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Performance Analysis of Hydrokinetic Turbine Using Shroud Ratio Comparison under Yaw Misalignment Condition

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Abstract

This research aims to analyze the performance of hydrokinetic turbines under yaw misalignment conditions using descriptive statistical methods on coefficient of power (Cp) data. Tests were conducted at water velocities of 0.7, 0.9, and 1.1 m/s for three types of turbine shrouds consisting of turbines without shrouds, turbines with two different types of shrouds, at yaw angles from 0° to 25° with 5° intervals. The study concludes that the performance of each turbine type is significantly influenced by the combination of water flow velocity and yaw angle. The diffuser type has the highest Cp value at every yaw angle, but its performance decreases with increasing yaw angle. The Blade type has poorer performance compared to the diffuser at every yaw angle and has the best performance at a combination of 1.1 m/s velocity and 5° yaw angle. Meanwhile, the shroud type has more stable performance and is not greatly affected by variations in velocity and yaw angle. Based on the analysis of changes in average Cp values with changes in yaw angle at V 0.7 m/s, all three turbine types experienced an increase in Cp value at a yaw angle of 5, with the shroud experiencing the most significant increase. At V 0.9 m/s, the diffuser and shroud types were able to maintain their average Cp values at every yaw angle, while the blade type decreased with increasing yaw angle and experienced a significant decrease at a yaw angle of 25. At V 1.1 m/s, the diffuser and blade types experienced a decrease in performance with every increase in yaw angle, but the shroud type was able to maintain the same Cp value and even experienced a significant increase at a yaw angle of 5.

Keywords: Turbine, Hydrokinetic, Yaw Misalignment, Diffuser, Shroud.

1. Introduction

Hydrokinetic energy is an alternative form of energy sourced from water currents and has great potential to be developed as an environmentally friendly energy source. One way to convert hydrokinetic energy into electricity is by using a turbine [1]. Through the extraction process, the turbine can convert pressure changes into electrical energy by reducing the fluid flow velocity, thus causing a decrease in linear momentum of water. According to the law of conservation of momentum, the amount of thrust force generated is equal to the rate of momentum decrease, so the greater the momentum decrease, the greater the thrust force produced [2]. Horizontal axis hydrokinetic turbines are one of the devices used to extract hydrokinetic energy [3]. Horizontal axis hydrokinetic turbines work on the same principle as wind turbines. The lift force generated due to fluid flow on the rotor blades produces torque on the turbine shaft, which is then converted into electricity by a generator. Due to the force of gravity, the

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behavior of water currents is more predictable than that of wind caused by atmospheric changes. This leads to reliable and predictable electricity generation from water currents. Unlike conventional hydroelectric power plants that require dams to provide water head, in this method, the turbine is placed in a river or ocean current and produces electricity without significant environmental changes [4]. The operation of horizontal axis hydrokinetic turbines is similar to wind turbines, so they can experience a decrease in power coefficient (Cp) during yaw misalignment. This situation can cause dynamic congestion and variable loading on the rotor blades, resulting in the loss of yaw stability, causing excessive induction loads on the rotor and turbine structure [5].

Yaw misalignment is an angular imbalance of the turbine rotor that can affect the efficiency and performance of the turbine in the process of extracting kinetic energy into electrical energy. Like wind turbines, hydrokinetic turbines face changes in the direction of river and ocean currents that affect their performance [6]. This imbalance can cause energy losses and power loss in the turbine, and can also cause damage to the turbine mechanism if not repaired promptly. Performance evaluation of hydrokinetic turbines under yaw conditions is necessary to predict power performance and stability in off-axis flows. The effect of yaw angle is crucial in designing yaw control mechanisms in shroud designs to optimize hydrokinetic turbine performance [7], [8]. The addition of shrouds to hydrokinetic turbines is called by various names such as duct, shroud, wind-lenses, nozzle, concentrator, diffuser, and augmentation channel. The purpose of adding shrouds is to increase the water flow towards the turbine, thereby increasing the power produced by the turbine. However, so far there is no proper design standard to improve turbine performance based on yaw angle.

