screw Turbine Prototype," aiming to conduct an in-depth analysis of the existing issues.
2. LITERATURE REVIEW

According to C. Rorres (2000) in his paper, he explains about the parameters and design of Archimedes Screw, where the geometry of the Archimedes screw is controlled by certain external parameters (outer radius, length, and inclination) and specific internal parameters (inner radius, number of blades, and blade pitch). External parameters are usually determined by the screw’s location and the amount of water to be lifted. However, internal parameters can be chosen freely to optimize the screw’s performance [1].

Adly Havendri and Hendro Lius (2009) in their final project titled “Design and realization of a prototype screw-type water turbine (183rchimedes183 turbine) for low-head microhydro power generation in Indonesia.” Conducted the design of an Archimedes turbine with the following specifications: a turbine with 3 blades, a length of 1 meter, a turbine angle of 30°, using carbon steel ASTM A53 for the turbine material. In this research, the power to be generated by the designed Archimedes turbine was 100 watts. Based on these specifications, the design of the Archimedes turbine was developed into a prototype [2].

Prasetyo, C. B., Golwa, G. V., Kusuma, T. I., & Jabar, M. A. (2022). “Design and Construction of an Archimedes Turbine Prototype for Household Water Tanks Using Chris Rorres Formulaion.” Journal of Technology and Industrial Innovation (JTI), 3(1). The development of the Archimedes turbine prototype was carried out to maximize the potential energy from water tanks for use as a pico-hydroelectric power generator. The number of blades and the helix 183rchim the helical turbine were used as internal parameters, while the outer radius of the turbine, the length of the turbine, and the inclination of the turbine shaft were used as external parameters. Both of these parameters constitute the geometry of the helical turbine. Flow rate and head are typically used to determine external parameters. 183rchim hoped that the research on the laboratory-scale design of the Archimedes turbine can be used as an experimental study for the production of pico-hydroelectric power generators. The geometry of the turbine can be obtained using Chris Rorres’ formulation. The results of the prototype design of the Archimedes turbine have the following specifications: the rotor construction has a single helical blade with a helix range of 29.28 mm, an outer blade radius (R_o) of 101.66 mm, and an inner blade radius (R_i) of 54 mm. The helix range is 12.06 mm, and the effective turbine inclination is 35 degrees [3].

The Archimedes screw turbine can operate at low heads below 10 meters, does not require a penstock, is easy to maintain and install. This research aims to determine the variations in water flow rate on Torque, hydraulic power, generator power, and turbine efficiency produced by the Archimedes screw turbine. The variations in water flow rate used in this study are 1 liter/s, 1.5 liters/s, and 2 liters/s. The results of this study indicate that the variations in water flow rate are directly proportional to the performance of the micro-hydro power plant (PLTMH), where the turbine torque and generator efficiency at a flow rate of 2 liters/s are 12.76%, at a flow rate of 1.5 liters/s are 9.07%, and at 1 liter/s are 1.16% [4].

A generator is a device whose operation is based on electromagnetic induction (Jaya et al., 2017). Electromagnetic induction is widely used to convert kinetic energy into electrical energy. The voltage produced by the generator depends on the speed of the turbine that rotates the generator’s rotor. The higher the turbine’s rotation speed, the greater the voltage generated. This device utilizes the turbine’s rotation to generate electricity that will supply power to loads such as lamps [5].

This research aims to determine the power characteristics and efficiency of the Archimedes screw turbine under constant head conditions, tested in a closed channel. The Archimedes screw turbine used had an outer diameter (do) of 330 mm, an inner diameter (di) of 89 mm, a blade spacing of 160 mm, a blade angle of 40 degrees, and a shaft length of 2000 mm. Shaft rotation speed measurements were taken for each flow rate variation using a tachometer, with a load capacity of up to 4000 watts. Under constant head conditions, various flow rates (Q) were used: Q1 0.01535 m³/s, Q2 0.02162 m³/s, Q3 0.03074 m³/s, Q4 0.04001 m³/s, and Q5 0.04471 m³/s. The research results showed a maximum power output of 72.01 watts at a flow rate of Q4 0.04001 m³/s, with the turbine shaft rotating at 229.99 rpm, and an efficiency value of 12.98% at the same flow rate and turbine shaft rotation speed [6].

