

Experimental study on a laboratory-scale Archimedes screw turbine using pitch-to-diameter ratio for low-head hydropower

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Abstract

The Archimedes screw is a hydropower technology well-suited for low-head applications. This study investigates the performance of a laboratory-scale Archimedes screw turbine for low-head hydropower applications by varying Pitch to Diameter Ratio ($P/D = 0.3, 0.38, 0.45, 0.52$) and inclination angle ($\beta = 22^\circ, 25^\circ, 27^\circ$). Experiments were conducted in a controlled water flow environment to evaluate torque, power output, and efficiency at different rotational speeds. Results indicate that both P/D and β significantly influence energy conversion. The highest performance was achieved at $P/D = 0.45$ and $\beta = 22^\circ$, producing a peak torque of 0.36 Nm, a power output of 2.4 W, and a maximum efficiency of 52.37%. Lower inclination angles contributed to improved hydraulic energy capture due to better water filling and reduced slippage. These findings highlight the importance of optimizing geometric parameters to enhance turbine performance in small-scale, sustainable energy systems. The results offer design guidance for implementing Archimedes screw turbines in rural or off-grid low-head hydropower scenarios.

Keywords:

Archimedes screw, pitch-to-diameter ratio P/D , inclination angle β , low-head hydropower

1 Introduction

Water is one of Indonesia's most abundant natural resources, crucial in daily life and energy generation. Flowing water with a certain height difference (head) and discharge rate contains mechanical energy that can be harnessed for power generation. One of the most effective methods for converting this energy into mechanical power is through the use of water turbines. These turbines can subsequently generate electricity, making them a fundamental component of renewable energy solutions, particularly in Small-Scale Hydroelectric Power Plants (SHPs) [1]. The development of water turbines dates back to the early 18th century, with significant advancements occurring in the 19th century. Since then, small-scale hydropower systems have been widely implemented to provide electricity to rural and remote communities, offering a sustainable alternative to conventional power sources [2]. Various studies and designs on small-scale turbines have been widely conducted, including those by [3]–[12]. Various designs and experimental studies on small-scale turbines have been reported, including those by Peng et al. [3], Woldemariam and Lemu [4], Amalia et al. [5], and others [6]–[12].

Among various turbine designs, the Archimedes screw turbine has gained attention as an efficient solution for low-head and low-flow water sources. This type of turbine utilizes a helical blade (screw) that rotates with the water flow, transferring kinetic energy to a generator via a rotating shaft [9]. Recent advancements have reaffirmed the effectiveness of Archimedes screw turbines in various low-head and flow conditions. Erinofardi et al. [13] highlighted the practicality of simplified turbine configurations suitable for rural, low-head applications. Maulana et al. [14] employed Computational Fluid Dynamics (CFD) analysis to evaluate pressure performance and validated the results through experimental comparison. Meanwhile, another study by Maulana et al. [15] investigated the effects of blade number and pressure distribution patterns, emphasizing numerical strategies for optimizing turbine performance.

Several key design parameters influence the efficiency and performance of an Archimedes screw turbine, including screw diameter (D), hub diameter (d), inclination angle (β), and screw pitch (P). Previous experimental studies have demonstrated that inclination angle significantly affects turbine performance, with optimal efficiency achieved at approximately 22° [16]. Furthermore, Saroinsong et al. [17] reported that turbine inclination impacts overall efficiency, with a 25° slope yielding 89% efficiency at a flow rate of 0.5 m/s. For a two-blade design, the highest generator power and efficiency were attained with a 30° slope and a pitch distance of $1.2 R_0$ (where R_0 is the outer screw turbine radius) [18]. Several studies have conducted CFD simulations with an inclination angle of 45° and reported varying peak efficiencies, namely 82% [19] and 80% [20].

In addition to the inclination angle, the number of helical turns in the screw has been identified as a crucial factor influencing turbine efficiency. A study found that the optimal configuration for achieving the highest efficiency of 81% was a turbine with two blades and three helical turns, concluding that the number of helical turns plays a more significant role than the number of blades in determining efficiency [21]. Moreover, CFD simulations indicate that an increase in pitch ratio results in a corresponding increase in torque generation [22].

Another critical parameter affecting turbine performance is the ratio of hub Diameter to Screw Diameter (d/D). Previous studies indicate that an optimal ratio of 0.42 yields an efficiency of 40.23% [23]. However, the influence of the Pitch to Diameter Ratio (P/D) on turbine efficiency remains insufficiently explored. Since pitch distance directly impacts the screw's rotational speed and overall efficiency, a deeper understanding of its effect is crucial for optimizing turbine performance.

