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The Effect Of Pitch Ratio On Screw Turbine Performance With Tip Fin

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ABSTRACT

A water turbine is an energy conversion machine that converts water head into shaft movement. In screw-type turbines, performance is influenced by several parameters including outer diameter, inner diameter, rotor length, head angle, number of blades, and pitch distance. This research uses a screw turbine type with a tip fin. The research aims to determine the performance of screw turbines with tip fins on mechanical power and efficiency. The research independent variables consist of pitch ratio and flow rate. The pitch ratio variations used are 1.2; 1.4 and 1.6 while the variations in flow rate used are 3 l/s, 3.5 l/s, and 4 l/s. The method used in this research is experimental. This study's data analysis employed the two-way Anova method with an alpha (α) of 5%. Anova's results show that the P-value of the interaction of the two independent variables, pitch ratio and water discharge, is <0.05, meaning that the independent variables have a significant influence on the performance of the screw turbine. The highest turbine performance results were at a pitch ratio of 1.4 at a water flow rate of 4 l/s resulting in an efficiency value of 34.91% and a mechanical power value of 6.82 watts at a rotational speed of 125 RPM. The lowest turbine performance results at a pitch ratio of 1.2 with a flow rate of 3 l/s resulting in an efficiency of 22.64% and a mechanical power of 3.32 watts at a rotational speed of 56 RPM.

Keywords: screw turbine, pitch ratio, tip fin, mechanical power, efficiency

Introduction

Indonesia has many energy sources, both non-renewable and renewable. Non-renewable energy sources include fossil fuels in the form of coal, natural gas, and petroleum. Meanwhile, renewable energy is in the form of solar energy, water energy, air energy, and geothermal energy. In 2006, the Ministry of Energy and Mineral Resources stated that oil reserves would run out in 23 years, natural gas in 62 years, and coal in 146 years [1]. With that fact, unfortunately, the energy most widely used by Indonesian people today is non-renewable. On the other hand, abundant water resources have not been utilized optimally. Hydroelectric Power Plants are expected to be able to fulfill the electricity supply for the Indonesian people [2]. One of the generators that has been proven not to damage the environment uses renewable energy, a hydroelectric power plant [3]. The existence of large reservoirs in Indonesia is used to store water and is also used for electrical energy, this is because the water supply in Indonesia is quite abundant and has been developed to produce water energy into electrical energy [4]. Research related to the development of water turbines has been widely carried out. The types of turbines being developed include propellers [5] or V-shaped ocean Current Turbines which were developed by simulation using QBlade software showing

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that blade aspect ratio and solidity greatly influence efficiency and self-starting capability [6]. Indonesia has many rivers that are not large and have low heads. One type of water turbine that has the potential to be developed in these conditions is the screw turbine. The advantages of using a screw turbine are that it does not require high costs, is simple and easy to use, the fish ecosystem is not disturbed, also maintenance and operation are easy [7-8]. The screw turbine is one of the turbines in the Pico Hydropower plant, namely a small-scale power plant that uses water power as its driving force, such as in irrigation canals, rivers, or natural waterfalls by utilizing the height of the waterfall head and the amount of water discharge [9]. The performance of a screw turbine depends on several parameters, namely rotor length, outer diameter, inner diameter, tilt angle, number of blades, and pitch [10]. Several researchers carried out analytical methods in the form of a single equation developed to estimate the geometry of Archimedes threads [11]. The presented theoretical model [12] can be used to predict ASG performance and especially to determine the optimal flow rate or rotational speed. To be effective at low screw filling, the gap leakage model will be improved. Other researchers present useful considerations regarding the selection of parameters of Archimedes screw turbines during their design, the formula for calculating the outer diameter of the screw is obtained based on a simple approximation of the bucket volume and a correction factor [13]. Research regarding the head angle of screw turbines has also been carried out [3, 14-15] where there is an optimal operating angle for Archimedes screw turbines.

