Study on the Efficiency of the Savonius Hydro Turbines Installed in Water Pipes

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Abstract

Hydroelectric power generation has predominantly been large-scale, relying on infrastructure like dams, and rivers. There has been significant expansion of various types of water pipe systems, industrial, and irrigation systems, and there is growing interest in sustainable energy, especially in regions with limited electricity access. For this study, we chose the Savonius turbine, a vertical cross-flow turbine classified as a low-head turbine. The Savonius hydro turbine (SHT) offers benefits like operation at low flow rates and head, and simplified maintenance. However, its low efficiency limits its application. This study aimed to enhance SHT efficiency for small water pipes with low flow and head, focusing on the factors influencing turbine performance. The factors studied were the number of blades, the number of stages, the phase shift angle, the stage height ratio, the aspect ratio (AR), and the use of a baffle plate. The tests involved testing the coefficient of power (C_P), the coefficient of torque (C_m), and the tip speed ratio (TSR). Twelve types of SHT were installed with a guide vane to adjust the inlet angle to 30°. The turbines were installed in 4-inch PVC pipes. The volumetric flow rate of water through the pipes was varied, with values of 5, 10, 15, 20, and 25 m^3/hr. The results indicated that the SHT M5-1 with 3 blades, 3 stages, a height ratio of 1:1:1, a 60° angle of phase shift, AR=1.4, and a baffle plate, exhibited the highest efficiency at a flow rate of 25m^3 /hr. The C_P, $C_{m,}$ and TSR were measured at 0.272, 0.313 and 0.871 respectively. Furthermore, the study also concluded that the SHT model M5-1 outperformed the SHT model M1-2, showing increases in the C_p of 0.174 and C_m of 0.198. ANOVA analysis was used to examine the parameters that affect turbine efficiency. It was found that the six factors and flow rate significantly influenced turbine efficiency. Notably, the M5 - 1 turbine exhibited the highest efficiency, which aligns with the experimental results.

Keywords: Savonius hydro turbine, Baffle plate, Guide vane, Coefficient of power, Coefficient of torque, ANOVA

Introduction

Hydro turbines are the most widely used method of converting kinetic energy to mechanical energy in water to generate electricity. Public utilities could generate electric energy in small-scale water supply systems, community wastewater systems, industrial wastewater systems, or agricultural irrigation systems, distinct from large-scale hydropower generation. This study focussed on low-flow rate, and low-head, water pipe systems. Chen et al. (2013) presented a graph demonstrating the relationship between flow rate and head for various turbine types. They highlighted the Kaplan turbine's superior performance at low flow rates and heads. However, its installation can be challenging due to its water flow redirection, complicating integration into existing pipe systems. Conversely, cross-flow turbines offer similar operating characteristics and are more readily adaptable to small water pipeline systems.The Savonius turbine is one type of cross-flow turbine that was developed and first used in the year 1920. It was used in both wind and water turbines, including being used for electricity generation in rivers and tide-power generation in the ocean (Abulnaga, 1988).

The previous study by Ahmed & Zahed (2014) indicated that the SHT with 2 blades has a higher C_p than the 3-blade hydro turbine. A further study by (Hamzah et al., 2018), which included 2-blade and 3-blade turbines in sewage pipes with a water velocity of 0.80m/s, concluded that the turbine with 2 blades had a

64% improvement over that with 3 blades. Hamzah et al.'s tests with turbines 2-6 blades with an aspect ratio of 1 and an angle of attack 70°, concluded that the turbine with 3 blades has the highest C_p = 0.23; TSR=1.8. The turbine with 6 blades had the lowest C_p. (Talukdar et al., 2018) found that the C_p increased when the velocity of flow increased.

Research by (Khan et al., 2009) indicated that the number of stages of blades also affects the C_P. The SHT was used in 1-stage, 2-stage, and 3-stage rotors, with flow velocity = 1.0m/s; TSR=0.80, that study found that the 2-stage rotor had the highest C_P = 0.048. The 1-stage rotors had C_P at 0.038 and the 3-stage rotors at 0.040. Although the 2-stage rotor had the C_P, in rotors with more than 1-stage, a phase shift would affect the C_P. Another finding was that the 2-stage rotor, with a diameter of 0.142m, AR=0.36, and phase shift of 0° and 90°, phase-shifted 90° rotor was an efficiency increase of 28% over the 0° phase rotor which also had lower efficiency than the 1-stage rotor (Nakajima et al., 2008).

Influence of AR on the C_p

In investigating the influence of AR, with AR=0.53, the hydro turbine recorded a C_P =0.19, and with AR=1.06, the C_P was 0.05. This shows that the AR is inversely proportional to the C_P (Ibrahim et al., 2014). It was also found that a higher AR caused a higher pressure drop than rotors with a lower AR (Mabrouki et al., 2014). This shows the importance of AR in the efficiency of the rotors. Hence a study that thoroughly investigates the relationship is important. **A** further study on AR by (Patel et al., 2017), using AR=0.22 to 0.44 found that the C_P increases when AR increases. C_P is highest when AR =1.80 because kinetic energy is lost when AR increases.

Hydro turbine Blades

The material used to cover the hydro-turbine blades contributed to the efficiency of water circulation. If the cross-sectional area covered 50% of the turbine then the efficiency of the hydro turbine was measured at 43.83%. This is an improvement of 6.59% compared to the hydro turbines without blade coverings.

Other Factors Affecting C_p

Guide vane implementation significantly influences the coefficient of performance (CP) in small hydro turbines (SHTs). Studies demonstrate that guide vanes enhance efficiency, with varying degrees of impact depending on turbine staging and vane deflection angle. Specifically, increased efficiency and CP values are observed with optimized vane angles, while deviations reduce performance. This trend is consistent across multiple studies, highlighting the critical role of guide vane design in SHT optimization (Golecha et al., 2011; Prasetyo et al., 2018; Payambarpour et al., 2019; Sakti et al., 2019; Prawira & Wihadi, 2019).