The factor that most influences the performance of the Archimedes screw turbine is the angle of inclination of the head and turbine blades. The objective of this literature review is to determine the optimal angles of inclination for the head and turbine blades of the Archimedes screw turbine to achieve the highest efficiency when applied in a Hydropower Plant (PLTA) for maximum electrical power generation. The method employed by the authors of the reviewed journal articles involved direct experimentation by designing a prototype Archimedes screw turbine. They conducted measurements of turbine rotation, generator rotation, generator output power, and other relevant parameters. Utilizing the data from these collective research studies, it was concluded that the Archimedes screw turbine achieves the highest efficiency when it has 2 turbine blades with a blade angle of 28°, and a head inclination angle of 40° [7].

The measurements conducted in the modeling of this micro-hydroelectric power generator include: water flow rate, turbine rotation, generator rotation, voltage, current, torque, as well as generator output power and
efficiency. These parameters were measured by altering the water flow onto the turbine blades from head angles of 0°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 70°, 80°, and 90°. The highest measurement results were obtained at a head angle of 400 degrees. The generated power output was 10.92 watts, the torque was 0.60 Nm, and the efficiency was 14%. The obtained results are still relatively low because the turbine rotation is insufficient to drive the generator, where the generator’s torque exceeds that of the turbine. This is influenced by the low water flow rate in the modeling of this micro-hydropower generator [8].

Archimedean screws are being used for power generation for more than one decade. Compared to other turbines, this new, ultra-low head technology is still a niche product. The presented work includes a site inquiry, an operator survey, comprehensive field measurements, and extensive laboratory tests. It assesses the prevalence of the turbine, its application, operational experiences as well as design alternatives and design guidelines. Specific investment costs range from 0.5 to 2 €/kWh and operating costs are comparatively low due to a wide screen spacing and the general robust structure. Mean plant efficiencies were 69% and the six top-performing plants achieved peak efficiencies above 75%. The concept of the rotary screw turbine was evaluated. In the main experimental tests of seven different screw designs efficiencies of up to 94% were recorded [9].

A computational fluid dynamic (CFD) simulation of an Archimedes screw generator (ASG) was carried out in conjunction with laboratory-scale experiments to determine the effect of inclination angle and number of blades on ASG power production and performance. Good agreement was found between the model and experiment; the CFD model had relative errors in hydraulic efficiency of less than 2% in optimal cases. Both the experiments and CFD simulations were carried out for inclination angles between 10° and 38°. Afterwards CFD was used to simulate the effect of three different numbers of blades (3, 4 and 5) of an ASG with common design parameters. Overflow and gap leakage losses were found to increase at higher inclinations – these losses decreased with the addition of blades. For this particular ASG setup, the 5-bladed screw generated the most power. The 4 and 5-bladed screws had their highest efficiencies at inclination angles between 20° and 24.5°. The 3-bladed screw was found to have its highest efficiencies at comparatively lower inclination angles, with the simulations finding the optimal angle to be approximately 15.5°. Both CFD simulations and the experiments showed that overflow leakage started to happen much sooner at higher inclination angles, as expected [10].

The potential for renewable energy sources in Indonesia is rich enough to be used as an alternative energy source. The availability of hydro energy potential can be developed into a Mini Hydro Power Plant. One type of turbine that has been developed is the Archimedean turbine which is capable of utilizing low headwater sources. The AH-01 and AH-02 screw turbine prototypes have been made at Andalas University and testing was necessary to determine the optimal discharge for mechanical performance. Testing of the screw turbine prototype type AH-01 (screw angle 23°) and AH-02 (screw angle 26°) was carried out by varying the flow rate and shaft angle for the two types of screw turbine prototypes to determine mechanical performance and efficiency of the turbines. The test results show that the AH-02 screw turbine prototype has higher mechanical power than the AH-01 screw turbine prototype. The maximum mechanical power of each AH-01 and AH-02 screw turbine prototype is 5.77 and 7.54 Watts at a flow rate of 0.00139 m³/s [11].