In this research, a new screw turbine design was carried out. Screw turbines are equipped with fins on the edge of the thread which are called fin tips. This research aims to determine the effect of pitch ratio and flow rate on mechanical power and efficiency in screw turbines with fin tips.

Methods

This research was carried out using experimental methods. The independent variables of this research are variations in pitch ratio and water flow rate to determine their effect on screw turbine performance which includes mechanical power and efficiency. Figure 1 shows a research flowchart that explains the steps of this research.

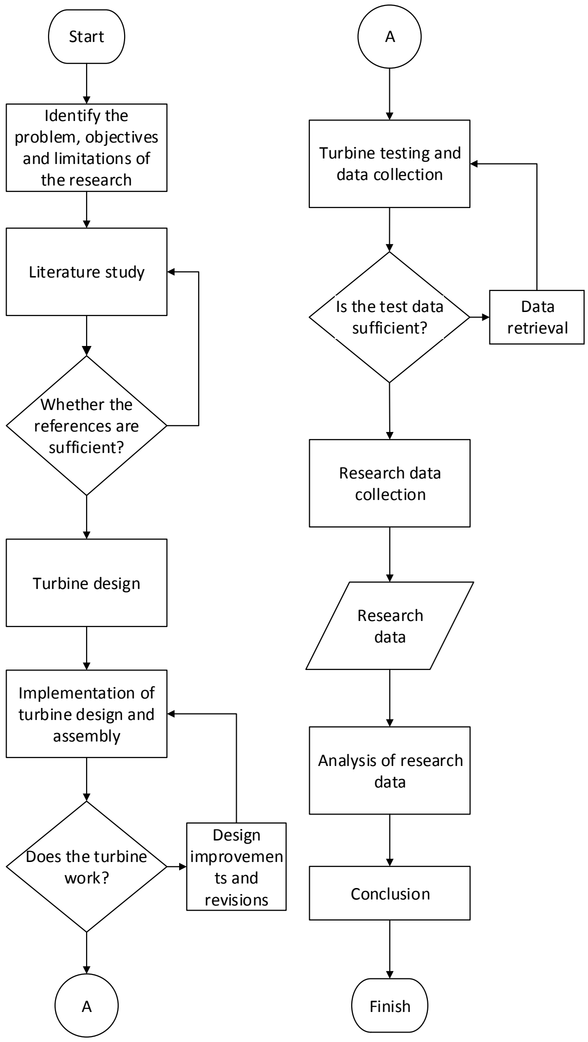

Figure 1. Research Flow Diagram

The variables used in this research are independent variables consisting of pitch ratio and flow rate. The pitch ratio is the ratio between the pitch distance and the outer diameter of the screw turbine. The pitch distance and outer diameter of the thread are shown in Figure 2. This research uses pitch ratio variations of 1.2, 1.4, and 1.6. The flow rates used are 3 l/s, 3.5 l/s, and 4 l/s.

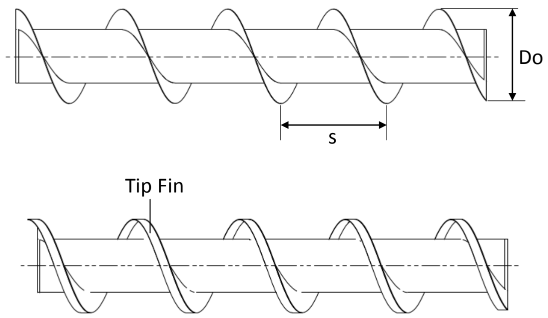

Figure 2. Pitch distance (s), diameter outer (Do), and tip fin

The controlled variables in this study are; turbine head inclination is 30º, with a hub ratio of 0.54 and a tip fin height of 20 mm. The dependent variables in this research are mechanical power and mechanical efficiency.