Based on previous research, it has been shown that the use of a shell on hydrokinetic turbines results in a significant improvement in performance and power, including at larger yaw angles [9]. In yaw conditions, the shell is able to overcome changes in the direction of water flow that reduce the performance of hydrokinetic turbines. However, studies have shown that different shell designs have different effects on the performance of hydrokinetic turbines under yaw conditions [10]. In order to improve the efficiency of hydrokinetic turbines under yaw conditions, a thorough evaluation of the shell design to be used on hydrokinetic turbines is necessary. This evaluation should consider factors such as water flow velocity, turbine size, and the yaw angle faced by the hydrokinetic turbine [11]. Therefore, the use of a shell on hydrokinetic turbines is expected to enhance the efficiency and performance of hydrokinetic turbines under different operating conditions.

Based on the problem outlined above, a quantitative study was conducted using descriptive statistical methods to determine the type of turbine shroud that can work optimally at various yaw angles and fluid flow velocities. The performance analysis of the horizontal hydrokinetic turbine was carried out by evaluating the data distribution and examining the correlation using a correlation heatmap. Performance variables such as Coefficient of Power (Cp) and Tip Speed Ratio (TSR) were analyzed at various yaw angles and fluid flow velocities to determine the type of turbine that performs well [12]. This analysis was carried out by comparing three types of turbine designs: without shroud, with diffuser, and with shroud. The results of this study provide a more comprehensive overview of the performance of hydrokinetic turbines under yaw misalignment conditions.

2. Research Methodology

This research method is a quantitative study using descriptive statistical methods. The purpose of this study is to analyze the performance of hydrokinetic turbines under yaw misalignment conditions using data obtained from experimental testing using hydrokinetic turbines. In this study, the data used was taken from Kaggle [13], and analyzed using descriptive statistical methods which include data distribution analysis and correlation analysis using correlation heatmaps. Furthermore, an analysis will be conducted on the Cp and TSR variables at various yaw angles with each type of turbine shell.

This study also aims to determine the type of turbine that performs well at various fluid flow speeds and yaw angles. By conducting this analysis, it is expected to provide an overview of the performance of hydrokinetic turbines under yaw misalignment conditions and assist in improving the performance of hydrokinetic turbines. The research steps can be seen in Figure 1.

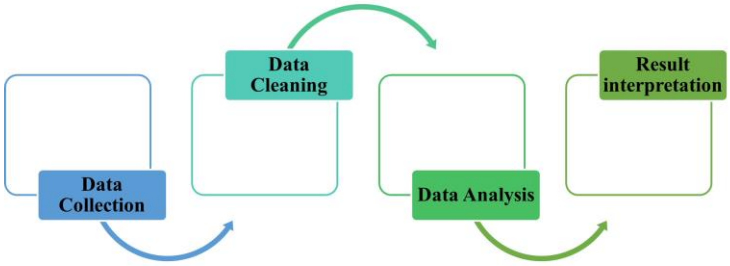

Figure 1. Research Steps

2.1 Data Collection

The data used in this study was obtained from Kaggle.com [13], which is the result of experimental testing using hydrokinetic turbines. This dataset contains data on the coefficient of power (Cp) of a 19.8 cm diameter hydrokinetic turbine with a horizontal axis when operated under yaw misalignment conditions. Tests were conducted at water velocities of 0.7, 0.9, and 1.1 m/s for three types of turbine shells, including a turbine without a shell, and two different types of shells. The experiments were conducted for yaw angles ranging from 0° to 25° with 5° intervals. The output power and thrust force of the turbine were experimentally measured in a water tunnel. The results were corrected using a theoretical model that takes into account the effects of free surface proximity and blockage from the water tunnel [13]. This dataset has five variables, including:

- V: Freestream Velocity
- Gamma: Yaw Angle
- TSR: Tip-speed Ratio
- Cp: Coefficient of Power
- Type: 1. Blade (Without shell), 2. Diffuser (Shell with a smaller inlet than outlet), 3. Shroud (Shell with a smaller diameter between inlet and outlet) [10]. This can be seen in Figure 2 below.