This study aims to address that gap by experimentally investigating the effects of the P/D ratio on torque, power, and efficiency of an Archimedes screw turbine under constant flow conditions. The goal is to identify the optimal P/D and inclination configurations for enhancing performance in low-head applications. The findings are expected to support the design of more efficient small-scale hydropower systems, particularly for rural electrification and renewable energy deployment.

2 Research methodology

The experiment was conducted using an Archimedes screw turbine tested at three β : $22^\circ, 25^\circ$, and 27° , and four P/D : 0.30, 0.38, 0.45, and 0.52. This resulted in 12 test combinations under identical flow conditions.

2.1 Research scheme

The experimental setup is shown in Fig. 1, where a screw turbine is mounted on a frame. The lower end of the screw turbine is attached with a hinge connection, allowing the turbine's inclination to be adjusted.

The upper position of the screw can also be adjusted to allow for modifications to the turbine's inclination angle. The turbine inclination angle is set and measured using a digital angle level. An image of the digital angle level is shown in Fig. 2.

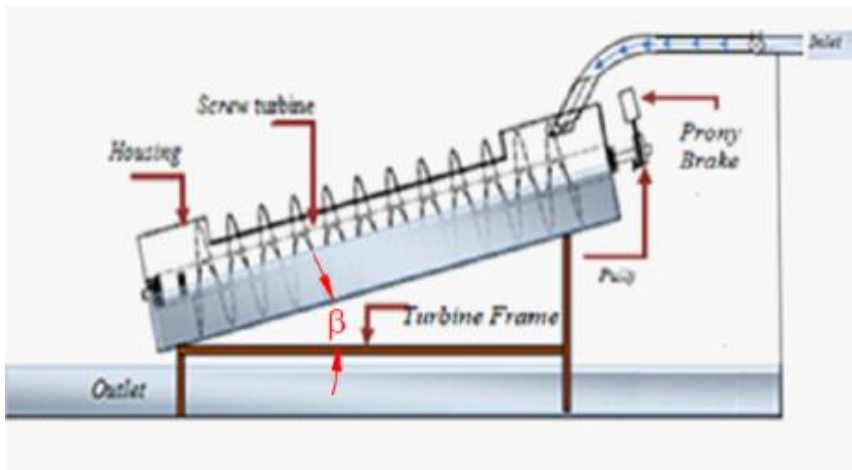


Fig. 1. Experimental setup showing the mounting of the Archimedes screw turbine, flow direction, and adjustable frame components



Fig. 2. Close-up view of the digital angle level used to set turbine inclination precisely

At the inlet section, a 2-inch hose is installed to introduce water as incoming flow (in the experiment, this hose is directly connected to flowing water in a channel). The water entering the screw turbine is measured based on the amount of water flowing from the channel through the inlet pipe, and its flow rate is recorded before being directed into the turbine, as shown in Fig. 3.

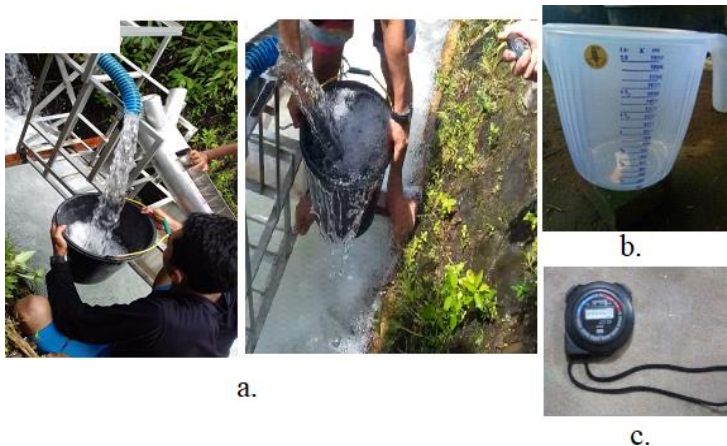


Fig. 3. Illustration of water inflow system with inline flow rate measurement before entry to the turbine

To ensure test consistency and reproducibility, the water source used was a steady open-channel flow with an average velocity of approximately 0.5 m/s, measured prior to entering the turbine. The ambient water temperature was maintained at approximately 27°C

throughout the testing period. Visual observation confirmed that the water flow exhibited low turbulence and stable characteristics, ensuring minimal fluctuation during turbine operation. These flow conditions, along with the fixed combinations of inclination angles and P/D ratios, were maintained uniformly during all experimental trials. To clarify the testing steps and how each variable was systematically applied, a flowchart of the experimental procedure is presented in Fig. 4.

