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Computational Fluid Dynamics Method for Predicting Savonius Water Turbine Performance with Fin-Blade

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ABSTRACT

Hydropower is Indonesia's second most significant renewable energy source, following solar energy. It possesses a substantial capacity of 75,000MW, constituting around 17.8% of the overall renewable energy portfolio in the country. However, hydropower installations in Indonesia account for only 0.061% of the available potential, leaving a considerable gap. One effort to bridge the gap is the development of a water turbine. Because Savonius has been a popular turbine in recent years, this research was conducted using one. Because of the Savonius's simple structure, it is simple to modify. This study aims to determine how the number and size of fins affect the performance of the Savonius water turbine. Computational Fluid Dynamics with two-dimensional analysis was used in this study. The Fluent Solver and the Ansys Student version software were used in this study. The variations included no fins, one fin, and two fins on the rotor. The k-shear Stress Transport (SST), which produces accurate findings by combining the k-model for free flow and the standard k-model for boundary (wall) flow. Inlet velocities of 0.3m/s, 0.65m/s, and 0.9m/s were utilized for the research simulations. At a flow velocity of 0.65m/s and a TSR of 0.77, the power coefficient is increased by 13.8% by adding two fins compared to the configuration without fins. The findings were subsequently subjected to a two-factor factorial design analysis. The findings indicate that the number of fins and the TSR factor exert a substantial impact. However, two factors have no influence on each other.

1. INTRODUCTION

The United Nations has set 17 Sustainable Development Goals (SDGs) for 2030, one of which is Clean Energy and Adorable. Indonesia needs to contribute SGDs. Clean energy is energy that comes from renewable sources and has low emissions. From 1965 to 2022, the global consumption of renewable energy varied between 6 and 9% [1]. This is a global concern for boosting the usage of renewable energy. Bio-energy [2], wind energy [3] and hydropower [4] research have all contributed to a better understanding of the processing of new energy. With a potential of 75,000MW, hydropower is Indonesia's largest renewable energy source. Indonesia has 4,621MW of hydropower installed, but this is far from enough [5]. Renewable energy capacity and deployment in Indonesia are depicted in Figure 1. Figure 2 demonstrates how far behind the installation of hydro energy is from where it could be.

Attempts to close the gap include creating a hydro turbine. Hydro turbines are required for harvesting the useable electrical energy of hydropower. Hydro turbines are classified into several types, the most prevalent of which are Axial Flow and Cross Flow. In a cross-flow turbine, water enters the runner tangentially, flows through it transversely, and exits it radially, transferring some of its kinetic energy to rotate the runner [6]. The performance of cross-flow turbines is influenced by geometric parameters such as the number of blades [7] and the angle of the runner blades [8]. Savonius is a type of cross-flow hydro turbine [9]. In recent years, hydro-turbines of the Savonius type have become increasingly common. Studies of the Savonius turbine have been conducted using both experimental [10] and Computational Fluid Dynamics (CFD) approaches [11].