Archimedean screw turbines are becoming increasingly popular at low-head hydro sites in Europe due to their high efficiency (over 80% in some installations), competitive costs, and low environmental impact. This paper focuses on the optimal design and performance of Archimedes Screw Turbines at the Arinta waterfall, located in a small town in the Ekiti West Local Government Area of Ekiti State, Nigeria. The performance of an Archimedes screw used as a generator depends on both internal and external parameters, as well as the head and flow at the site. One crucial parameter in the screw turbine design is the pitch or blade period. The public power supply system in Nigeria is unreliable, affecting the daily lives of the average citizens. Therefore, there is a need for an additional, efficient, and cost-effective power supply. The Archimedean screw is an energy converter with efficiencies ranging from 79% to 84%. It represents an attractive alternative for other turbines in low-head hydropower applications. Installing this type of system will provide a more convenient lifestyle for the people in Erijyan town, ultimately contributing to the country’s economic development [12].

A study has been conducted to determine the dimensions of the turbine blades and the angle of the turbine shaft in Archimedes screw turbines. This research investigates several turbine parameters, including the determination of blade dimensions and the angle of the turbine shaft to achieve optimal turbine performance. The determination of the dimensions of the Archimedes screw turbine blades follows C. Rosres’ formulation, which maximizes the volume of water between the turbine blade spirals. The dimensions of the Archimedes screw turbine blades for a fluid power potential with a 2-meter head and flow rates ranging from 20 to 40 liters per second have the following specifications: the rotor construction has 2 helical blades, a helical pitch of 413 mm, an outer blade radius © of 408 mm, and an inner blade radius (Ri) of 109 mm. Furthermore, the calculation of the length of the helical path is performed to achieve a helical pitch of 413 mm. The length of the helical path can be obtained using two methods: helix equation calculation or software-based drawing simulation. Both methods result in a helical path length of 802 mm. The determination of the optimum angle of the turbine

Design Of Laboratory- Scale Archimedes Screw Turbine Prototype.. (Andre Marce Nahak)
shaft inclination is calculated based on the gravitational force and hydrostatic force acting on the volume of water between the two helical blades. This calculation yields an optimum shaft inclination angle of 32° [13].

The need for electrical energy is increasing every year. The present electrical energy remains largely dependent on fossil energy and can not be renewed. Indonesia is one of the countries rich in renewable energy potential. The abundant energy in Indonesia is water energy as a mini / microhydro scale generator. The development of hydro power is to utilize the potential energy flow of water that has certain head and debit. Then the potential energy is converted by turbine and generator into electrical energy. The purpose of this paper is to conduct a theoretical study to design the optimal angle of Archimedes screw with a relatively easy design method. Based on the results obtained geometry and arch angle Archimedes screw design with 0.050 m external diameter, 0.030 m internal diameter 0.055 m and slope angle (α) 45° generates shaft power of 5.11 Watt at 50 rpm rotation capable of producing efficiency 89% with head 1 m and debit 0.5 m/s [14].

The study of Archimedes screw turbine as a micro-hydro power-plant is being developed in this decade. Screw turbine has some advantages, namely no need draft-tube, fish-friendly, and can be operated in low head (H < 10 m). The aim of this research is to recognize the performance of Archimedes screw turbine due to flow rate effect and its slope and also to reveal flow phenomenon that occurred among blades of the screws. Physical model of the screw turbine was made with acrylic as represented laboratory scale. Geometrical shapes are three blades, screw angle of 30º, ratio radius of 0.54, pitch of 2.4R0. Measured and observed variables are turbine’s rotation, torsion, and flow visualization with inlet flow rate variable (c0) are 0.3 m/s, 0.4 m/s, and 0.5 m/s, respectively. And the turbine’s slope variables (α) are 25º, 35º, and 45º. According to experimental data, the maximum turbine efficiency is 89% that occur at 0.5 m/s of flow rate and 25º of shaft slope. The result of this research reveals that the largest hydraulic power occurs in the turbine shaft’s slope (α) of 45º in the amount of 16.97 with turbine’s rotation of 350 rpm. Output power of screw turbine occurs in the turbine shaft’s slope (α) of 45º in the amount of 5.11 watt and rotation of 182 rpm. The highest efficiency is 89% occur in turbine’s rotation of 50 rpm in the turbine shaft's slope of 25º with y = 1R0. The result of this study show that the performance of the screw turbine is more maximum on the lower shaft’s slope that automatically become better operating in low head and rotation [15].