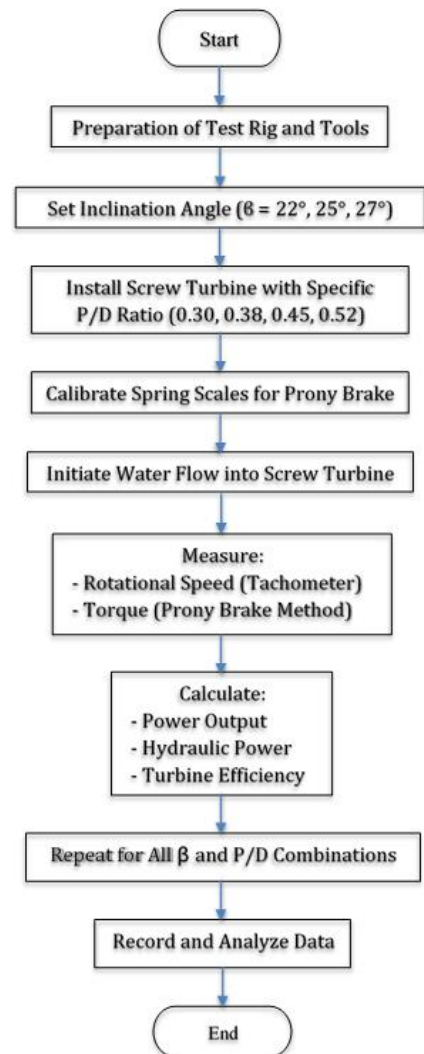


Fig. 4. The experimental procedure for Archimedes screw turbine testing

2.2 Power measurement using the Prony brake technique

In the Prony brake technique, a belt is wrapped around a rotating pulley. This rotating pulley is coaxial with the screw turbine. The placement of two scales equipped with a belt and wrapped around the pulley, which is coaxial with the screw, is shown in Fig. 5.



Fig. 5. Prony brake setup

Due to the frictional force on the pulley caused by the scales being lifted/tightened to apply a load on the wheel, the tension in the pulley is read as forces F_1 and F_2 . The forces F_1 and F_2 are measured using a scale with an accuracy of two decimal places. In the Prony brake technique, a belt is wrapped around the pulley, with both ends connected to the scales. When the scales are lifted or tightened, the pulley experiences a frictional load from the belt, as illustrated in the free-body diagram shown in Fig. 6.

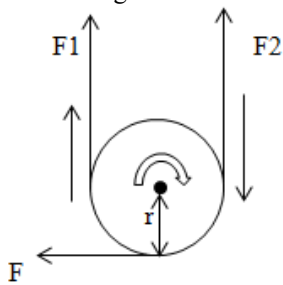


Fig. 6. Forces acting on the prony brake

The tension in both belts generates a frictional force F at specific contact points on the pulley, allowing the establishment of moment equilibrium at those contact points, as shown in Eqs. (1)-(5).

$$\sum M = 0 \quad (1)$$

$$F \cdot r + F_1 \cdot r - F_2 \cdot r = 0 \quad (2)$$

$$F \cdot r = F_2 \cdot r - F_1 \cdot r \quad (3)$$

$$F \cdot r = (F_2 - F_1) \cdot r \quad (4)$$

$$F = F_2 - F_1 \quad (5)$$

The frictional force F generates torque on the pulley, which is formulated in Eq. (6). The resulting torque is obtained by multiplying the frictional force acting on the pulley by its radius. In this study, the pulley used has a radius of $r=30$ mm.

$$T = F \times r \quad (6)$$

The power generated by the Archimedes screw turbine is calculated using Eq. (7), where n is the rotational speed of the screw in Revolutions Per Minute (RPM), measured using a tachometer, as shown in Fig. 7.

$$P_{turbine} = T \frac{2 \cdot \pi \cdot n}{60} \quad (7)$$



Fig. 7. Prony brake measurement and Archimedes screw rotation measurement using a tachometer

2.3 Efficiency calculation

The efficiency of the turbine is the ratio of the shaft power of the turbine to the potential power of the water flow. The turbine efficiency is expressed by the Eq. 8:

$$\eta_{turbine} = \frac{P_{turbine}}{P_{hydraulic}} \times 100\% \quad (8)$$

where $\eta_{turbine}$ represents the turbine efficiency (%), $P_{turbine}$ is the shaft power of the turbine, and $P_{hydraulic}$ is the hydraulic power. The hydraulic power of the water is formulated in Eq. (9).

$$P_{hydraulic} = \rho \cdot Q \cdot g \cdot h \quad (9)$$

where $P_{hydraulic}$ is the hydraulic power (W), ρ is the fluid density (kg/m^3), Q is the flow rate (m^3/s), g is the gravitational acceleration ($9.81 \text{ m}/\text{s}^2$), and h is the head (m).