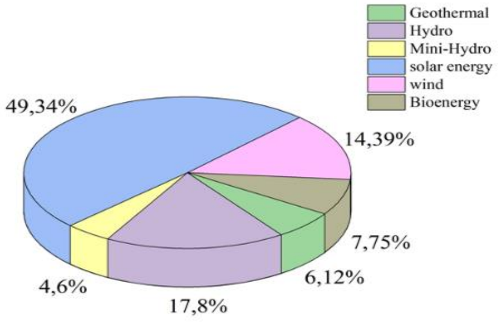

Figure 1. Capacity of renewable energy

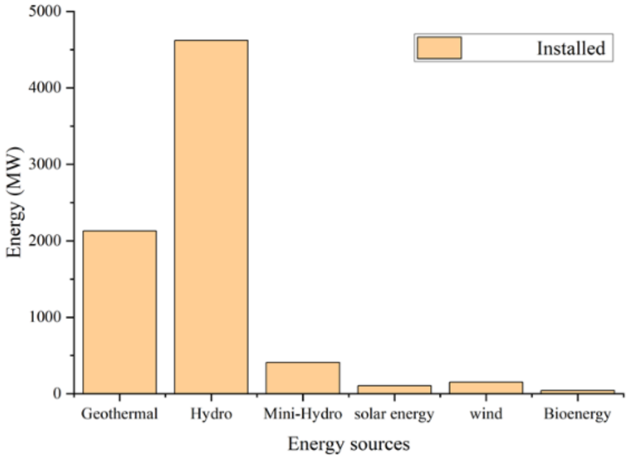

Figure 2. Installed of renewable energy power plants

Extensive research has been carried out to enhance the efficiency of turbines. Modification has been carried out are blade shape factor [10], Helix-Blade [12], Aspect Ratio [13], Multi-Stage [14], the addition of deflectors [15], material [16], and Number of Blades [17]. The geometry factor is a significant determinant of turbine performance. Sure, researchers modify the geometric properties to enhance its overall performance [18]. The performance of the Savonius is affected by changes in the bending angle of the blades at 120°, 135°, and 150°. The results showed that the bending angle of 135° can increase the Cpmax to 0.24 [10]. The shape of the blade is one of the aspects that significantly impacts Savonius' performance. With shape modification, research has been conducted, followed by the helix angle of 0°, 90°, and 180°. The results show that the change in blade shape accompanied by a helix angle of 90° produces the best cp max compared to angles of 0° and 180°. Cpmax produced by the rotor is 0.258 [12]. Both shape alteration and the number of blades influence the performance of the Savonius. This study shows that a rotor with three blades performs better than two blades in each blade shape [17].

In the research on the Savonius rotor, geometric modification is an effective way to improve the Savonius performance. In the present study, the rotor undergoes a modification to enhance the Savonius turbine's performance. The alteration implemented in this study involves the addition of fins to the Savonius rotor. The research used the CFD-method on the Savonius water turbine in two-dimensional ANSYS Student version software with the Fluent solver. The research findings were then subjected to a factorial design analysis to ensure the relevance of each factor's influence [19]. A factorial design analysis can confirm the effect or extent of the relevance of these elements. Factorial design analysis has been utilized to examine many factors in the context of biodiesel [20], single-factor Savonius application [21], and other types of turbines [22].

2. DESIGN AND PERFORMANCE PARAMETER

A turbine is a device that transforms energy from several sources into practical mechanical energy. Turbines can be categorized into different categories based on their axis of rotation, which are utilized in a variety of industrial and energy applications. Turbines are generally categorized into three varieties based on their axis orientation: horizontal, vertical, and diagonal. Each category possesses unique characteristics and benefits that are suitable for specific uses. Understanding the various types of turbines depending on their axis is crucial for developing an effective and dependable energy system. This article will discuss many types of turbines, along with their applications and advantages.

The Savonius turbine is classified as a drag-type turbine, characterized by its configuration of semicircular blades organized in the shape of the letter "S." These blades consist of a concave blade and a convex blade, both oriented to face the direction of fluid flow. The drag coefficient exerted on the concave blade has more significance compared to that of the convex blade [23]. According to the findings presented in Figure 3, it can be observed that the concave blade induces a more pronounced drag force, resulting in the rotation of the rotor. The Savonius turbine possesses the benefit of a straightforward configuration and the ability to function effectively at low fluid velocities. In contrast, the traditional design of the Savonius turbine is associated with the drawback of inefficiency [24].

The Savonius turbine works by converting kinetic energy from water into mechanical energy through rotor rotation. The moving fluid encounters the Savonius turbine rotor. This rotor is round or half-cylindrical, with two curved blades placed vertically. When water flows, the higher pressure on one side of the rotor provides a thrust force, which causes the rotor to rotate. This principle pertains to the operation of the Savonius turbine. When fluid flows through the rotor, a pressure difference exists between the front and back surfaces of the rotor.

According to Newton's Law of Action and Reaction, increased pressure on the front side causes the rotor to revolve to balance the force. When the rotor rotates, the fluid flow's kinetic energy is transferred to rotational mechanical energy. This energy can then be used to power generators or other machines that produce electricity or do mechanical tasks. Although Savonius turbines have lower efficiency than other turbines, such as horizontal turbines, their simple design and ability to generate electricity at low speeds make them ideal for use in places with weak or changeable winds. Turbines with Savonius rotors are very suitable for use in Indonesia, whether implemented using wind power or hydropower. River speeds in residential areas in Indonesia are relatively diverse, so the advantages of the Savonius rotor, which can operate at low fluid velocities, can be implemented in Indonesia, which has various water flow velocities.