Examples of research that utilizes turbines to generate energy in small pipes. (Hoffmann et al., 2013) study on the Radial flux energy harvester placed on the water pipeline to power up metering devices which produced a water flow rate of 20 L/min, the device generated electricity up to 720 mW. The energy generated is deficient but sufficient enough to power up low-power usage devices such as a smart meter. (Jusoh et al., 2014) studied in-pipe hydropower to harness the flow of water from household piping. The system utilized a butterfly-type water turbine, which is connected to a DC generator and installed in a water pipe a diameter 30 mm. The amount of electricity generated by this system is relatively low. To enhance efficiency, it may be beneficial to replace the existing turbine with a more effective design, such as a solid or hollow spherical blade turbine or a cross-flow turbine. (Teruhisa et al., 2018) conducted a laboratory study on electricity generation from sewage systems of high-rise buildings. The turbine blades were circular turbines with different numbers of blades. There were also water guides that helped control the water. The test used mechanical loads of 3 blade sizes, which showed that 6 blades had the highest efficiency of 39.6%. (Chen et al., 2013) designed and tested a turbine with blades like the Savonius turbine to generate local electronic equipment power. They applied a vertical-axis and drag-based turbine in a 4-inch pipeline and increased its output power to 88 W increased the number of blades to12, added a deflector, and hollowed the turbine center. A drag-based turbine turbine for small-diameter tubes and lift-based turbines for large-diameter tubes were studied and tested by (Tao et al., 2018). Recently, researchers have studied the effects of the deflector shape and aspect ratio of a new two-blade Savonius turbine. They found that the blockage coefficient and angle affect the shape of the deflector and the aspect ratio of the turbine affects the flow rate, output torque, and efficiency of the turbine. However, the increase in the deflector parameter is only positive up to a certain amount (Payambarpour et al., 2020) and (Ali et al., 2023) designed and tested the effect of three different three deflector shapes of dual-channel deflectors compared with a single channel of in-pipe Savonius turbine. They found all dual-channel deflectors. The efficiency of the Savonius turbine is lower with a dual-channel deflectors compared to a single-channel. Ali et al (2023) also examined an additional moving guide vane (MGV) deflector, which led to a more efficient turbine compared to a single-channel design and performed effectively at both high and low flow rates. As mentioned in the previous study, it was proven that turbine efficiency depends on many conditions. Few novel turbine designs are suitable for in-pipe installations. Therefore, the objective of this study was to identify the design parameters that optimize the efficiency of the Savonius turbine for low-flow and low-head in small pipe systems.

The Current Study

Improving the design of the Savonius turbines for enhanced efficiency is needed to identify the relationship between different factors on C_P. For example; the number of blades, the number of stages, the turbine stage ratio, the aspect ratio (AR), and a baffle plate. This study focuses on small diameter pipes with low flow rates and low head by comparing the C_P of old and new design SHT to in - pipes water.

Parameter effect and efficiency of Savonius Hydro turbine

1. Parameters for Improvement

This study focused on the different factors that impact the C_P of the SHT installed in water pipes with low head and discharge. Factors studied include, No. of blades, N_b; No. of stages, N_s; whether it is phase shifted; Height of level of turbines, H_s; Aspect ratio, AR; and Guide vane; to improve the efficiency of the SHT over the old designs.

2. Performance of Savonius Hydro turbine

To measure the efficiency of the hydro turbine, we use this Equation 1 to measure power input (P_{input})

$$P_{input} = \frac{1}{2}\rho A V_1^3 \quad (1)$$

where P_{input} is the power of water input measured in (W) $\dot{m}$; Discharge flow is measure in (kg/s) ρ is the density of water measured in kg/m^3; V_1 is the velocity of water measured in m/s and A is the cross-sectional area receiving water measured in m^2.

Mechanical energy (P) is measured by Equation 2.

$$P = T \, x \, \omega \qquad (2)$$

where T is he torque measured by a Prony brake (N.m); ω is the angular velocity of hydro turbine shaft (rad/s).

The torque from a Prony brake can be obtained from $T=F_p x R_p$, where F_p is the tensile force exerted by the Prony brake on the weight scale, R_p is the radius of the pulley connected to the turbine (Pongsakorn & Ratchaphon, 2016).

The coefficient of power, C_p is the ratio of mechanical energy to power input measured by Equation 3.

$$C_p = \frac{P}{P_{input}} \qquad (3)$$

The coefficient of torque, C_m is the ratio of torque generated by the turbine to the input of water power. This also gives us the efficiency of the hydro turbine is measured by Equation 4.

$$C_m = \frac{Tx\omega}{\frac{1}{2}\rho A V^3} = \frac{Tx(V/R)}{\frac{1}{2}\rho A V^3} = \frac{T}{\frac{1}{2}\rho A V^2 R} \qquad (4)$$

where V is the velocity of water (m/s); A is the cross-sectional area of the water received by the turbine (m^2); T is the torque of the hydro turbine (N.m); and R is the radius of the hydro turbine (m).

In addition to the C_P and C_m of the hydro turbine, the TSR is another variable of interest. This is the ratio of the linear velocity of the blade's tip to the velocity of water flowing through the turbine. This can be measured using Equation 5.

$$TSR = \frac{\omega \times r}{V} = \frac{C_p}{C_m} \qquad (5)$$

where radius, r is measured in m. (Saini & Saini, 2020)

Limited research exists on in-pipe water turbine design and development. The present investigation revealed that while in-pipe designs offer simplicity and improved low-flow performance (Roth, 1985), their contribution to overall electrical generation efficiency remains relatively low, necessitating further optimization.

Materials and Methods

1. Equipment for testing the Savonius hydro turbine system

Fig. 1 shows the equipment used in testing the SHT system. No.1 is the 1,000-litre water tank; No. 2 is the centrifugal water pump. No.3 is the maximum flow rate regulated at 30m^3/h and head ranging 10-22 m. No.5 are PVC water pipes measuring 4 inches in diameter. No.6 is the Ultrasonic flow meter to measure the flow of water through the test system. The test section is shown in Fig.2. No.4 is the bypass valve that is seen in Fig. 3 and 4. Next is No.7 which is the transparent plastic deflector used to control the flow of water through the test system that allows the researchers to observe the flow and response of the turbines seen in Fig. 1 which also shows the guide vanes that are installed on the inlet section of the test system. No.8 shows the SHT which can also be seen in Fig. 5. No.9, seen in Fig. 8, is the proximity sensor that measures the number of revolutions (rpm) of the turbine. No.10 is the Prony brake which measures the torque in the system (range 0.00147-1.47 Nm). No.11, shown in Fig. 5 and 6, shows the water output from the test system in the pipes to the water tank which is then pumped back into the system. Fig. 7 is the system to measure the torque of the hydro turbine. Measurements were taken using LabVIEW to record and present the data in the test system.