2.4 Calibration process of the spring-based measuring device

To ensure the accuracy of the measurement results, both spring-based scales were calibrated by comparing their readings with known standard masses, as illustrated in Fig. 8. The calibration process was conducted incrementally up to a total load of 2 kg (2000 grams). The results of this calibration were then plotted into calibration curves for each scale, as shown in Fig. 9. These curves were used to verify the linearity and precision of the instruments prior to their use in the experimental setup.

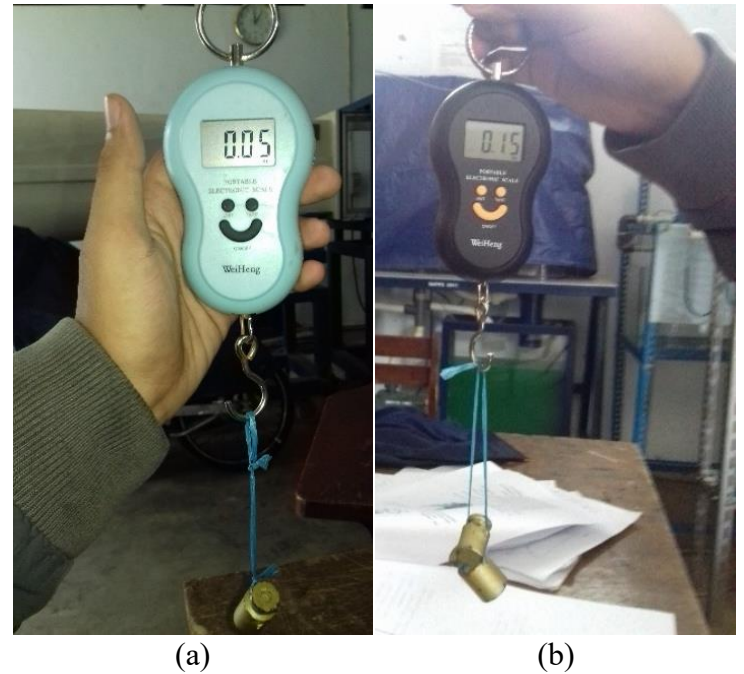


Fig. 8. Calibration process of Spring Scale 1 (a) and Spring Scale 2 (b)

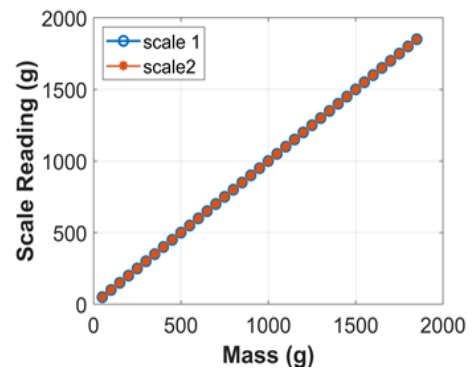


Fig. 9. Calibration graphs of both scales used in load measurement

Based on the calibration results, the spring-based scales exhibit linear response with an estimated measurement uncertainty of ± 0.02 kg. The handheld tachometer used in this study has a precision of ± 1 RPM. Possible experimental errors may arise from belt misalignment, operator timing in reading peak RPM, and slight flow variations during measurement. These uncertainties were taken into account when interpreting the turbine performance results.

2.5 Experimental variations

In this study, the inclination angle (β) of the Archimedes screw turbine was varied at (β) 22° , 25° dan 27° (Table. 1). Additionally, the pitch distance was also varied to create four different P/D ratio

Table 1. Dimensional variations and inclination angle variations in the experiment

Inclination Angle β	Head (H) m	Variations	L3 (mm)	L2 (mm)	L1 (mm)	D (mm)	d (mm)	P (mm)	P/D	N (Number of Screws)
22°	0.25	A ₂₂ $^\circ$	860	760	650	142	32	44	0.3	15
		B ₂₂ $^\circ$	860	760	650	142	32	54	0.38	12
		C ₂₂ $^\circ$	860	760	650	142	32	64	0.45	10
		D ₂₂ $^\circ$	860	760	650	142	32	74	0.52	9
25°	0.3	A ₂₅ $^\circ$	860	760	650	142	32	44	0.3	15
		B ₂₅ $^\circ$	860	760	650	142	32	54	0.38	12
		C ₂₅ $^\circ$	860	760	650	142	32	64	0.45	10
		D ₂₅ $^\circ$	860	760	650	142	32	74	0.52	9
27°	0.33	A ₂₇ $^\circ$	860	760	650	142	32	44	0.3	15
		B ₂₇ $^\circ$	860	760	650	142	32	54	0.38	12
		C ₂₇ $^\circ$	860	760	650	142	32	64	0.45	10
		D ₂₇ $^\circ$	860	760	650	142	32	74	0.52	9