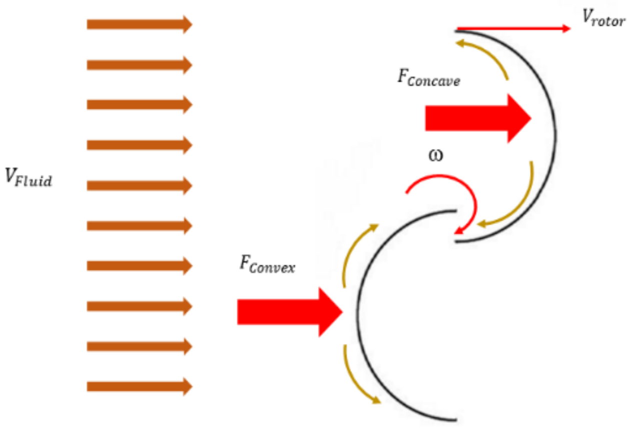

Figure 3. Savonius working principle

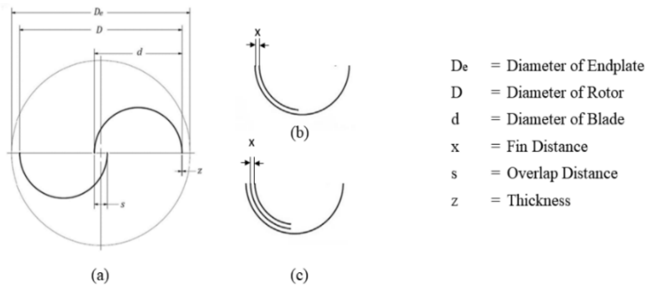

Figure 4. Savonius rotor design: (a) without a fin, (b) 1-fin and (c) 2-fin

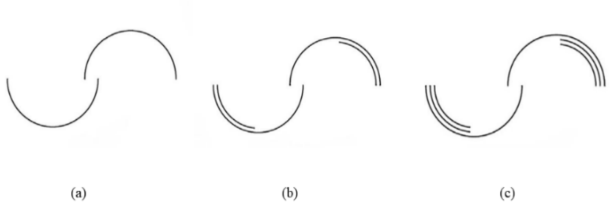

Figure 5. Rotor: (a) without a fin, (b) 1-fin and (c) 2-fin

This study was conducted in two dimensions using a typical Savonius rotor. Figure 4 depicts the rotor's primary design. The rotor is 196.2mm in diameter, the blade is 109mm in diameter, the endplate is 260mm in diameter, and the overlap and fin spacing are 21.8mm and 4.36mm respectively. The used thickness is 2mm. The conventional variation, the variation with one fin, and the variation with two fins were all depicted in Figure 5.

The performance parameters of Savonius wind turbines are characterized by the coefficients of power (Cp) and moment (Cm). The torque derived from the investigation is transformed into Cp (coefficient of power) and Cm (coefficient of moment) by the utilization of multiple equations. Eqs. (1)-(4) below illustrate the demonstration of the Savonius rotor's performance [25].

$$Cp = \frac{T\omega}{\frac{1}{2}\rho V^3 A} \tag{1}$$

$$Cm = \frac{T}{\frac{1}{2}\rho V^2 AR} \tag{2}$$

$$\lambda = \frac{\omega R}{V} \tag{3}$$

$$Cp = \lambda . Cm \tag{4}$$

3. NUMERICAL MODELING

The investigation was conducted in two dimensions. The research is undertaken in two dimensions due to the fact that the Savonius profile can be accurately represented by a two-dimensional profile, as its geometry can be projected in a two-dimensional form. The advantage of conducting research in two dimensions is that it allows for a faster procedure due to the reduced amount of meshes compared to three-dimensional research.

Meshing is the first step in the research process after making the rotor design [14]. The meshing technique employed at the blade tip utilizes edge sizing. An inflation layer is applied on the surface of the blade with the purpose of increasing the mesh density in order to accurately capture fluid dynamics variations. Meshing has a maximum skewness of 0.7. The number of elements used in meshing is 132,852 elements. Figure 6 shows the results of meshing on the Savonius rotor.