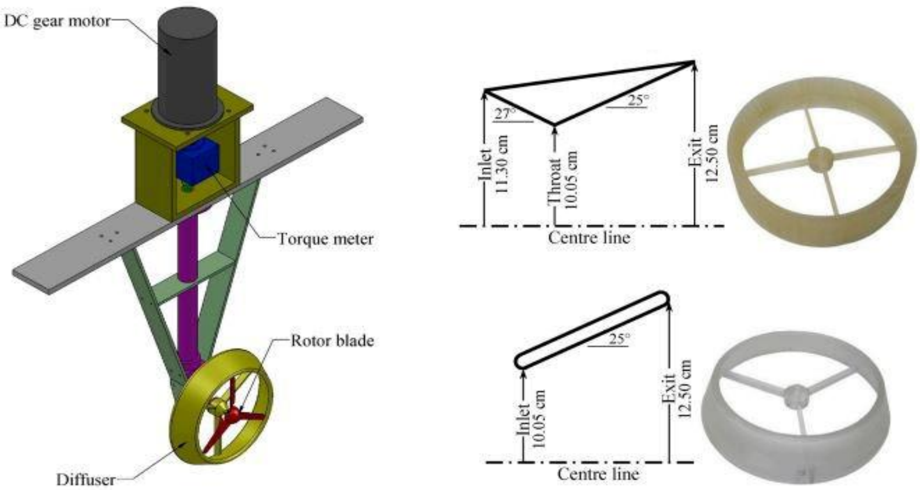

Figure 2. Types of Casings in A Water Turbine (Blade, Diffuser, and Shroud)

This data can be used for analyzing the performance of hydrokinetic turbines during yaw operation, such as determining the pattern of the yaw angle effect on the turbine's coefficient of power and evaluating the effectiveness of various types of casings used [14], [15].

2.2 Data Analysis

To obtain maximum analysis results, the analysis conducted in this research involves several stages:

- Determination of Data Proportions for Each Turbine Type: This stage aims to determine the data proportions for each turbine type (blade, diffuser, and shroud) in the dataset. This percentage can help understand the existing data distribution and can be used to facilitate further analysis.

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- Analysis of Cp and TSR at Various Yaw Angles: In this stage, the analysis of Cp and TSR data is conducted at various yaw angles. This can help determine how the performance of a hydrokinetic turbine is influenced by the yaw angle and fluid flow velocity, which can be calculated using Equations 1 and 2 as follows:

$$TSR = \frac{R\omega}{v} \quad (1)$$

Where TSR (Tip Speed Ratio) is the ratio of the tip speed of the blades and the fluid flow velocity that drives it, R is the radius of the blades, ω is the angular velocity of the blades in radians per second, and V is the fluid flow velocity through the blades.

$$Cp = \frac{Q\omega}{\frac{1}{2}\rho A V^2} \quad (2)$$

Where Cp is the power coefficient, which is the ratio of the power produced by the turbine to the maximum potential power that can be generated by the fluid flowing through it, Q is the fluid flow rate through the turbine, ω is the angular velocity of the turbine in radians per second, ρ is the fluid density, A is the cross-sectional area of the fluid flow through the turbine, and V is the fluid flow velocity through the blades.

- Analysis of Maximum Cp Value: In this stage, the analysis of the maximum Cp value is conducted for all types of turbines at each yaw angle and various fluid velocities. This analysis can help determine the potential energy that can be maximized through the improvement of hydrokinetic turbine performance, which can be calculated using Equation 3.

$$Cp_{max} = \frac{p_{max}}{\frac{1}{2}\rho A V^2} \quad (3)$$

Where P_{max} is the maximum power generated by the turbine (in watts), ρ is the fluid density, A is the cross-sectional area of the fluid flow through the turbine, and V is the fluid flow velocity through the blades.

- Analysis of Average Cp: In this stage, the analysis of the average Cp is carried out for all turbine types at various angles and fluid velocities. This analysis can help determine the consistency of the performance of all turbine types and help understand the interrelationship between their performances.
- Percentage Change in Cp Value: In this stage, the visualization of the percentage change in Cp value is carried out at each yaw angle with various fluid velocities. This can facilitate the analysis of changes in hydrokinetic turbine performance and determine which turbine has the largest change at each yaw angle and how much change occurs.

2.3 Result interpretation

Interpreting the analysis and visualization results of turbine performance, drawing conclusions, and providing recommendations for further development.