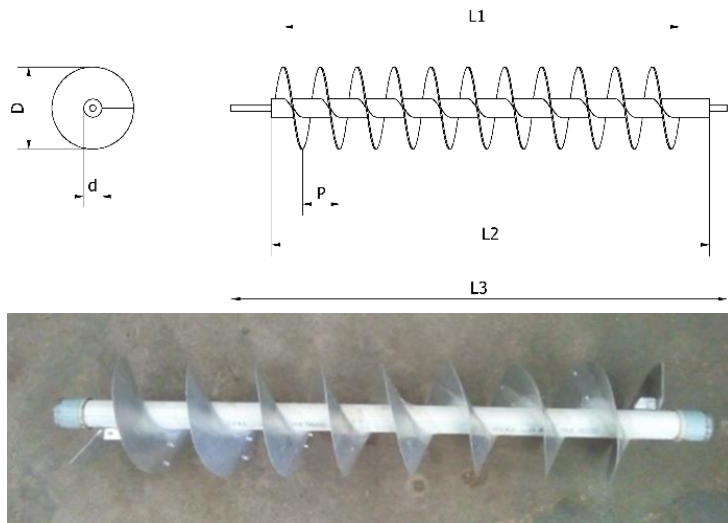


Fig. 10. Test model design

The parameter description in Fig. 10 are d is hub diameter (32mm), D is screw diameter (42mm), P is pitch (44mm, 54mm, 64mm, and 74mm), L₁ is screw length is 650mm, L₂ is hub length (760mm), L₃ is shaft length (860mm)

3 Results and discussion

3.1 Torque

The experimental results consist of curves showing the relationship between rotational speed, inclination angle, torque, power, and turbine efficiency. Additionally, a more detailed analysis will be conducted on the case that produces the highest values for torque, power, and efficiency, presented in the form of torque, power, and efficiency spectra.

The analysis of the 3D curve in Fig. 11 shows that the variation in the P/D significantly affects the generated torque. For all inclination angles (β), a P/D ratio of 0.45 consistently yields the highest torque compared to other P/D variations, while a P/D of 0.3 produces the lowest torque. This trend is evident across the entire range of rotational speeds (RPM). The graph also indicates that an inclination angle of $\beta=22^\circ$ results in the highest torque compared to $\beta=25^\circ$ and $\beta=27^\circ$, particularly when the P/D ratio is 0.45. At lower rotational speeds (40–100 RPM), the differences in torque among the various P/D ratios are even more pronounced, demonstrating that an inclination angle of $\beta=22^\circ$ provides a higher torque under low-speed operating conditions. As the rotational speed increases to 200 RPM, the torque values gradually decrease for all combinations of β and P/D; however, the overall relationship pattern remains consistent.

These findings are in strong agreement with the experimental study by [24], which identified an inclination angle of 22° as the

most effective for maximizing torque in Archimedes screw turbines. The detailed dimensions of the screw model used in this research are shown in Fig. 10, with P/D ratios of 0.30, 0.38, 0.45, and 0.52. The clearance between the screw and the outer casing is 2 mm, resulting in an outer casing diameter of 146 mm.

most effective for maximizing torque in Archimedes screw turbines. In the present work, $\beta = 22^\circ$ consistently yielded the highest torque across all P/D ratios, particularly at P/D = 0.45.

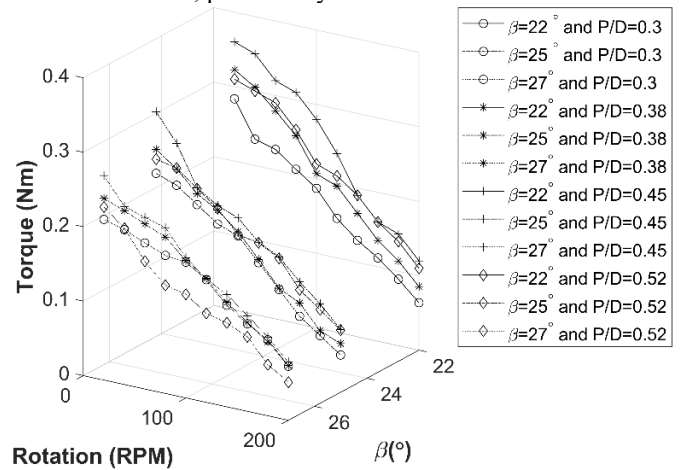


Fig. 11. 3D curve illustrating the relationship between rotational speed (RPM) and inclination angle ($^\circ$) on generated torque (Nm). Maximum torque was observed at $\beta = 22^\circ$ and P/D = 0.45, particularly at low RPM (30–60), highlighting the superior torque performance of this configuration