The modeling domain is broken up into two sections: the stationary domain and the rotating domain [26]. The rotating domain is considered to be the inner domain, while the stationary domain is considered to be the outer domain. In this modeling, the computational domain takes the form of a square and has dimensions of 12D on each side. The Savonius turbine can be found in the geographically precise middle of the stationary domain. The simulation domain and boundary conditions are depicted in Figure 7. Shear Stress Transport (SST) is the name of the turbulence model utilized [27]. At the velocity inlet, the boundary conditions are set at 0.3m/s, 0.65m/s, and 0.9m/s, respectively. There is an anti-slip surface on the boundary wall of the blade. A pressure of 0Pa, considered relatively static, serves as the boundary condition for the outlet section. Modeling has been conducted under steady-state circumstances. Figure 8 shows the results of benchmarking research modeling with the research of Sharma and Sharma [28]. Benchmarking results show an error of 4.37%. This value is acceptable because the error value in CFD research is 7% [29].

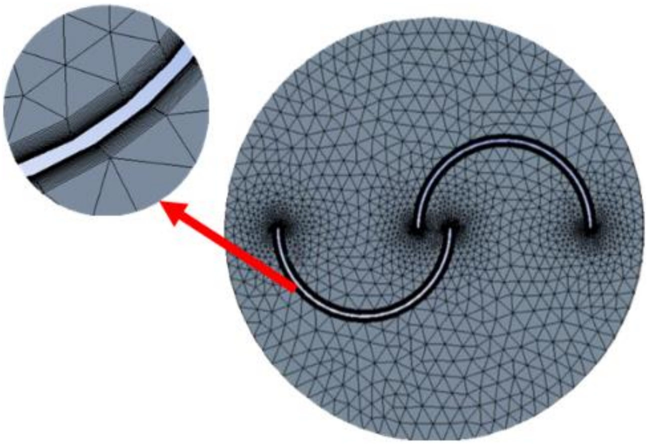

Figure 6. The result of meshing from geometry

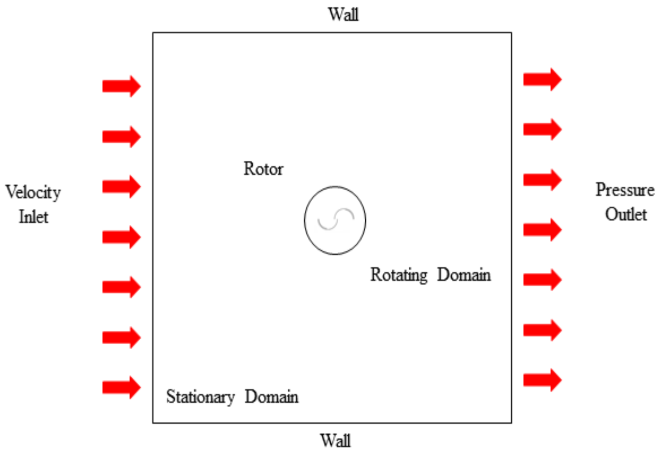

Figure 7. Schematic of simulation modeling

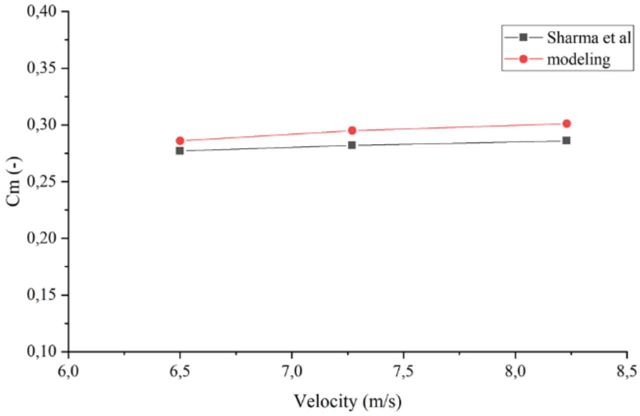

Figure 8. Benchmarking graph

4. RESULT AND DISCUSSION

A study utilized Computational Fluid Dynamics (CFD) methodology to investigate the impact of incorporating a fin into the Savonius rotor. The study was carried out utilizing the Ansys Student Version software with the Fluent Solver in two dimensions. The outcomes derived from the simulation manifest as torque, which is subsequently subjected to Eqs. (1)-(4) to ascertain the magnitude of the aerodynamic efficacy of the Savonius rotor. The research used two versions of fin numbers, specifically 1 and 2. The investigation was conducted at TSR values of 0.97, 0.77, and 0.63.