Each hydro turbine was tested at water flow rates 5, 10, 15, 20, and 25 m^3/h (or velocity 0.15, 0.29, 0.44, 0.58, and 0.7 m/s), and 12 different types of turbine designs were tested.

The data was collected and analyzed. The research conclusions are summarized in this article.

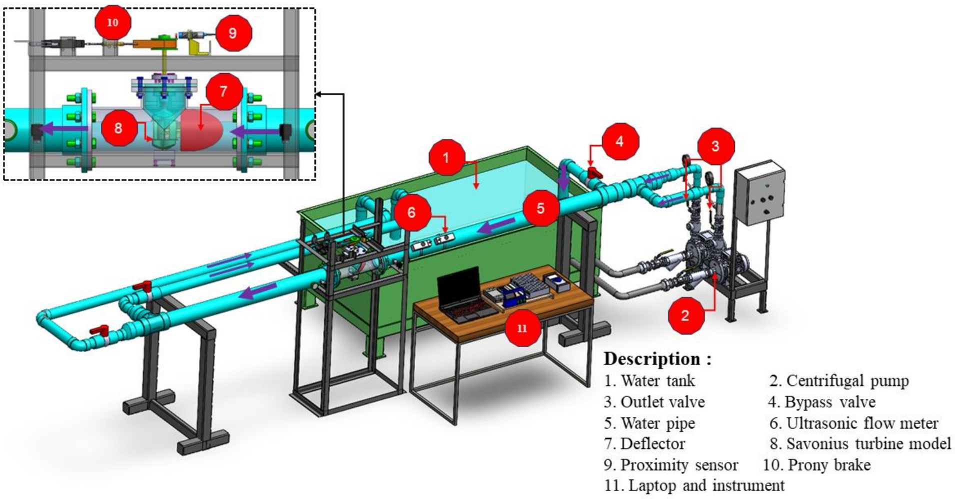


Figure 1 Equipment used in the testing the Savonius hydro turbine

Figure 2 Test section

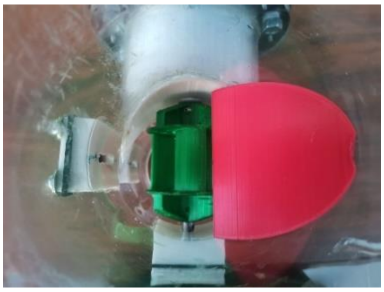


Figure 3 Guide vane (red colour)

Figure 4 Ultrasonic Flow Meter

Figure 5 Flow Sensor positioning

Figure 6 Proximate sensor to measure the speed of the turbine

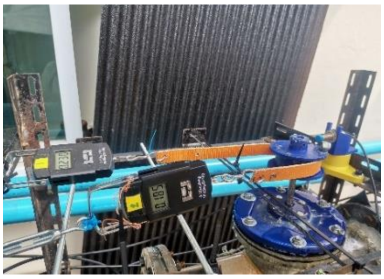


Figure 7 System to measure the torque of the hydro turbine

2. Savonius hydro turbine model

The hydro turbines used in the test system were quickly produced using a 3D printer to ensure the designs were accurate according to the required specifications. The turbine and deflector are made of Polyethylene Terephthalate Glycol (PETG). PETG is a kind of plastic generated from renewable resources and is of acceptable strength and impact resistance. The parameters chosen for developing the SHT model were selected for practicality in production. This required that the turbine structure be straightforward, which would make manufacturing easy and allow for operation in a variety of conditions. Additionally, it was important to ensure that the results could be efficiently compared.

This test utilized an aspect ratio (AR) of 1, with a semi-circular blade width equal to the turbine's radius. The turbine was fully enclosed at the top and bottom (e=0), as depicted in Fig. 8(A). To enhance efficiency, a 30° guide vane was installed, as shown in Fig. 8(B), following the design principles outlined by Menet (2004).

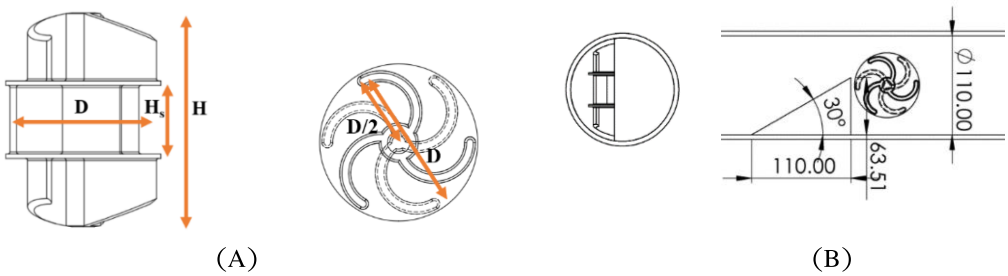


Figure 8 Parameters of the SHT (A) and guide vane (B)

The details of the relationship between the different factors and the efficiency of the SHT identified in this study are:

1) Influence of the number of blades (N_b) based on Mohamoud, 2013 using 2, 3 and 4 blades designated model M1-1, M1-2 and M1-3 respectively to determine the most efficient number of blades.

2) Influence of the number of levels (N_s) and the angle of phase shift to determine the most efficient design as shown in the models M2-1, M2-2, M2-3 and M2-4.

3) Influence of stage height ratio of the turbine (H_s) and the angle of the phase shift. This is shown in models M3-1 and M3-2.

4) Influence of the AR as seen in models M4-1 and M4-2. This was compared with the commonly used efficient hydro turbine design. After testing these 4 parameters the most efficient design can be used to compare against No.5

5) Influence of the baffle plate in the efficiency of the SHT design as seen in model M5-1.