The experimental setup is presented in Figure 3. Water is pumped into the upper tank container and then flows to the turbine by opening the output valve. The flow rate used is adjusted to the independent variables of this research. The flow rate is monitored on the flowmeter display control to check whether the target has been achieved. When the turbine is rotating, the RPM is measured using a tachometer, and the force on the turbine shaft is measured using a rope brake dynamometer where a certain load will be given to provide a braking effect so that the torque can be calculated at a certain rotation. The water that comes down from the screw turbine is collected in the lower tank which will be pumped again to the upper reservoir continuously. The bypass line is used as a water outlet when setting the water flow rate on the main line so as not to damage the water pump.

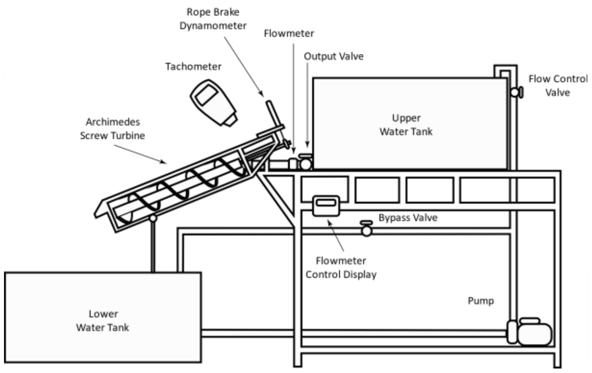

Figure 3. The experimental setup

The results of the experiment are load data (F) and RPM rotation (n) with 3 replications each. These data are then calculated to find mechanical power and efficiency. But before that, it is necessary to calculate the torque obtained using Equation 1.

$$T = (F_2 - F_1) \times R \quad (1)$$

After the torque value is obtained, the next step is to calculate the mechanical power that will be generated from the torque value, using Equation 2.

$$P_M = \frac{2.\pi.n.T}{60} \quad (2)$$

The hydraulic power is calculated using Equation 3. Water density (ρ) is 997 Kg/m3 and flow rate (Q) is the independent variable. The height of the falling water (H) is obtained from the trigonometry equation between the rotor length and the inclination angle.

$$P_H = \rho.g.Q.H \quad (3)$$

Turbine efficiency (η) is obtained from the comparison between mechanical power and hydraulic power as shown in Equation 4.

$$\eta = \left(\frac{P_m}{P_H}\right) \times 100\% \quad (4)$$

This study's data analysis employed the two-way Anova method with an alpha (α) of 5%.

Results and Discussions

The highest mechanical power experimental data is shown in Table 1.

Table 1. Highest mechanical power in each replication

Pitch Ratio	Mechanical Power (watt)		
	Q=3 l/s	Q=3,5 l/s	Q=4 l/s
1,2	3,325	4,437	5,354
	3,265	4,530	5,241
	3,363	4,519	5,276
1,4	4,553	5,748	6,679
	4,609	5,800	6,806
	4,759	6,110	7,121
1,6	4,567	4,555	5,004
	4,481	4,540	5,147
	4,605	4,677	5,082

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The highest efficiency experimental data is shown in Table 1.

Table 2. Highest efficiency in each replication

Pitch Ratio	Efficiency (%)		
	Q=3 l/s	Q=3,5 l/s	Q=4 l/s
1,2	23,147	26,594	27,178
	23,147	26,293	27,06
	23,416	26,498	27,551
1,4	31,697	34,301	34,878
	32,091	34,257	34,677
	32,136	34,262	35,186
1,6	31,8	26,181	26,101
	31,589	26,095	25,411
	32,064	27,913	25,537

The highest mechanical power and efficiency data in Tables 1 and 2 were then processed and tested statistically. The statistical data processing process uses Minitab software. Figure 4 is the result of statistical analysis obtained using the Minitab software application.