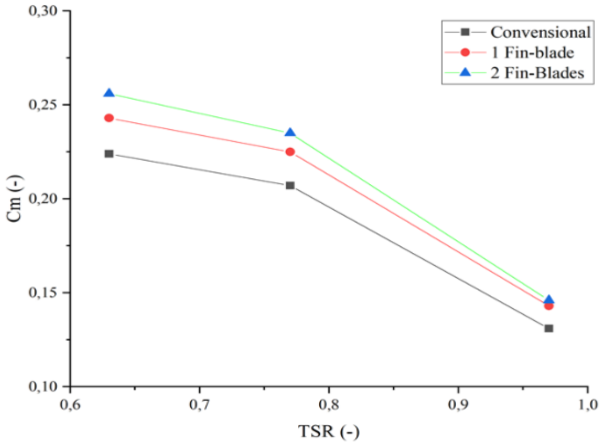

Figure 9. Graph of Cm vs. TSR

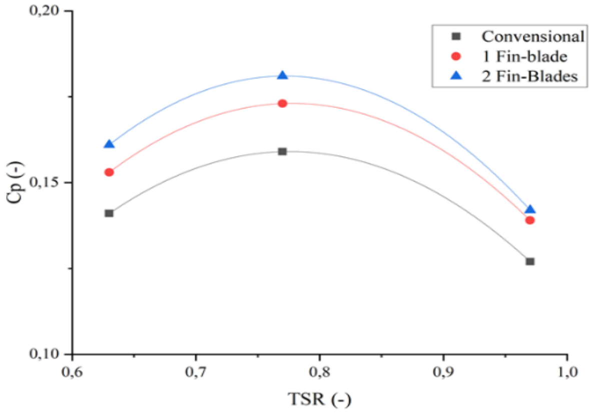

Figure 10. Graph of Cp vs. TSR

Figure 9 shows that the torque coefficient (Cm) value tends to decrease as the TSR value increases. With the addition of a 1-fin, the Savonius water turbine produces the greatest torque coefficient value at TSR 0.63, which is 0.243. The lowest torque coefficient is found at TSR 0.97, which is 0.143. The highest torque coefficient on adding 2-fins is achieved at a TSR of 0.63, which is 0.256. Meanwhile, the lowest torque coefficient value found at TSR 0.63 is 0.146.

The connection between the power coefficient and the tip speed ratio is seen in Figure 10. The turbine achieves its highest average power coefficient when 1-fin is added, occurring at a Tip Speed Ratio (TSR) of 0.77, resulting in a value of 0.173. In contrast, the minimum average power coefficient observed at a tip-speed ratio (TSR) of 0.97 is 0.139. The turbine achieves its highest average power coefficient, measuring 0.181, when 2-fins are incorporated, and the tip-speed ratio (TSR) is set at 0.77. In contrast, the minimum power coefficient value observed for a tip speed ratio (TSR) of 0.63 is 0.142. The data indicates an observed increase in the Cp value, starting from TSR 0.63 and reaching its maximum at TSR 0.77. Nevertheless, a decline in the Cp value was observed subsequent to its peak at TSR 0.97.

Figure 11 depicts the simulation's pressure distribution. The number of fins on the primary blade of the turbine must be chosen carefully in order to increase the average power coefficient value. The increased number of fins will shorten the distance between the fins and the primary turbine blade.

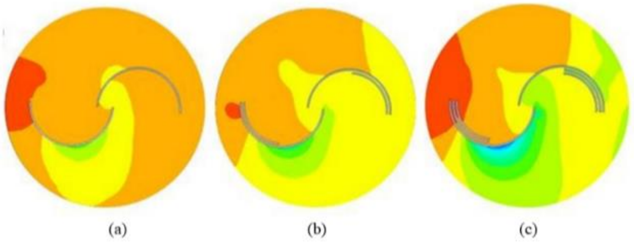

Figure 11. Pressure contours on the rotor: (a) without fins, (b) 1-fins, and (c) 2-fins

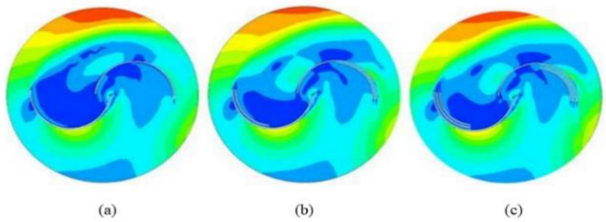

Figure 12. Velocity contours on the rotor: (a) without fins, (b) 1-fins, and (c) 2-fins