6) The details of the different models and parameters are shown below in Table 1 and Fig. 9a-9l.

In addition to conducting experiments to assess the turbine's efficiency, a statistical analysis was performed using ANOVA to confirm the differences in parameters affecting the efficiency of the SHT. The independent variables included flow rates (5, 10, 15, 20, and 25 m^3/hr.), and turbine models (examining the effect of the number of turbine blades with models M1-1, M1-2, and M1-3). The response variable used to evaluate turbine efficiency was the power coefficient for each turbine. A Post Hoc Test (Tukey's HSD) was employed to identify which groups had statistically significant differences.

Table 1 Parameters of the 12 SHT test systems

Model	H*	D*	AR	N_b	N_s	H_s	Phase shifted	Baffle plate
M1-1	72	72	1	2	1	-	0	Yes
M1-2	72	72	1	3	1	-	0	Yes
M1-3	72	72	1	4	1	-	0	Yes
M2-1	100	72	1.4	2	2	1:1	0	NO
M2-2	100	72	1.4	2	2	1:1	90	NO
M2-3	100	72	1.4	3	3	1:1:1	0	NO
M2-4	100	72	1.4	3	3	1:1:1	60	NO
M3-1	100	72	1.4	3	3	1:2:1	0	NO
M3-2	100	72	1.4	3	3	1:2:1	60	NO
M4-1	100	84	1.2	3	3	1:1:1	60	NO
M4-2	100	62.5	1.6	3	3	1:1:1	60	NO
M5-1	100	72	1.4	3	3	1:1:1	60	Yes

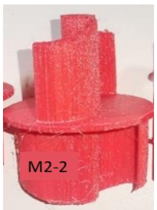
*Unit: mm.

(a) Model M1-1
(with baffle plate)

(b) Model M1-2
(with baffle plate)

(c) Model M1-3
(with baffle plate)

(d) Model M2-1
(without baffle plate)



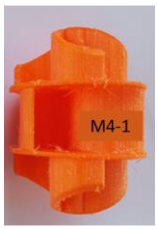
(e) Model M2-2
(without baffle plate)

(f) Model M2-3
(without baffle plate)

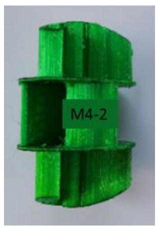
(g) Model M2-4
(without baffle plate)

(h) Model M3-1
(without baffle plate)

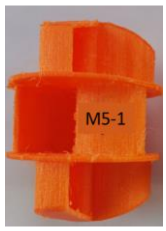
(i) Model M3-2
(without baffle plate)



(j) Model M4-1
(without baffle plate)



(k) Model M4-2
(without baffle plate)



(l) Model M5-1
(with baffle plate)

Figure 9 The12 SHT model used in the test system

Results and Discussion

This research identified the relationship between different parameters on the efficiency of the SHT C_p and C_m of 12 SHT in the test system. Each model was tested with a water discharge rate of 5, 10, 15, 20 and 25m^3/h (or velocity 0.15, 0.29, 0.44, 0.58, and 0.7 m/s) with a guide vane of angle 30^o. Each model was measured using the Prony brake to determine the torque and speed of revolutions of the turbine. Data collected was used to calculate torque, C_p and C_m which will be discussed in the following sections.

1. Study of the influence of number of blades (N_b)

From the Table 2, it is clear that after testing the 3 models with a guide vane of 30^o, model M1-2 has the highest C_p and C_m and also the fastest turbine rotation measured at 421.35 rpm when water discharge flow rate is 25m^3/h. The 3-blade turbine(M1-2) offers the highest efficiency due to its optimized design and the optimal gap between the blades. This gap allows water to strike the blades consistently, resulting in more uniform energy capture and improved performance. The design ensures that the blades interact with the water flow in the most efficient manner, reducing turbulence and maximizing energy conversion. In addition to improved energy capture, the 3-blade (M1-2) configuration facilitates easier and smoother startup of the turbine. The reduced drag and better alignment of the blades with the water flow make it easier for the turbine to begin rotating at lower speeds, enhancing overall operational efficiency. Furthermore, the torque distribution across the blades is significantly higher compared to other configurations, such as the 2-blade (M1-1) and 4-blade (M1-3) models. This enhanced torque distribution allows the turbine to generate more power with less effort. As a result, the 3-blade turbine outperforms both the 2-blade (M1-1) and 4-blade (M1-3) models in terms of efficiency, as indicated by its Cp, Cm, and TSR values of 0.098, 0.115, and 0.85, respectively, as shown in Table 2.

Table 2 Maximum $C_{p,}$ C_m and TSR with AR= 1.4, Guide Vane of 30^o for models M1-1, M1-2, and M1-3

Model	$C_{p,max}$	C_m at $C_{p,max}$	**TSR** at $C_{p,max}$	**Speed** (RPM)	**Flow rate** (m^3/hr)
M1-1	0.043±0.005	0.062±0.007	0.758±0.022	374.03±9.606	25
M1-2	**0.098±0.008**	**0.115±0.009**	**0.850±0.010**	**421.35±5.507**	**25**
M1-3	0.042±0.005	0.056±0.006	0.749±0.017	370.69±8.239	25

The ANOVA analysis examined how the number of turbine blades and the water flow rates significantly affected (the efficiency of the SHT). This analysis was conducted with an error rate of 5% and a confidence level of 95%. The results showed that all control factors had a significant impact on the response, as evidenced by p-values less than 0.05. However, the flow rates factor had a greater effect (p-value = 0.008, F-value = 7.595) than the turbine model factor (p-value = 0.039, F-value = 4.999). The ANOVA explained a variance in the data (R^2 = 83.5%) and other details can be seen in Table 3.

Subsequently, a Post Hoc Test (Tukey's HSD) was performed. The comparison of the SHT models revealed that the M1-1 and M1-3 turbines did not differ significantly, while the M1-2 and M1-3 (p-value = 0.042) showed a significant difference between model pairs M1-2 was higher than that of M1-3. In conclusion, the M1-2 turbine demonstrated the highest efficiency in this case.