3. METHOD

The initial step in creating the Archimedes turbine prototype is to search for references, including journals and previous research, that discuss Archimedes turbines. Next, the design of the Archimedes Screw Turbine (AST) is calculated using the guidelines provided by C. Rorres 2000 [1]. Subsequently, the prototype AST is designed, and once the design is complete, laboratory-scale experiments with the AST are conducted. The desired data from these experiments includes voltage and turbine rotation data.

3.1 Experimental Design

The following is the experimental design that will be conducted in this study:

From Figure 2 above, the generator used is an AC voltage output generator, but it is converted into DC voltage using a rectifier circuit. The following is the rectifier circuit used:

Design Of Laboratory- Scale Archimedes Screw Turbine Prototype.. (Andre Marce Nahak)
3.2 Research Procedure

During the experimental phase, the research steps are as follows: Prepare the light bulb as the test object and the Archimedes Screw turbine as the equipment used to test the research object. Prepare the assembled light bulb in parallel, complete with its potentiometer as the voltage regulator for the testing. Set up a voltmeter, ammeter, tachometer, stopwatch, and connecting cables. Position the Archimedes Screw turbine under the water tank that has been prepared. Connect the generator cables of the Archimedes Screw turbine to terminals that are already connected to multimeters for voltage and current measurements, then connect them to the prepared light bulb. (load testing). Once everything is ready, adjust the water flow rate in the water tank so that water can flow into the Archimedes Screw turbine through the prepared hose. Measure the turbine's rotation for each water valve opening using a tachometer. Measure the voltage generated by the generator. For load testing, measure the rotation, voltage, and load current for each water valve opening.

3.3 Variables or Data

3.3.1 Water flow rate data.

Water discharge data is information or measurements that record how much water flows through a specific location or channel during a particular period of time. Water discharge is typically measured in units of volume per unit of time, such as liters per second (L/s) or cubic meters per second (m³/s). Water discharge data is crucial in various applications, including water resource management, water infrastructure planning, flood management, hydroelectric energy production, and environmental monitoring. The information on water discharge aids in making decisions related to water usage, resource allocation, and mitigating water-related risks, such as floods or droughts. This data can be obtained through direct measurements using suitable equipment or through the use of mathematical models to estimate water discharge based on existing data.

3.3.2 Voltage and current data during testing under no-load and loaded conditions.

The voltage and current data during no-load and loaded testing are information or measurements that record the values of electric voltage and electric current that occur in an electrical system or equipment when in a no-load testing condition and when in a loaded testing condition. No-Load Testing: This is a test conducted on electrical equipment when there is no load connected to it. In this condition, the measured voltage and current depict the characteristics of the equipment without supplying power to any load. This information is essential for determining efficiency and power losses in electrical equipment. Loaded Testing: This is a test conducted when a load has been connected to the electrical equipment. In this condition, the measured voltage and current reflect how the equipment performs when delivering power to an actual load. This data helps assess the performance of the equipment in everyday usage situations and can be used to identify issues or maintenance needs.

Collecting voltage and current data during no-load and loaded testing is an important step in testing and understanding the operational characteristics of electrical equipment, as well as ensuring that the equipment functions according to the expected specifications.