3. Result and Discussion

3.1 Data Collection

The data used in this study were obtained from kaggle.com, which is the experimental testing data of a hydrokinetic turbine. The dataset contains the coefficient n of power (Cp) data of a hydrokinetic turbine with a diameter of 19.8 cm with a horizontal axis when operated under yaw misalignment conditions. Tests were conducted at water speeds of 0.7, 0.9, and 1.1 m/s for three types of turbine casings: a casing-free turbine and two different types of casings. Experiments were conducted for yaw angles from 0° to 25° with a 5° interval. The initial dataset contained 765 samples, and after the cleaning process, it now contains 754 samples.

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3.2 Data Analysis

Data analysis is used to understand the differences and similarities between the three types of casings, namely blade, diffuser, and shroud, at various yaw angles and with different water flow velocities. The data analysis consists of several stages:

3.2.1 Determination of Data Proportions for Each Turbine Type

The dataset consists of three turbine design data, where the percentage of each turbine data is fairly evenly distributed, with the blade having 29.6%, the diffuser having 35.9%, and the shroud having 34.6%, as shown in Figure 3.

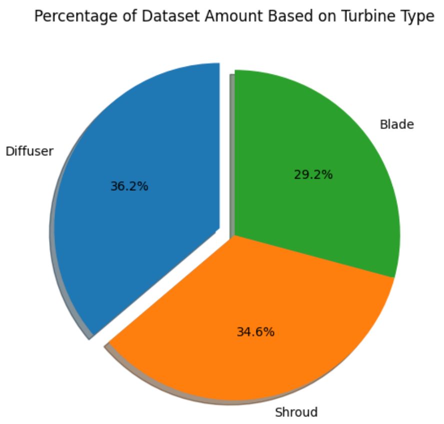

Figure 3. Comparison of the Number of Data for Each Turbine Type

This dataset consists of 5 variables, namely V, Gamma, TSR, Cp, and Type. The variable V has three data variations, namely 0.7 m/s, 0.9 m/s, and 1.1 m/s. The Type variable only has three types, namely blade, diffuser, and shroud. The Gamma variable has 6 angles consisting of 0, 5, 10, 15, 20, and 25. The values of these three variables are already known clearly. However, the TSR and Cp variables have many diverse values, so data visualization is needed to see their distributions. Data distribution visualization is the process of creating a visual that shows how values in a dataset are spread out. Its goal is to simplify understanding of trends and patterns in the data, such as whether data is evenly distributed or not, and how outliers (values that are very different) affect the distribution of data [16]. Visualization of data distribution using a violin plot is one way to visualize the shape of data distribution visually. This plot combines the aspects of a histogram and a kernel density plot, and shows how data is distributed along a scale. The plot shows the data distribution profile with the wide part indicating the density of data and the middle part indicating the shape of the distribution. This helps in understanding how data is spread out and how data distribution differs between variables. The distribution of TSR data can be seen through the visualization in Figure 4. Each turbine type has a relatively uniform and even distribution of TSR values. However, upon closer inspection, it appears that the distribution of TSR values in the Blade type is smaller compared to the distribution of TSR values in the Diffuser and Shroud types. The wide part of the violin plot in the middle indicates that the TSR values in each turbine type have a high concentration in that part.

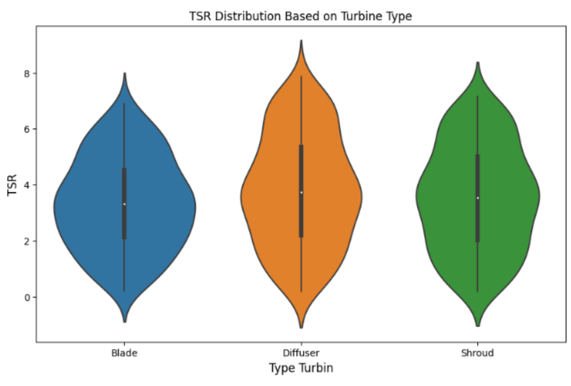

Figure 4. Distribution of TSR Data for Each Turbine Type

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If previously TSR had a distribution of data that was almost even for each turbine type, it is not the case for the distribution of data for Cp (coefficient of power) values. The visualization results for Cp values can be seen in Figure 5, where the blade type has a much lower range of Cp values compared to the diffuser and shroud types, although it has a low range of values, but this blade type has a high concentration of values, which can be seen from the widening of the violin plot at the top [17]. The diffuser type has a wide range of variation between data, which can be seen from the higher shape of the violin plot compared to other turbine types. The shroud type has a shape of the violin plot that is quite high but still below the diffuser type, and the shape of the Shroud plot looks almost the same as the Blade type, where the top part of the plot appears larger indicating that the Cp values in the Shroud type are more concentrated at higher values.