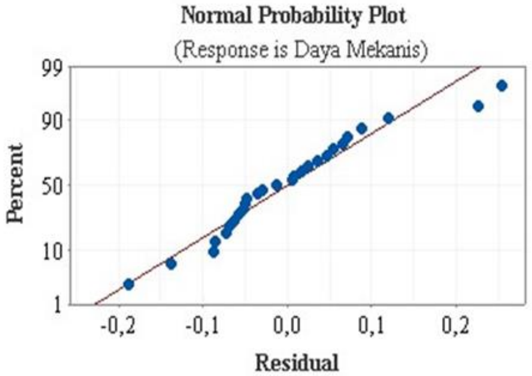

Figure 4. Normal probability plot of mechanical power

Figure 4 shows the plotting points approaching the red diagonal line or normal line, meaning that the distribution of this research data follows a normal distribution under statistical data requirements.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pitch Ratio	2	9,9169	4,95846	357,42	0,000
Debit (Q)	2	11,1833	5,59166	403,07	0,000
Pitch Ratio*Debit (Q)	4	2,7269	0,68173	49,14	0,000
Error	18	0,2497	0,01387		
Total	26	24,0769			

Figure 5. ANOVA for mechanical power

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,117783	98,96%	98,50%	97,67%

Figure 6. Model summary for mechanical power

Anova in Figure 5 shows that the P-value flow rate is less than the predetermined alpha (P-value>α. This means that the water flow rate has a significant effect on the mechanical power of the screw turbine. The pitch ratio also has a P-value of less than 0.05, which means that the pitch ratio also has a significant effect on the mechanical power of the screw turbine. The interaction of the two variables on turbine performance shows a value of less than 0.05, which means that in this study there is an interaction between the two variables.

The coefficient of determination or R^2 value was 97.67% (Figure 6). The coefficient of determination value serves to see the effect of pitch ratio and water flow rate on mechanical power. The more the value of the coefficient of determination approaches 100%. This means that the more significant the two independent variables are in influencing the dependent variable.

Figure 7 shows a normal probability plot of efficiency. The plotting points approach the red diagonal line or normal line, meaning that the distribution of this research data follows a normal distribution under statistical data requirements.

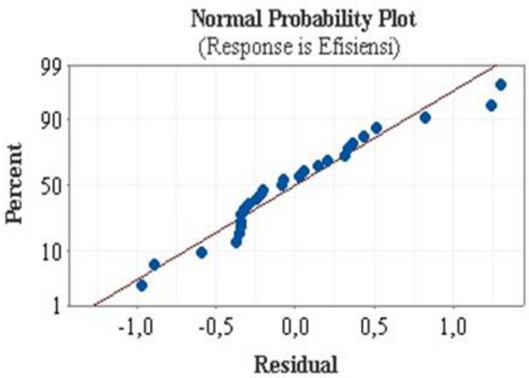

Figure 7. Normal probability plot of efficiency

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Pitch Ratio	2	332,874	166,437	386,94	0,000
Debit (Q)	2	3,148	1,574	3,66	0,046
Pitch Ratio*Debit (Q)	4	104,102	26,026	60,50	0,000
Error	18	7,743	0,430		
Total	26	447,868			

Figure 8. ANOVA for efficiency

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,655851	98,27%	97,50%	96,11%

Figure 9. Model summary for efficiency

Anova in Figure 8 shows that the P-value flow rate is less than the predetermined alpha (P-value>α). This means that the water flow rate has a significant effect on the screw turbine efficiency. The pitch ratio also has a P-value of less than 0.05, which means that the pitch ratio also has a significant effect on the screw turbine efficiency. The interaction of the two variables on turbine performance shows a value of less than 0.05, which means that in this study there is an interaction between the two variables.

The coefficient of determination or R^2 value was 96.11% (Figure 9). The coefficient of determination value serves to see the effect of pitch ratio and water flow rate on screw turbine efficiency. The more the value of the coefficient of determination approaches 100%. This means that the more significant the two independent variables are in influencing the dependent variable.

The effect of pitch ratio on mechanical power is shown in Figure 10. Changes in mechanical power occur with each variation in pitch ratio. The curve trend shows that there is an increase in mechanical power as the pitch ratio increases, but after reaching the peak, with the next increase in pitch ratio, the mechanical power will decrease. The highest value of mechanical power is achieved at a pitch ratio of 1.4 with a flow rate of 4 l/s which produces mechanical power of 6,82 watts at 125 RPM. The lowest mechanical power is produced at a pitch ratio of 1.2 and a flow rate of 3 l/s of 3,32 watts at 56 RPM.