3.3.3 Turbine rotation data.

Turbine rotation data is information that records the speed or number of rotations performed by a specific turbine or rotating machine in a system. This data is crucial for measuring and understanding the turbine’s performance, especially in various applications such as hydropower plants, aircraft, ships, and industrial machinery. In some applications, turbine rotation data can include information such as: Rotational Speed (RPM - Revolutions Per Minute): This information records how many rotations the turbine undergoes in one minute. RPM is a common measurement for assessing the rotational speed of a turbine. Speed Changes (Delta RPM): This data can record changes in the turbine’s speed over a specific period. It can provide insights into how the turbine adapts to various operational conditions. Total Number of Rotations: This is the cumulative count of rotations that the turbine has undergone since the start of its operation. It is often used in equipment monitoring and maintenance to determine when maintenance or component replacement is needed.
Turbine rotation data is highly important for assessing efficiency, performance, and reliability in various applications. It can also be used to analyze operational trends, detect potential issues, and plan necessary maintenance activities.

3.3.4 Turbine rotation and voltage regulation data.

Rotation and voltage regulation are concepts used in the world of engineering and electronics to measure and control changes in rotational speed and electrical voltage within a system. Here’s a brief explanation of both:

**Rotation Regulation:**
- Rotation regulation is the ability of a device or system to maintain or control the rotational speed of a machine or rotating device.
- It is often used in the context of machinery such as electric motors, turbines, generators, or other rotating equipment.
- Rotation regulation is essential to ensure that rotating machines or devices can operate at the desired speed according to the application's requirements.

**Voltage Regulation:**
- Voltage regulation refers to the ability of a system or electronic device to maintain or control the level of electrical voltage at a specific point in an electrical circuit.
- It is typically applied to equipment such as transformers, voltage regulators, and power supplies.
- Voltage regulation is important to ensure that the voltage provided or received by electrical equipment remains within safe limits and complies with the required specifications.

Both rotation and voltage regulation are fundamental principles used to maintain the stability and performance of rotating devices and electrical equipment. They are used in various applications, including industrial, electrical, and automotive industries, to meet specific needs in controlling rotation and voltage according to desired standards.

4. RESULTS AND DISCUSSION

In determining the dimensions of the Archimedes screw turbine, a specific number of helical blades (N) has been chosen, which is 3. Referring to Table 1 for the optimal AST ratio parameters for various blade numbers, the values obtained for N = 3 are as follows:

\[
\begin{align*}
p^* &= 0.5357 \\
\lambda^* &= 0.2217 \\
\lambda^* v &= 0.0598 \\
v &= 0.2697
\end{align*}
\]

For the inner diameter of the Archimedes turbine \((D_i)\), a value of 11.4 cm has been established. Consequently, the inner radius of the Archimedes turbine can be determined as \((R_i) = 5.7 \text{ cm}\).

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter</th>
<th>Mark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Turbine length (L)</td>
<td>80 cm</td>
</tr>
<tr>
<td>2.</td>
<td>Pitch Skrup (S)</td>
<td>25.53 cm</td>
</tr>
<tr>
<td>3.</td>
<td>Turbine inner diameter (D_i)</td>
<td>11.4 cm</td>
</tr>
<tr>
<td>4.</td>
<td>Turbine outer diameter (D_o)</td>
<td>21.28 cm</td>
</tr>
<tr>
<td>5.</td>
<td>Number of blades (Z)</td>
<td>3 buah</td>
</tr>
<tr>
<td>6.</td>
<td>Water heads</td>
<td>± 40 cm</td>
</tr>
<tr>
<td>7.</td>
<td>Inclination angle</td>
<td>30°</td>
</tr>
<tr>
<td>8.</td>
<td>Turbine weight</td>
<td>10.80 Kg</td>
</tr>
</tbody>
</table>

3.1. Data Experimental Results

Data collection was carried out by varying the water discharge entering the Archimedes Screw Turbine (AST) and rotating the turbine. This research was conducted in two stages: testing the Archimedes Screw Turbine's operation without load and operating it under load, with the load simulated using a light bulb. The following is the data obtained during the experiments:

3.1.1 Water discharge data

Water discharge data was obtained through manual measurements using containers. These containers were used to collect the water discharged from the turbine. The water entering the turbine would rotate the
turbine shaft, and then the water would exit the turbine and enter the collection container. By comparing the duration of water flow through the turbine and the volume of water collected in the container, the water discharge rate was determined in the experiments. The water discharge data is presented in Table 2:

<table>
<thead>
<tr>
<th>No</th>
<th>Symbol</th>
<th>Water discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q1</td>
<td>$0.0008 , m^3/s$</td>
</tr>
<tr>
<td>2</td>
<td>Q2</td>
<td>$0.002 , m^3/s$</td>
</tr>
<tr>
<td>3</td>
<td>Q3</td>
<td>$0.003 , m^3/s$</td>
</tr>
<tr>
<td>4</td>
<td>Q4</td>
<td>$0.006 , m^3/s$</td>
</tr>
</tbody>
</table>

### 3.2. Data from No-Load Testing

Testing During the no-load testing experiment, variations in water discharge were conducted four times, resulting in the following data:

<table>
<thead>
<tr>
<th>No</th>
<th>Water discharge</th>
<th>Turbine rotation (Rpm)</th>
<th>Voltage DC (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q1</td>
<td>68.3</td>
<td>7.34</td>
</tr>
<tr>
<td>2</td>
<td>Q2</td>
<td>139.1</td>
<td>17.48</td>
</tr>
<tr>
<td>3</td>
<td>Q3</td>
<td>246.1</td>
<td>30.56</td>
</tr>
<tr>
<td>4</td>
<td>Q4</td>
<td>309.3</td>
<td>41.02</td>
</tr>
</tbody>
</table>

Figure 3 illustrates that turbine rotation affects the generated voltage. From the above graph, it can be observed that water flow rate significantly influences the turbine rotation. As the inflow water rate into the turbine increases, the turbine rotation speed also increases. Therefore, it can be concluded that water flow rate is directly proportional to turbine rotation, where higher water flow rates result in higher turbine rotation speeds. The highest turbine rotation speed occurs during water flow rate Q4, at 309.3 Rpm.

### 3.3. Data from Load Testing

In the loaded testing experiment, the load was simulated using a light bulb. This experiment was conducted by varying the water discharge four times, and the testing results are as follows:

<table>
<thead>
<tr>
<th>No</th>
<th>Water discharge</th>
<th>Turbine rotation (Rpm)</th>
<th>Voltage DC (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Q1</td>
<td>40.2</td>
<td>3.07</td>
</tr>
<tr>
<td>2</td>
<td>Q2</td>
<td>105.1</td>
<td>10.99</td>
</tr>
<tr>
<td>3</td>
<td>Q3</td>
<td>195.8</td>
<td>21.86</td>
</tr>
<tr>
<td>4</td>
<td>Q4</td>
<td>243.4</td>
<td>27.42</td>
</tr>
</tbody>
</table>
Table 4 presents the processed data of voltage, current, and turbine rotation during the load testing. The data in the table indicates that the highest voltage is obtained at a discharge rate with a turbine rotation of 243.4 RPM, while the lowest voltage is recorded during the Q1 water discharge with a turbine rotation of 40.2 RPM. A lower water discharge leads to a smaller force that rotates the blades. This signifies that increasing the water discharge will also increase the generated voltage, a trend observed during the no-load testing as well. The voltage increase is attributed to the higher water flow pushing the turbine blades to rotate faster, consequently resulting in higher generated voltage.

![Graph of the Relationship between Turbine rotation and Voltage](image)

Figure 4. Graph of the Relationship between Turbine rotation and Voltage

From the obtained data, we can visualize the turbine rotation and voltage during the no-load testing and load testing in the form of the following graphs:

![Graph of Turbine Rotation Comparison during No-load and Load Testing with Variations in Water Flow Rate](image)

Figure 5 Graph of Turbine Rotation Comparison during No-load and Load Testing with Variations in Water Flow Rate

Figure 5 above shows that the turbine rotation during both no-load and load testing exhibits a linear relationship, where the turbine rotation increases in accordance with the water flow rate used to drive the turbine. The highest turbine rotation occurs at a water flow rate of 0.006 m³/s, with the turbine rotating at 309.3 Rpm during the no-load testing. However, during the load testing, the turbine rotation decreases to 245.4 Rpm at the same water flow rate of 0.006 m³/s.
Figure 6 Graph comparing voltage during no-load and load testing with the same water flow rate