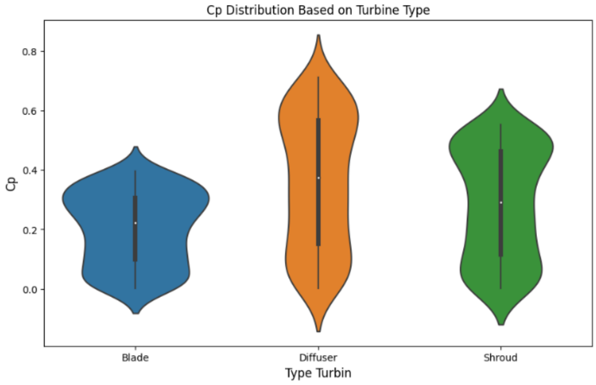
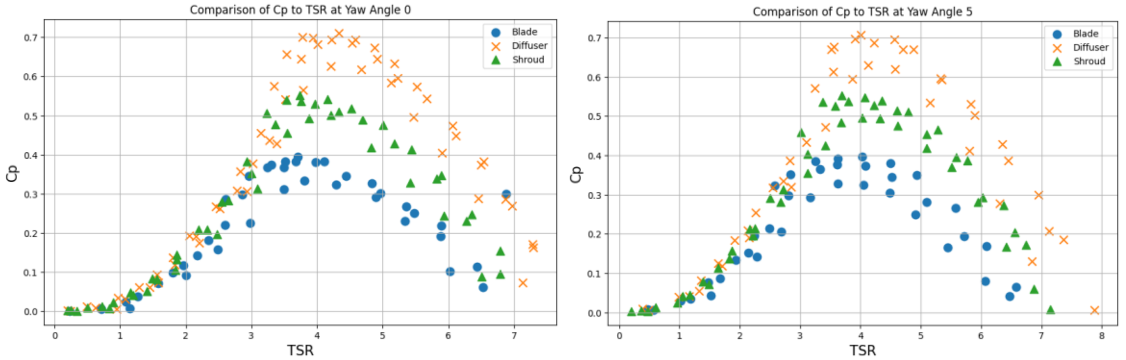


Figure 5. Coefficient of Power Value Distribution for Each Turbine Type

3.2.2 Analysis of CP and TSR at Various Yaw Angles

The power coefficient (Cp) is one of the important parameters for determining the performance of hydrokinetic turbines. Cp measures how efficient a turbine is in converting the energy of water flow into mechanical energy. A high Cp value indicates that the turbine is capable of converting a large amount of water flow energy into mechanical energy, thus it can be used to produce more electrical power [18]. This states that Cp is one of the important parameters for determining the performance of hydrokinetic turbines. The next step is to analyze the Cp value with TSR at various yaw angles, this analysis aims to see how the Cp and TSR values are affected by various yaw angles on each type of turbine using a scatter plot, for further details see Figure 6.

Based on the visualization results in Figure 6, it can be seen that the Diffuser turbine type always produces higher Cp values at every yaw angle compared to the Blade and Shroud types. The visualization results from the scatter plot can explain why the Cp graph of the Blade type in the violin plot appears lower compared to the Cp values of the Diffuser and Shroud types. This is because the Blade type has inferior performance at every yaw angle when compared to the performance of the Diffuser and Shroud types. The Diffuser type has a design that causes the fluid flow to experience an increase in pressure when passing through a smaller inlet and into a larger outlet. This helps to maximize the energy potential of the fluid flow [19].