Moreover, these results align with the theoretical review presented by Nurdin and Himawanto [22], who reported that increasing the pitch ratio improves torque performance. Although their study did not involve direct experimentation, it referenced CFD simulations by Waters [25], which showed that a larger pitch increases the volume of water retained in each screw chamber, thereby enhancing rotational force. The agreement between these prior theoretical insights and the present experimental data reinforces the conclusion that the configuration of $\beta = 22^\circ$ and P/D = 0.45 provides optimal torque performance for low-head hydropower applications.

3.2 Torque spectrum

Based on the color map in Fig. 12, the horizontal axis represents the rotational speed (RPM), while the vertical axis represents the inclination angle (β) variation from 22° to 27° . The color scale indicates the generated torque values. It can be observed that the region with the highest torque is located at the lower inclination angle of around 22° , especially when the rotational speed is relatively low to moderate (approximately 30–60 RPM). As the rotational speed increases toward 120 RPM, the torque values tend to decrease across all inclination angles, and similarly, an increase in the inclination angle to 25° or 27° also results in lower torque values. This pattern reinforces the previous findings that a configuration with P/D=0.45 and $\beta=22^\circ$ is optimal for achieving maximum torque,

while higher inclination angles and/or higher rotational speeds tend to reduce the torque output. Thus, the color map provides a clear visual representation of the influence of the combination of inclination angle and rotational speed on the torque performance of the screw turbine with a P/D ratio of 0.45.

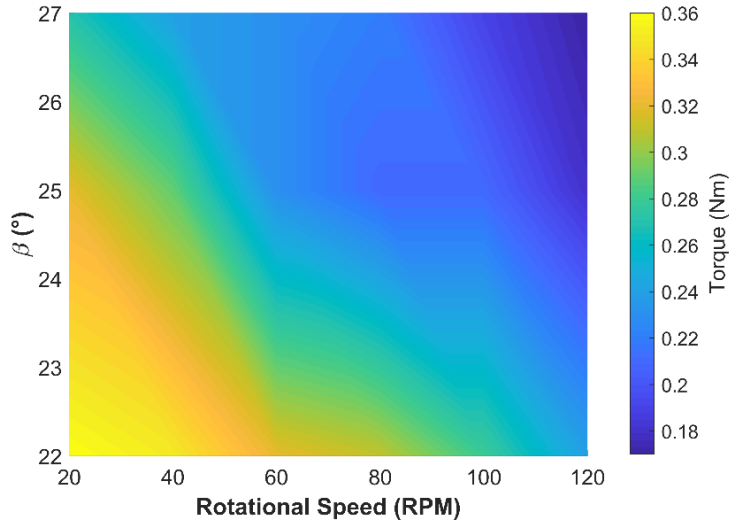


Fig. 12. Spectrum of rotational speed and inclination angle versus generated torque at P/D 0.45

3.3 Power

The 3D curve in Fig. 13 clearly indicates that the generated power is highly sensitive to changes in rotational speed (RPM), inclination angle (β), and P/D. An increase in rotational speed up to a certain point generally increases the power output, before the power declines at higher speeds. Additionally, the curves for inclination angles of 22°, 25°, and 27° reveal distinct differences in the power peaks; certain angles achieve higher peak power than others. In general, larger P/D ratios (for example, 0.45 or 0.52) tend to yield higher maximum power, while a smaller P/D ratio (0.3) produces relatively lower power across the full range of rotational speeds. This indicates that there exists an optimal operating point—at a specific combination of inclination angle and rotational speed—to maximize the power output. Consequently, determining the appropriate operating conditions, including the selection of the inclination angle (β), P/D ratio, and rotational speed, is crucial for optimizing the performance of the screw turbine system in terms of power.