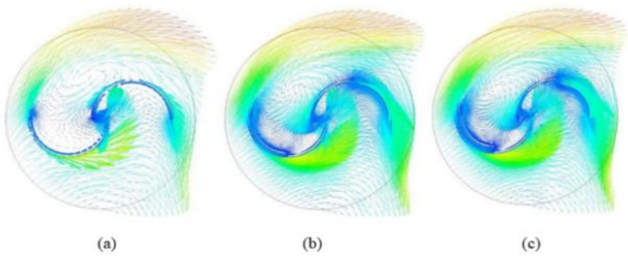

Figure 13. Vector velocity on the rotor: (a) without fins, (b) 1-fins, and (c) 2-fins

As demonstrated in Figures 12 and 13, shortening the distance between the blades with additional blades can enhance the distribution of flow velocity impacting the blades. The figure demonstrates that the wake zone of the rotor with fins is smaller. Figure 12 shows the fluid velocity vector. The vector distribution demonstrates that there is a reverse direction at the edge of the concave blade, both on the concave and convex blade.

ANOVA in a two-factor factorial design is a statistical technique that determines if there are significant variations in group means across two independent factors and if there is an interaction between these factors. A two-factor factorial design involves two factors that impact the response variable, and ANOVA is used to assess the influence of each factor on the data's variability. The analysis procedure starts by computing the overall variability, followed by the variability attributable to the factors (sum square between), and the variability not accounted for by the factors (sum square within). The F-ratio is derived by comparing the mean square across groups with the mean square within groups to examine the significance of differences between groups and interactions between factors. An ANOVA analysis can offer crucial insights for making statistical judgments by determining if group differences are due to observed causes or random variation. This study enables researchers or decision-makers to comprehend the collective impact of several factors on the observed response variable in a two-factor factorial design.

A comprehensive examination of the simulation outcomes has been conducted utilizing a two-factor factorial design study. The findings are presented in Table 1. In order to ascertain the magnitude of the factor's influence, it is imperative to compare the F_0 value presented in Table 1 with the F value provided in Table 2. The observed F_0 value for the TSR factor surpasses the F value presented in Table 2, indicating a noteworthy impact of TSR. The performance of the Savonius turbine holds considerable significance. The data shown in Table 2 indicates that the value of F_0 is bigger than that of F, as evidenced by the number of fin factors. Nevertheless, the F_0 value observed in the interaction (AB) of the two factors does not indicate any significant interaction between the factors. This is evident from the comparison of the F_0 value in AB, which is lower than the F value reported in Table 2. This factorial design analysis shows that the TSR factor and geometry factor (adding Fin) in the modeling have a considerable impact on turbine performance. However, because the two parameters have no influence on each other, they will have an impact on turbine performance even if not paired with others.

Table 1. Table of variance analysis for two factors

Source of Variation	Sum of Squares	DOF	Mean Square	F_0
TSR (A)	0.00184	2	0.000922	**590.72**
Fin (B)	0.00056	2	0.000281	**179.87**
AB	0.00001	1	0.00001	**6.68**
Error	0.00001	3	0.000002	
Total	**0.00242**	**8**		

Table 2. The F distribution's value [11]

	Degrees of Freedom	Value
$F_{0.05\,(2,3)}$	2	**9.55**
$F_{0.05\,(2,3)}$	2	**9.55**
$F_{0.05\,(1,3)}$	**1**	**10.13**

5. CONCLUSIONS

Based on the findings obtained from the simulation:

- it was observed that the inclusion of a single fin in the Savonius water turbine resulted in an 8.8% increase in the coefficient of power (Cp) at a tip-speed ratio (TSR) of 0.77 in comparison to the performance of the Savonius water turbine without any fins.
- Including two fins has been seen to enhance the coefficient of power (Cp) of the turbine by 13.8% compared to the Savonius water turbine lacking fins.
- When doing a comparative analysis of the performance enhancement of a water turbine, it is observed that the inclusion of 1-fin and 2-fins in a Savonius water turbine result in a discernible difference.
- Specifically, the Savonius water turbine equipped with 2-fins exhibits a more excellent Cp value of 5%.

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NOMENCLATURE

A	swept area of the rotor, m^2
Cm	coefficient of power, -
Cp	coefficient of moment, -
R	Radius of rotor, m
T	torque, Nm
V	velocity, m/s

Greek symbols

ρ	density, kg/m^3
ω	angular velocity, rad/s
λ	Tip speed rasio, -