(A) (B)

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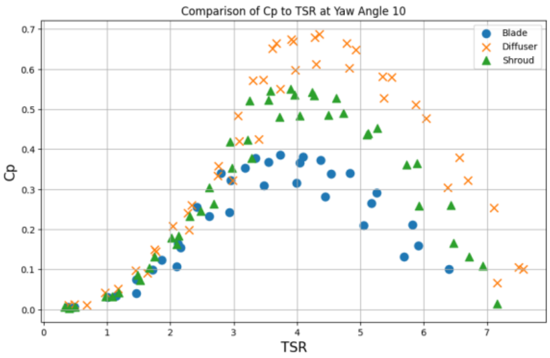

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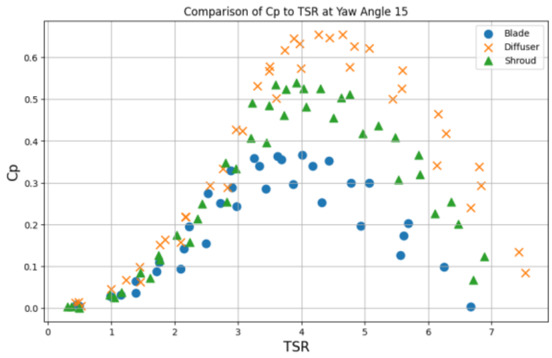
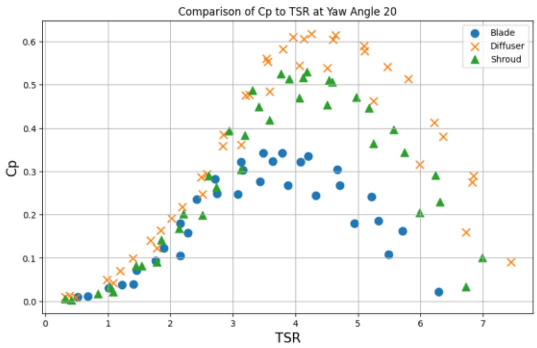


(D)



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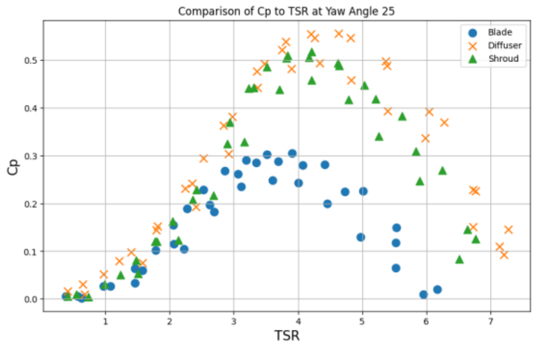

(F)

Figure 6. Comparison Graph of Cp Versus TSR at Yaw Angles (A, B, C, D, E, and F)

3.2.3 Analysis of Maximum Cp Value

Further analysis was conducted to determine the maximum Cp values for each turbine type at every yaw angle and fluid velocity variation. This can provide an overview of the energy potential that can be generated by each turbine type under various conditions. This analysis was carried out to determine how much power each turbine type can produce at each yaw angle and fluid flow velocity variation. The results of the maximum Cp values for each turbine type with various yaw angles and fluid velocity variations can be seen in Table 1, where the Blade type has a maximum Cp of 0.396 at a velocity of 1.1 m/s with a yaw angle of 5, the Diffuser type has a maximum Cp of 0.711 at a velocity of 0.9 m/s with a yaw angle of 0, and the Shroud type has a maximum Cp of 0.552 at a velocity of 1.1 m/s with a yaw angle of 5. This indicates that not only fluid velocity affects the energy potential that can be produced by a turbine, but the yaw angle also plays an important role. This also shows that higher fluid velocities do not always result in maximum Cp values, and smaller yaw angles do not always produce high Cp values as seen in Table 1.

Table 1. Maximum Cp and yaw angle results.

No	Type	Gamma	V	TSR	Cp
1	Blade	0	1.1	3.709	0.395
2	Blade	5	1.1	4.030	0.396
3	Blade	10	1.1	3.732	0.386
4	Blade	15	1.1	4.011	0.366
5	Blade	20	1.1	3.487	0.342
6	Blade	20	1.1	3.793	0.342
7	Blade	25	1.1	3.909	0.305
8	Diffuser	0	0.9	4.333	0.711