Table 3 Analysis of variance for the influence of number of blades

Source	*DF*	*Sum of Squares*	*Mean Square*	*F-value*	*p-value*
Corrected Model	6	0.011[a]	0.002	6.730	0.008
Intercept	1	0.007	0.008	26.476	0.001
Model	2	0.003	0.001	4.999	0.039
Flow rates	4	0.008	0.002	7.595	0.008
Error	8	0.002	-	-	-
Total	15	0.021	-	-	-
(a) *R-sq* = 83.5%			*R-sq* (adj) = 71.1%		

2. Study of the influence of the number of stages (N_s) and angle of phase shift

This section focused on the relationship between the number of stages using 2-blade and 3-blade turbines with an AR of 1.4 and a guide vane angle of 30°. The results show that models M2-3 and M2-4, with 3 stages, are more efficient than models M2-1 and M2-2, which have 2 stages. This is because the 3-stage turbines are more efficient than the 2-stage turbines due to their larger surface area, which captures more energy from the water, increases torque, and reduces energy loss from turbulence. When comparing 3-stage turbines, we observe that the 3-stage, 60° phase-shifted M2-4 has a higher efficiency than the 3-stage, 0° phase-shifted M2-3. This is because, with a 60° phase shift per stage, the water flow is more evenly distributed, ensuring smoother rotation and higher efficiency compared to a 0° phase shift. Model M2-4, the 3-stage, 3-blade turbine with a 60° phase shift, delivers the best results in the study, with Cp, Cm, and TSR values of 0.160, 0.185, and 0.864, respectively. M2-4 also has the highest speed of revolutions at 431.04 rpm when the water discharge rate is 25 m^3/h, as shown in Table 4.

Table 4 Maximum $C_{p,}$ C_m and TSR with AR= 1.4, Guide Vane of 30° for models M2-1, M2-2, M2-3 and M2-4

Model	$C_{p,max}$	C_m at $C_{p,max}$	TSR at $C_{p,max}$	Speed (RPM)	Flow rate (m^3/hr)
M2-1	0.080±0.008	0.112±0.009	0.709±0.011	354.84±3.448	25
M2-2	0.109±0.008	0.145±0.010	0.749±0.016	370.45±7.348	25
M2-3	0.122±0.009	0.154±0.010	0.792±0.012	393.28±5.196	25
M2-4	**0.160±0.006**	**0.185±0.008**	**0.864±0.014**	**431.04±4.899**	**25**

The ANOVA analysis examined how the number of stages and angle of phase shift and the flow rates of water significantly affected (the efficiency of the SHT). The results indicated that the p-values for each factor were low (less than 0.05), showing that all control factors had a significant impact on the response. However, the flow rates factor had a greater effect (p-value = <0.001, F-value = 22.134) compared to the turbine model factor (p-value = 0.027, F-value = 4.334). The ANOVA explained a variance in the data (R^2 = 89.4%) and other details can be seen in Table 5.

Subsequently, a Post Hoc Test (Tukey's HSD) was performed. The comparison of the SHT models revealed that the M2-2, M2-3, and M2-4 turbines did not differ significantly, while the M2-1 and M2-4 (p-value = 0.022) showed a significant difference and it was found that the mean difference value between model pairs M2-4 was higher than that of M2-1. In conclusion, the M2-4 turbine demonstrated the highest efficiency.

Table 5 Analysis of variance for the influence of the number of stages and angle of phase shift

Source	*DF*	*Sum of Squares*	*Mean Square*	*F-value*	*p-value*
Corrected Model	7	0.050[a]	0.007	14.506	<0.001
Intercept	1	0.053	0.053	107.663	<0.001
Model	3	0.006	0.002	4.334	0.027
Flow rates	4	0.043	0.011	22.134	<0.001
Error	12	0.006	-	-	-
Total	20	0.108	-	-	-
(a) *R-sq* = 89.4%			*R-sq* (adj)= 83.3%		

3. Study of the influence of stage height ratio (H_s)

From tests in section 2, the study concluded that 3-stage turbines with a proportional stage height ratio (1:1:1) performed the best. For comparison, this study used a stage height proportion of 1:2:1 This study concluded that the proportion 1:1:1 performed better than the 1:2:1, since the turbine with a stage height ratio of 1:1:1 has a consistent energy capture area across each stage, ensuring a more balanced torque distribution throughout the turbine. This balanced distribution leads to smoother rotation, as the force exerted on each blade is more evenly spread. As a result, the turbine operates more efficiently, with less turbulence in the water flow. This reduction in turbulence minimizes energy loss that typically occurs due to irregular flow patterns, thus enhancing the overall performance and efficiency of the turbine. Model M2-4, with a guide vane angle of 30^o, performed the best measuring C_p =0.160, C_m =0.185 and TSR = 0.864. It also achieved the highest discharge flow rate of 25m^3/h, as shown in Table 6. This result aligns with the conclusions in Table 6.

Table 6 Maximum $C_{p,}$ C_m and TSR with Guide Vane of 30^o for models M2-3, M2-4, M3-1 and M3-2

Model	$C_{p,max}$	C_m at $C_{p,max}$	TSR at $C_{p,max}$	Speed (RPM)	Flow rate (m^3/hr)
M2-3	0.122±0.009	0.154±0.010	0.792±0.012	393.28±5.196	25
M2-4	**0.160±0.006**	**0.185±0.008**	**0.864±0.014**	**431.04±4.899**	**25**
M3-1	0.040±0.005	0.056±0.006	0.712±0.019	353.81±7.745	25
M3-2	0.065±0.008	0.074±0.009	0.871±0.010	433.36±5.217	25

The ANOVA analysis examined how the stage height ratio and the flow rates of water significantly affected (the efficiency of the SHT). The results indicated that the p-values for each factor were low (less than 0.05), showing that all control factors had a significant impact on the response. However, the flow rates factor had a greater effect (p-value = 0.001, F-value = 9.648) compared to the turbine model factor (p-value = 0.013, F-value = 5.517). The ANOVA explained a variance in the data (R^2 = 82.1%) and other details can be seen in Table 7.