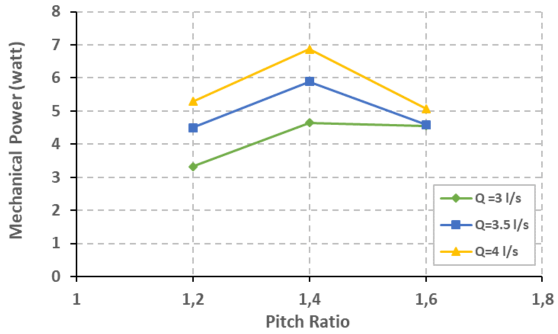

Figure 10. The effect of pitch ratio on mechanical power

Figure 11 shows the effect of water flow rate on mechanical power. Mechanical power along with increasing flow rate. It can be understood that the greater the flow rate, the greater the hydraulic power that can be converted into mechanical power. An increase in flow rate that exceeds the design capacity of the turbine will not increase mechanical power and will reduce the efficiency of the screw turbine.

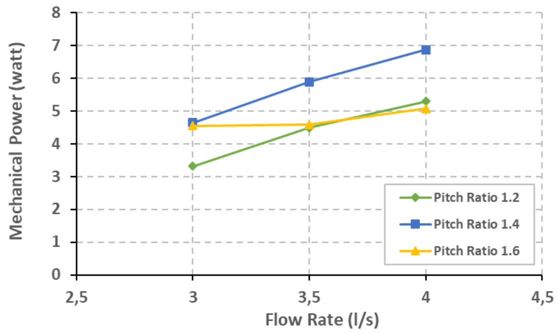

Figure 11. The effect of flow rate on mechanical power

The effect of pitch ratio on efficiency is shown in Figure 12. As with mechanical power, in the efficiency Figure 12, there is a certain pitch ratio value that produces the highest efficiency. When the pitch ratio is lowered or increased beyond this value, efficiency will decrease. In this experiment, the highest efficiency of 34.91% was achieved at a pitch ratio of 1.4, a flow rate of 4 l/s, and the lowest value was at a pitch ratio of 1.2 with a flow rate of 3 l/s, 22.64%.

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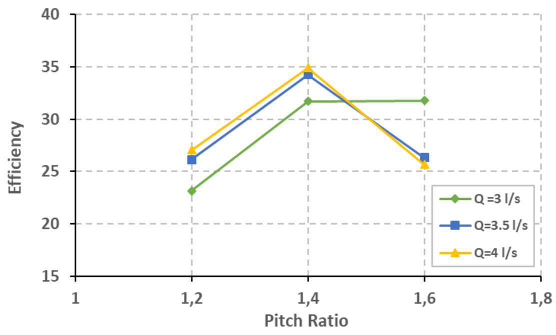

Figure 12. The effect of pitch ratio on efficiency

The effect of flow rate on efficiency is presented in Figure 13. The figure shows the effect of flow rate on efficiency. Increasing the flow rate increases efficiency. At a higher flow rate, the increase in efficiency is less than at a low flow rate. This shows that there will be a peak where increasing the flow rate will reduce efficiency. The increase in hydraulic power caused by an increase in flow rate is not comparable to the increase in mechanical power. This is mainly related to the capacity of the screw turbine.