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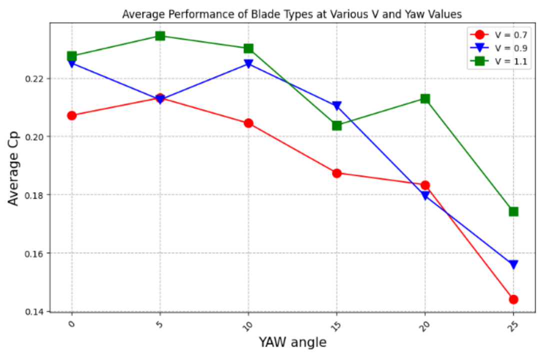
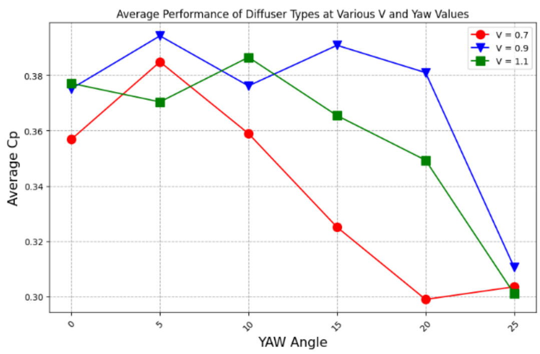
9	Diffuser	5	0.9	4.003	0.707
10	Diffuser	10	0.9	4.347	0.688
11	Diffuser	15	0.9	4.271	0.655
12	Diffuser	20	0.9	4.252	0.618
13	Diffuser	25	0.9	4.634	0.556
14	Shroud	0	1.1	3.733	0.551
15	Shroud	5	1.1	3.691	0.552
16	Shroud	10	1.1	3.901	0.550
17	Shroud	15	1.1	3.919	0.539
18	Shroud	20	1.1	4.185	0.530
19	Shroud	25	1.1	4.215	0.518

3.2.4 Analysis of Average Cp

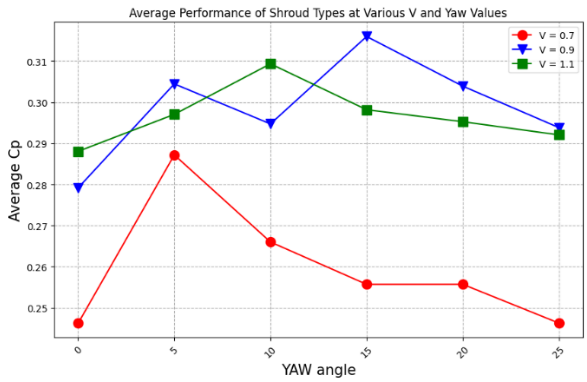
After analyzing the maximum Cp for all types of turbines at various yaw angles and velocity variations, the next step is to analyze the average Cp value at each yaw angle and velocity variation. This analysis provides information on the consistency of energy performance for each type of turbine under various yaw angles and velocity variations. This analysis is crucial to ensure the type of turbine that has the best performance in terms of energy efficiency and turbine performance consistency, as shown in Figure 7.



(a)



(b)



(c)

Figure 7. Comparison of average Cp values at various Yaw angles and V velocities, (a) Blade, (b) Diffuser, (c) Shroud

Based on the visualization in Figure 7, it can be seen that the Blade and Diffuser types experience a decrease in the average performance of Cp values for each increase in yaw angle. This occurs due to flow disturbances that cause turbulence and affect turbine efficiency with hydrokinetics [20]. Velocity V has a significant influence on the performance of Blade and Diffuser types. At a velocity of 1.1 m/s,

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the Blade type has a smaller decrease in performance compared to the Diffuser type. This can be said to be directly proportional to the results of the previous maximum Cp analysis, where the Blade type has better performance than the Diffuser type at a velocity of 1.1 m/s. Meanwhile, the Shroud type has different performance between the maximum Cp value analysis and the average Cp value analysis. The maximum Cp analysis results show that the Shroud type has the largest energy potential at the combination of V 1.1 m/s and yaw angle 5, but the average Cp value analysis results show that the Shroud type has better performance at the combination of V 0.9 m/s and yaw angle 15. These results indicate that the Shroud type has more stable performance and is not too influenced by variations in velocity and yaw angle, but the Diffuser type still obtains a relatively high average Cp value compared to all types.