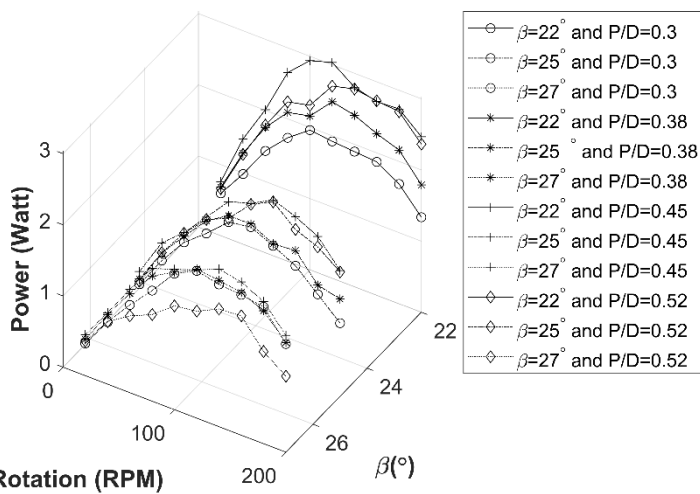


Fig. 13. Curve of the relationship between rotational speed and inclination angle versus generated power

3.4 Power spectrum

Since the power output tends to reach its maximum at a P/D ratio of 0.45, a more detailed analysis is conducted for this configuration. Based on the color map shown in Fig. 14, the horizontal axis represents rotational speeds ranging from 20 to 200 RPM, while the vertical axis illustrates the variation of inclination angles (β) from

22° to 27°. The color scale indicates the power output in watts. It can be seen that power generally peaks at intermediate inclination angles, approximately 23°–24° (noting that in this experimental case, the optimal is around 22°), particularly when the rotational speed is between 80 and 140 RPM. This optimal region is highlighted by a gradient toward yellow, signifying higher power outputs compared to other angle and speed combinations. In contrast, at higher (>25°) or lower (<22.5°) angles, as well as at very low (<40 RPM) or very high (>160 RPM) rotational speeds, the power output decreases. This trend suggests that the most efficient operation is achieved at an inclination angle of about 23°–24° and a rotational speed between 80 and 140 RPM, where the power output is maximized. These results emphasize that, with a P/D ratio of 0.45, selecting the optimal inclination angle and rotational speed is essential for obtaining the best power performance in the screw turbine.

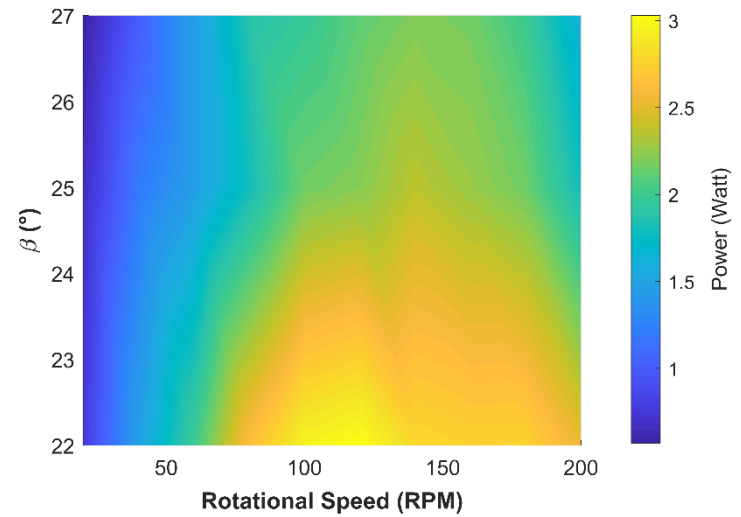


Fig. 14. Spectrum of rotational speed and inclination angle versus generated power at P/D 0.45

3.5 Efficiency

The 3D curve presented in Fig. 15 illustrates that both the inclination angle (β) and the P/D ratio are key parameters influencing the efficiency of the screw turbine. Among the various combinations examined, a 22° inclination angle consistently achieves the highest efficiency compared to angles of 25° or 27°. In addition, a P/D ratio of 0.45 outperforms others by providing relatively higher efficiency across the entire range of rotational speeds. In contrast, P/D ratios that are either lower (e.g., 0.3) or higher (e.g., 0.52) tend to result in reduced efficiency, particularly at moderate speeds. This trend indicates that the optimal configuration for maximizing the screw turbine system's efficiency is achieved with an inclination angle of 22° combined with a P/D ratio of 0.45, which aligns with previous findings that identified this configuration as having the best torque and power performance.

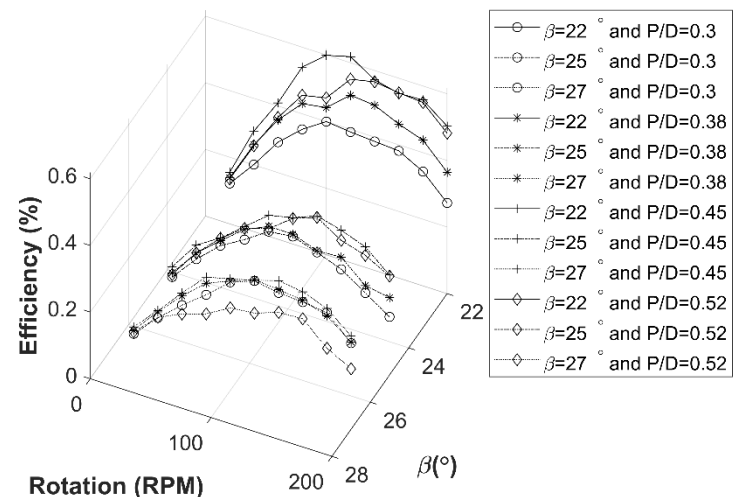


Fig. 15. Curve of the relationship between rotational speed and inclination angle versus screw turbine efficiency