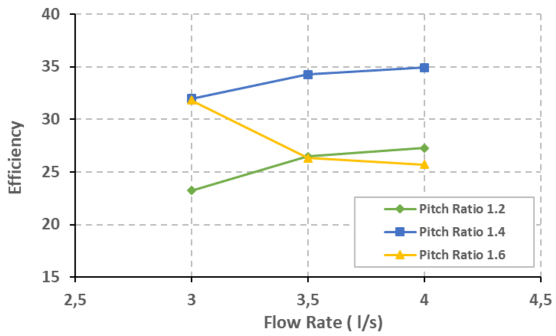

Figure 13. The effect of flow rate on efficiency

The interaction effect of pitch ratio and water flow rate on mechanical power is presented in Figure 14. A pitch ratio of 1.4 produces greater mechanical power compared to a pitch ratio of 1.6 at the same flow rate. This happens because screw turbine blades with a pitch ratio of 1.4 can convert water flow energy more efficiently than screw turbine blades with a pitch ratio of 1.6 or 1.2. If the pitch ratio is too small, then a lot of flow energy will be lost. The residence time of the water becomes longer because the path it takes becomes longer. With a long path, the possibility of losses will increase. If the pitch ratio is too large, the screw turbine blade angle is larger, resulting in more turbulence and energy loss due to friction between the screw turbine blade and the water flow. This may result in a decrease in output power.

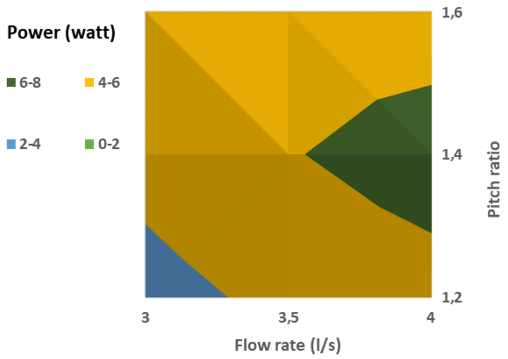

Figure 14. Interaction of flow rate and pitch ratio on mechanical power

The interaction effect of pitch ratio and water flow rate on efficiency is presented in Figure 15. At low flow rates, to obtain high efficiency it is necessary to use a turbine design with a high pitch ratio. The higher the flow rate, the use of a turbine with a lower pitch ratio will produce better efficiency. At low discharge, using a higher pitch ratio causes the water to come out faster and its momentum is converted into rotary motion. If at a small flow rate, a small pitch ratio is used, then the flow path will be longer. A low flow rate will result in a loss of momentum and many losses. On the other hand, at large discharges, using a small pitch ratio will result in higher efficiency. At large discharges, the flow energy is also large, able to overcome losses due to the length of the path. A low pitch ratio results in a greater number of threads per unit rotor length. This thread can reduce turbulence due to a large flow rate, thereby increasing efficiency.

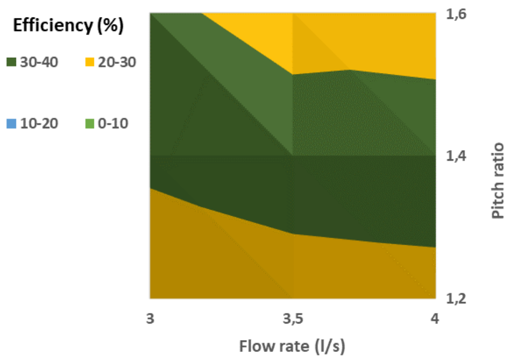

Figure 15. Interaction of flow rate and pitch ratio on efficiency

Conclusions

Based on the experiments and data analysis that have been carried out, it can be concluded that variations in pitch ratio and discharge greatly influence the mechanical power and efficiency produced by the screw turbine. The highest mechanical power value of 6,82 watts and the highest efficiency of 34,91% were obtained at a pitch ratio of 1.4 and a flow rate of 4 l/m. Compared to a pitch ratio of 1.2, a pitch ratio of 1.4 obtains greater power and efficiency. However, when the pitch ratio is increased to 1.6, the mechanical power and efficiency obtained are lower.

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Author Contributions

Conceptualization: S.A.; methodology: S.A.; hardware: M.M.A.; validation: S.A.; formal analysis: S.A.; Material and Manufacture: M.M.A.; writing—original draft preparation: S.A. and M.M.A.; writing-review and editing: S.A.; supervision: S.A.; funding acquisition: S.A. and M.M.A. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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