Subsequently, a Post Hoc Test (Tukey's HSD) was performed. The comparison of the SHT models revealed that the M2-4 and M3-1 (p-value = 0.016), M2-4 and M3-2 (p-value = 0.045) showed a significant difference and it was found that the mean difference value between model pairs M2-4 was higher than that of M3-1 and M3-2. In conclusion, the M2-4 turbine demonstrated the highest efficiency in this case.

Table 7 Analysis of variance for the influence of stage height ratio

Source	*DF*	*Sum of Squares*	*Mean Square*	*F-value*	*p-value*
Corrected Model	7	0.040[a]	0.006	7.878	0.001
Intercept	1	0.029	0.029	39.652	<0.001
Model	3	0.012	0.004	5.517	0.013
Flow rates	4	0.028	0.007	9.648	0.001
Error	12	0.009	0.001	-	-
Total	20	0.077	-	-	-

(a) *R-sq* = 82.1% *R-sq* (adj) = 71.7%

4. Study of the influence of Aspect Ratio, AR

From the results of the study described in Sections 2 and 3, where model M2-4 performed best with AR=1.4, this study compared the efficiency of the hydro turbine using AR=1.2 and 1.6 for comparison. It was concluded that model M2-4 with AR=1.4 was the optimal test outcome due to the balanced ratio between the height and width of the turbine, which can capture energy from the water efficiently across different levels. This balance ensures an even distribution of torque throughout the turbine, allowing the blades to interact with the water flow optimally. As a result, the turbine experiences smoother rotation, as the forces acting on each blade are more evenly distributed. This smooth operation reduces turbulence in the water, which in turn minimizes energy losses caused by irregular flow patterns. Consequently, the turbine achieves its maximum efficiency, ensuring that the captured energy is converted into rotational power with minimal loss. Model M2-4, with a guide vane angle of 30°, performed the best measuring C_p= 0.16, C_m=0.15 and TSR= 0.864. The study also found that the model M4-1 with AR=1.2 had the lowest efficiency recording C_p =0.128, and C_m =0.142, as shown in Table 8. Model M2-4 recorded the highest efficiency as mentioned in Section 2 and 3.

Table 8 Maximum C_p, C_m and TSR with Guide Vane of 30° for models M4-1, M2-4 and M4-2

Model	$\mathbf{C_{p,max}}$	$\mathbf{C_m}$ **at** $C_{p,max}$	**TSR** at $C_{p,max}$	**Speed** (RPM)	**Flow rate** (m^3/hr)
M4-1	0.128±0.018	0.142±0.019	0.897±0.019	387.15±6.325	25
M2-4	**0.160±0.006**	**0.185±0.008**	**0.864±0.014**	**431.04±4.899**	**25**
M4-2	0.136±0.016	0.197±0.021	0.692±0.019	323.87±5.207	20

The ANOVA analysis examined how the aspect ratio and the flow rates of water significantly affected the efficiency of the SHT. The results indicated that the p-values for the corrected model, intercept, and flow rates factor were low (less than 0.05), showing that all control factors had a significant impact on the response. However, the model variables displayed high p-values (greater than 0.05), suggesting that the model, specifically the aspect ratio of the turbine, had no significant effect on the dependent variable. The ANOVA explained a variance in the data (R^2 = 96.7%) which is close to 100% and other details can be seen in Table 9.

Table 9 Analysis of variance for the influence of aspect ratio

Source	*DF*	*Sum of Squares*	*Mean Square*	*F-value*	*p-value*
Corrected Model	6	0.053[a]	0.009	39.679	<0.001
Intercept	1	0.076	0.076	344.054	<0.001
Model	2	1.20×10^{-6}	6.00×10^{-7}	0.003	0.997
Flow rates	4	0.053	0.013	59.517	<0.001
Error	8	0.002	-	-	-
Total	15	0.130	-	-	-

(a) *R-sq* = 96.7% *R-sq* (adj) = 94.3%

5. Study of the Influence of the Baffle Plate

Based on the results discussed in Sections 2-4, which indicate that the SHT M2-4 design provides the highest efficiency, this section measures the influence of a baffle plate placed on both the top and bottom of the turbine in model M5-1. This would provide data for comparison with model M2-4, which lacks a baffle plate, as well as with the traditional M1-2 turbine model. The comparative study revealed that incorporating top and bottom baffle plates (M5 - 1) significantly increased efficiency compared to turbines without baffles (M2-4). This improvement stems from the baffles' ability to mitigate energy loss by reducing vortex flow at the blade tips and minimizing drag along the blade edges. Furthermore, the baffles enhance torque, enabling the turbine to extract more energy from the water, thus boosting overall efficiency. These findings provide strong evidence that the M5-1 turbine model achieves the highest efficiency. The data measured C_p = 0.272, C_m = 0.313, and TSR= 0.871, at the highest discharge flow rate of 25m^3/h, as seen in Table 10.

Table 10 Maximum C_p, C_m and TSR with Guide Vane of 30° for models M1-2, M2-4, and M5-1

Model	$C_{p,max}$	C_m at $C_{p,max}$	**TSR** at $C_{p,max}$	**Speed** (RPM)	**Flow rate** (m^3/hr)
M1-2	0.098±0.008	0.115±0.009	0.850±0.010	421.35±5.507	25
M2-4	0.160±0.006	0.185±0.008	0.864±0.014	431.04±4.899	25
M5-1	**0.272±0.017**	**0.313±0.018**	**0.871±0.014**	**432.88±5.132**	**25**

The ANOVA analysis examined how the baffle plate and the flow rates of water significantly affected (the efficiency of the SHT). The results indicated that the p-values for each factor were low ($p < 0.05$), showing that all control factors had a significant impact on the response. However, the flow rates factor had a greater effect (*p*-value = 0.002, F-value = 12.057) than the turbine model factor (*p*-value = 0.038, F-value = 5.042). The ANOVA explained a variance in the data (R^2 = 87.9%) and other details can be seen in Table 11.

Subsequently, a Post Hoc Test (Tukey's HSD) was performed. The comparison of the SHT models revealed that the M1-2 and M5-1 (*p*-value = 0.032) showed a significant difference and it was found that the mean difference value between model pairs M5-1 was higher than that of M1-2. In conclusion, the M5-1 turbine demonstrated the highest efficiency in this case.