From the above graph, we can observe a difference in the generated voltage between the no-load and load testing conditions. When a load is applied, the output voltage of the generator decreases. This phenomenon can be attributed to the increased power demand, causing a voltage drop in the system. Furthermore, it is evident that there is a linear relationship between voltage and water flow rate. As the water flow rate increases, the generated voltage also increases proportionally. The highest voltage is achieved at a water flow rate of 0.006 m$^3$/s, measuring 41.02 V under no-load conditions. When a load is introduced, the voltage decreases to 27.42 V at the same water flow rate of 0.006 m$^3$/s. The lowest recorded voltage is 3.07 V during load testing at a water flow rate of 0.0008 m$^3$/s.

From the collected data during the no-load and load testing, we can calculate the regulation of turbine rotation speed and voltage using the following formulas:

Rotation Speed Regulation = \[
\frac{\text{Turbine rotation speed during no-load testing} - \text{Turbine rotation speed during load testing}}{\text{Turbine rotation speed during no-load testing}} \times 100\
\]

(1)

Figure 7 Graph of Turbine Rotation Speed Regulation

Figure 7 illustrates the graph of turbine rotation speed regulation during the testing without load and with load. From the graph, it is evident that turbine rotation speed regulation is inversely proportional to the water flow rate (debit air). As the water flow rate increases, the turbine rotation speed regulation decreases. The smallest rotation speed regulation occurs at water flow rate Q3, with a value of 20.33%, while the largest rotation speed regulation occurs at water flow rate Q1, with a value of 41.14%. This relationship indicates that higher water flow rates result in more stable and consistent turbine rotation speeds, leading to lower regulation percentages.
The next step involves calculating the voltage regulation that occurs during the testing without load and with load. The formula used for voltage regulation is the same as the formula used to calculate turbine rotation speed regulation. Here is the calculation for voltage regulation:

\[
\text{Voltage Regulation} = \frac{\text{voltage during no-load testing} - \text{voltage during load testing}}{\text{voltage during no-load testing}} \times 100\% \tag{2}
\]

Figure 8 depicts the voltage regulation graph obtained during testing without load and with load. From the graph, it is evident that the highest voltage regulation occurs at water flow rate Q1, with a regulation of 58.17%. Voltage regulation tends to decrease at higher water flow rates, but at water flow rate Q4, there is an increase in voltage regulation of 33.15%. The smallest voltage regulation occurs at water flow rate Q3, which is 28.46%.

At water flow rate Q4, both turbine speed regulation and voltage regulation experience an increase. This phenomenon can be attributed to a faster overflow leakage and an increase in gap leakage, preventing the incoming water from rotating the turbine optimally. This issue could potentially be addressed by increasing the number of blades.

5. CONCLUSION

The designed AST prototype has the following specifications: 3 blades (N), inner diameter (Di) of 11.4 cm, outer diameter (Do) of 21.28 cm, turbine length (L) of 80 cm, screw pitch (\(\Lambda\)) of 25.53 cm, 3 helical turns (Z), and a turbine weight of 10.80 kg. Based on the conducted research, several conclusions can be drawn as follows: Voltage and water flow have a linear relationship, where a higher water flow leads to a greater voltage output. Turbine rotation and water flow also exhibit a linear relationship, with higher water flow resulting in increased turbine rotation. Voltage and turbine rotation show a linear relationship as well, where faster turbine rotation leads to higher voltage generation. The lowest turbine rotation regulation is 18.73% with a water flow of 0.0023 m\(^3\)/s, while the lowest voltage regulation is 22.38% with a water flow of 0.0026 m\(^3\)/s. Voltage regulation and turbine rotation regulation do not occur at the same water flow rate. An increase in voltage regulation is observed at a water flow rate of 0.006 m\(^3\)/s. This increase may be due to faster overflow leakage and increased gap leakage, preventing the turbine from reaching its maximum rotation. This issue could potentially be addressed by increasing the number of blade.

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