3.6 Efficiency spectrum

To provide a more comprehensive overview of the efficiency performance for the $P/D = 0.45$ configuration, an efficiency spectrum was mapped against variations in inclination angle (β) and rotational speed (RPM), as illustrated in Fig. 16. The mapping results reveal that the highest efficiency is consistently achieved at lower inclination angles, particularly around $\beta = 22^\circ$, and at moderate to high rotational speeds, although it remains unclear whether further increases in RPM will continue to enhance or rather reduce efficiency. Conversely, at higher inclination angles (e.g., $\beta = 25^\circ$ and 27°) or at very low rotational speeds, the efficiency tends to decline. This pattern supports previous findings that identified $P/D = 0.45$ as the most optimal configuration, underscoring the importance of selecting the appropriate inclination angle and rotational speed to maximize the efficiency of the screw system.

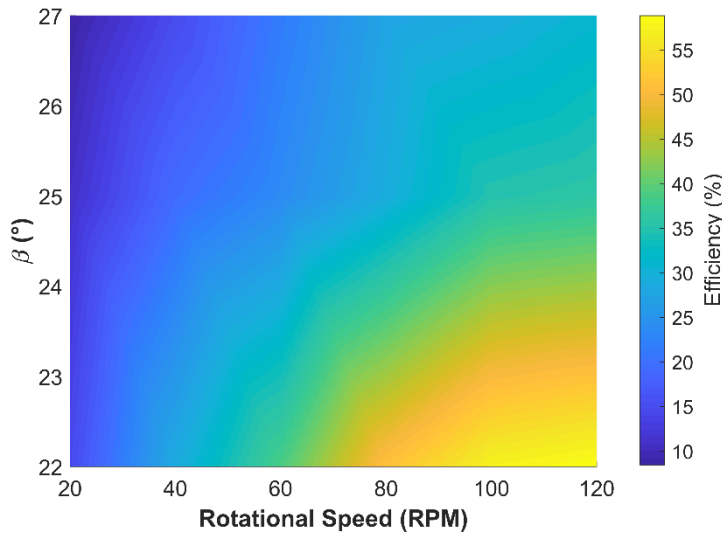


Fig. 16. Spectrum of Rotational Speed and Inclination Angle Versus Screw Turbine Efficiency at $P/D = 0.45$

The superior performance observed at a P/D ratio of 0.45 can be attributed to its ability to balance water volume retention with effective rotational dynamics. When the P/D is too small (e.g., 0.30), the screw becomes overly compact, restricting the volume of water transported per rotation and increasing frictional resistance. Conversely, a larger P/D such as 0.52 (as tested in this study) results in excessive spacing between screw threads, leading to partial water slippage and reduced torque transfer. Thus, the $P/D = 0.45$ configuration offers optimal flow containment and energy conversion, resulting in superior torque and efficiency outcomes. These results underscore the importance of selecting not only the correct P/D ratio but also the appropriate inclination angle and rotational speed to maximize overall turbine performance. Furthermore, the findings can inform the design of compact and efficient Archimedes screw turbines, particularly for rural or off-grid low-head hydropower applications.

4 Conclusion

This study confirms that the geometric configuration of (P/D) and inclination angle (β) have a critical role in the performance of Archimedes screw turbines for low-head hydropower applications. The combination of $P/D = 0.45$ and $\beta = 22^\circ$ produced the most efficient energy conversion that yielded a peak torque of 0.36 Nm, a power output of 2.4 W, and a maximum efficiency of 52.37%. These results suggest that shallower inclination angles improve turbine efficiency by increasing water capture and reducing slippage losses. The research demonstrates that careful parameter tuning can significantly enhance turbine output without requiring complex modifications or high manufacturing costs, making it particularly relevant for rural electrification and decentralized energy systems. Furthermore, the laboratory-scale outcomes lay a solid foundation for scaling the design to real-world, low-head sites. For future work, it is recommended to validate these experimental results through

CFD simulations and to conduct larger-scale testing under real flow conditions in order to assess long-term performance and structural resilience.

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