Table 11 Analysis of variance for the influence of aspect ratio

Source	*DF*	*Sum of Squares*	*Mean Square*	*F-value*	*p-value*
Corrected Model	6	0.086[a]	0.014	9.718	0.003
Intercept	1	0.088	0.088	60.298	<0.001
Model	2	0.015	0.007	5.042	0.038
Flow rates	4	0.071	0.018	12.057	0.002
Error	8	0.012	0.001	-	-
Total	15	0.186	-	-	-
(a) *R-sq* = 87.9%			*R-sq* (adj) = 78.9%		

The results from all five test sections yielded valuable insights into the performance of the twelve turbine types. Fig. 10 compares the power coefficients (Cp) for all turbines. Notably, the M5-1 turbine achieved the highest Cp of 0.272, while the M3-1 turbine had the lowest Cp of 0.04. Comparing the three-bladed M5-1 turbine with the conventional three-bladed M1-2 turbine (Cp = 0.098), the M5-1 demonstrated a Cp increase of 0.174. Figure 11 compares the torque coefficients (Cm) for all turbines. The M5-1 turbine exhibited the highest Cm of 0.313, while M1-3 and M3-1 had the lowest Cm of 0.056. The M5-1 turbine's Cm was 0.198 higher than that of the M1-2 turbine. Fig. 12 compares the tip speed ratios (TSR) of the SHT turbines. Most turbines had TSR values between 0.6 and 1.0, except for the M2-3 turbine, which had a TSR slightly above 1.0. Evaluating the SHT performance based on the relationship between Cp and Cm with TSR, as shown in Fig. 13 and 14, confirmed that the M5-1 turbine demonstrated the highest efficiency.

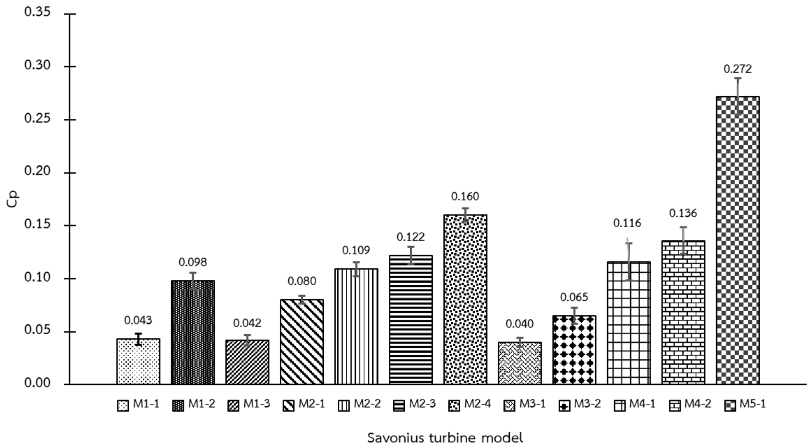


Figure 10 Maximum coefficient of power ($C_{p,\,max}$) against 12 Savonius hydro turbine model

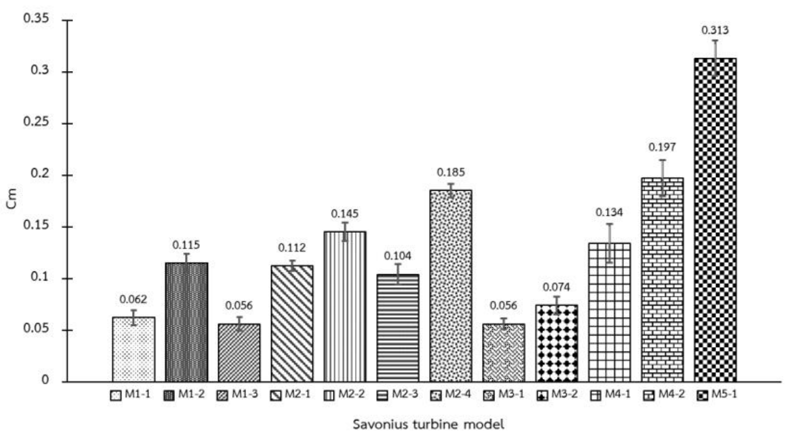


Figure 11 Coefficient of torque (C_m) at $C_{p,\,max}$ against 12 Savonius hydro turbine model

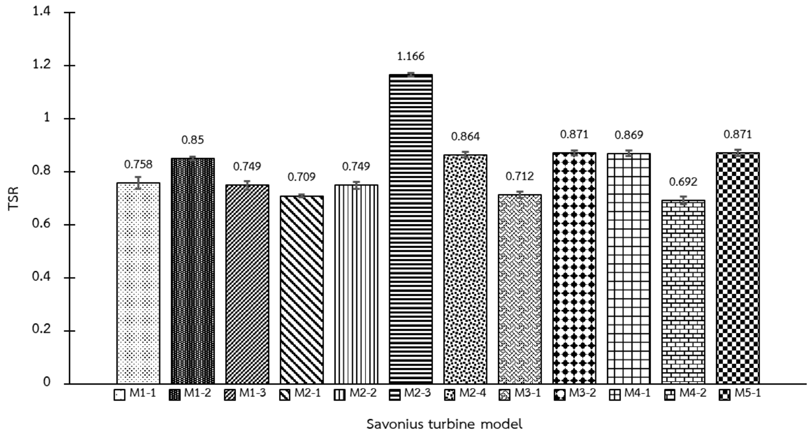


Figure 12 Tip Speed Ratio (TSR) at $C_{p,\, max}$ against 12 Savonius hydro turbine model

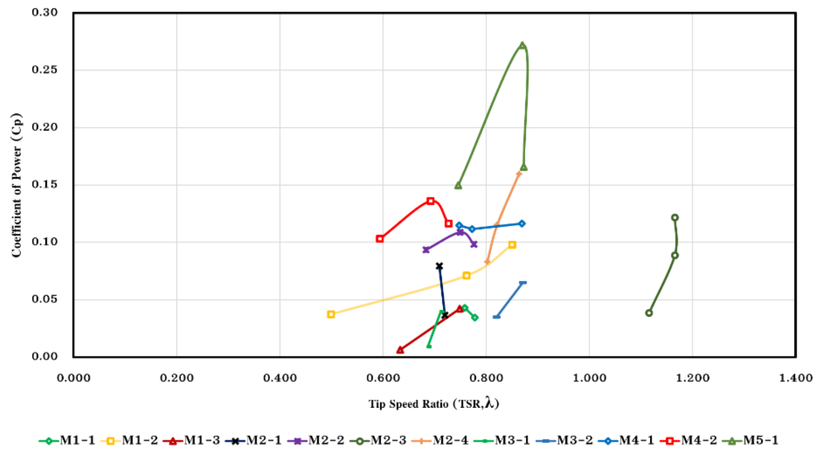


Figure 13 The performance of the power coefficient (C_p) for a 12-blade Savonius hydro turbine model.

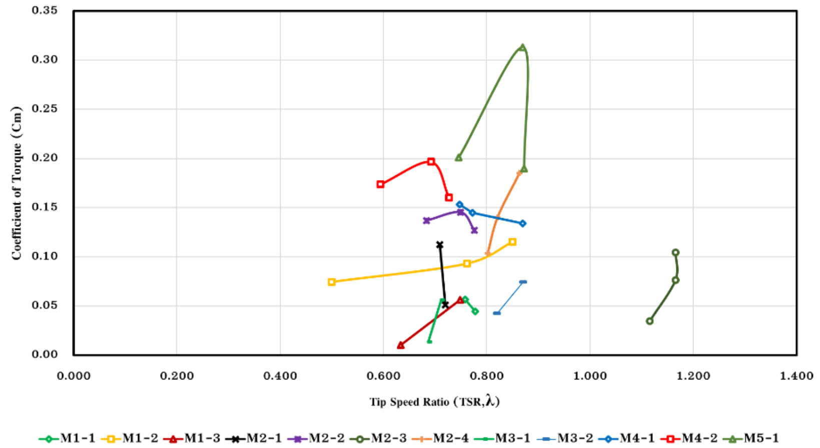


Figure 14 The performance of the torque coefficient (C_m) for a 12-blade Savonius hydro turbine model.

Conclusion and Suggestions

This study sought to measure the efficiency of the SHT in water pipes with low flow rates and heads which cause the hydro turbines to have low efficiency. These constraints have limited the use of these hydro turbines in electricity generation in public water pipes. These constraints motivated the researchers to conduct this study to improve the efficiency of the SHT in public-use water pipes by studying the influence of the number of blades, number of stages and phase shift angle, stage height ratio, aspect ratio and the use of baffle plates. The researchers designed and built 12 models of turbines and measured their efficiency at discharge flow rates of 5, 10, 15, 20 and 25m^3/h.

The results indicated that the SHT M5-1 the highest efficiency with 3 blades, 3 stages, a height ratio of 1:1:1, a 60° angle of phase shift, AR=1.4, and a baffle plate at a flow rate of 25m^3 /hr. The C_p = 0.272, C_m = 0.313, and TSR = 0.871. Furthermore, the study also concluded that the SHT model M5-1 outperformed the SHT model M1-2, showing increases in the C_p of 0.174 and C_m of 0.198.

In addition to conducting experimental tests, we performed a statistical analysis using ANOVA to further validate the differences in the parameters affecting turbine efficiency. The results indicated that the factors of the number of blades, the number of stages, the phase shift angle, the stage height ratio, and the baffle plate, as well as the flow rate, all had a significant influence on turbine efficiency. Notably, the M5 - 1 turbine exhibited the highest efficiency, which aligns with the experimental results.

The test results indicated that these six parameters have a significant impact on the efficiency and operation of the SHT, details can be seen in Table 12.

Table 12 Showing factors affecting efficiency of the Savonius Hydro Turbine

Factors	Model	$C_{p,max}$	Value	Response for affecting efficiency
Number of blades	M1-2	0.098	3	The appropriate gap between the blades allows for a consistent water inflow, reduces vortex formation, and enables smooth rotation by minimizing resistance against the blades.
Number of stages and phase shift angle	M2-4	0.160	3 stage,60° phase shift	A larger water intake area captures more energy, while the angle helps distribute the water flow, allowing the turbine to rotate smoothly.
Stage height ratio	M2-4	0.160	1:1:1	The balanced water intake at each stage helps evenly distribute torque and reduces the occurrence of turbulent flow.
Aspect ratio	M2-4	0.160	1.4	The balanced aspect ratio allows water intake at multiple levels, ensures even torque distribution throughout the turbine, and reduces vortex formation.
Baffle plate	M5-1	0.272	Leverage all previously acquired advantages with baffle plate	Reduces energy loss at the blade tips, allowing the turbine to capture more water.

Suggestions for future research.

- Investigate flow characteristics using Computational Fluid Dynamics (CFD) to gain a better understanding of the actual flow through the turbine, focusing on flow velocity and pressure at various points within the turbine and pipe system.
- Examine the effect of the gap in the turbine to minimize the pressure drop between the inlet and outlet. This could help reduce water head loss, allowing the turbine to operate effectively at low flow rates, low water heads, and unstable flow rates under actual operating conditions.

- Analyze the differences in materials used in turbine production, considering the long-term durability of turbines and conducting an economic assessment to determine their practicality for real-world applications.
- Explore the potential for expanding turbine sizes to accommodate larger pipe systems, such as those found in industrial plants or municipal water supply networks. This will allow researchers to design better hydro turbines in the future.

In conclusion, it is hoped that the results of this study and the test design will provide guidelines for future research under real working conditions. The goal is to develop the most efficient water turbine system for pipelines, particularly those operating with low flow rates and heads.

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Author Contributions

Author 1 (Supat Nuyam): Study conceptualization, methodology design, data interpretation and analysis, research, manuscript writing, review, and editing.

Author 2 (Ratchapon Suntivarakhon): Data interpretation and analysis, manuscript review and editing

Author 3 (Khanisorn Thanutwutthikorn): Data interpretation and analysis, manuscript review and editing

Conflict of Interests

The authors declare that he has no conflicts of interest.

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