3.2.5 Percentage Change in Cp Value

Efforts to produce a good, clear, and easy-to-understand analysis involve calculating and presenting the average change in Cp at each V speed and various yaw angles in the form of a percentage. This is because presenting data in the form of percentages makes it easier to compare changes that occur in each type of turbine and facilitates understanding of changes on the same scale, making it easier to draw conclusions and conduct further analysis.

Table 2. Percentage Change in Cp

No.	Yaw	V	Blade (%)	Diffuser (%)	Shroud (%)
1	0	0.7	0	0	0
2	5	0.7	2.895	7.838	16.633
3	10	0.7	-1.303	0.580	8.028
4	15	0.7	-9.534	-8.896	3.842
5	20	0.7	-11.498	-16.210	3.845
6	25	0.7	-30.501	-14.936	0.017

Based on Table 2, changes in Cp values for each type of turbine at velocity V 0.7 can be analyzed through changes in percentage Cp. The data above shows that at a yaw angle of 5 degrees, there is an increase in Cp percentage for Blade, Diffuser, and Shroud types. Blade type has an increase in Cp percentage by 2.895%, Diffuser type has an increase of 7.838%, and Shroud type has an increase of 16.633%. At a yaw angle of 10 degrees, Blade type has a decrease in Cp percentage by 1.303%. Meanwhile, Diffuser type has an increase in Cp percentage by 0.58% and Shroud type has an increase of 8.028%. At a yaw angle of 15 degrees, Blade type has a decrease in Cp percentage by 9.534%, Diffuser type has a decrease of 8.896%, and Shroud type has an increase in Cp percentage by 3.842%. At yaw angles of 20 and 25 degrees, Blade and Diffuser types experience a decrease in Cp percentage by 11.498% and 16.210%, respectively, while Shroud type remains stable with the same Cp percentage of 3.845%. From the analysis of percentage Cp changes at each yaw angle at velocity V 0.7, it can be concluded that Shroud type has a more stable performance and undergoes smaller changes compared to Blade and Diffuser types.

Table 3. Average Cp Value Changes

No.	Yaw	V	Blade (%)	Diffuser (%)	Shroud (%)
1	0	0.9	0	0	0
2	5	0.9	-5.568	5.085	9.058
3	10	0.9	-0.105	0.268	5.572
4	15	0.9	-6.534	4.175	13.190
5	20	0.9	-20.227	1.545	8.864
6	25	0.9	-30.762	-17.192	5.250

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In Table 3, the average changes in Cp values for each turbine type at a velocity of 0.9 m/s and various yaw angles can be observed. At this velocity, the Blade turbine shows a significant change in Cp value with respect to yaw angle, with a decrease of 5.568% at 5 degrees and decreases of 20.227% and 30.762% at 20 and 25 degrees, respectively. Meanwhile, the Diffuser shows a more stable variation with changes in Cp value that are not too significant with respect to yaw angle. Despite the variation, the Diffuser still shows better Cp values than the Blade at this velocity. However, 25 degrees yaw angle is the worst angle for the Diffuser, showing a decrease of 17.192%. The Shroud turbine shows very good and stable performance at a velocity of 0.9 m/s and increases its Cp values with increasing yaw angle, where a 15-degree yaw angle provides an increase in the average Cp value of up to 13.190%.

Table 4. Average Cp Values on Blade

No.	Yaw	V	Blade (%)	Diffuser (%)	Shroud (%)
1	0	1.1	0	0	0
2	5	1.1	3.037	-1.775	3.125
3	10	1.1	1.161	2.501	7.394
4	15	1.1	-10.439	-3.084	3.518
5	20	1.1	-6.396	-7.359	2.504
6	25	1.1	-23.476	-20.150	1.392

In Table 4, it can be seen that at a yaw angle of 5 degrees, the average Cp value on the blade increased by 3.037%, while it decreased by 1.775% on the diffuser and increased by 3.125% on the shroud. At a yaw angle of 10 degrees, the average Cp value on the blade increased by 1.161%, and on the diffuser, it increased by 2.501%, while it increased significantly by 7.394% on the shroud. However, at a yaw angle of 15 degrees, the average Cp value on the blade decreased by 10.439%, on the diffuser it decreased by 3.084%, while it increased by 3.518% on the shroud. At a yaw angle of 20 degrees, the average Cp value on the blade decreased by 6.396%, on the diffuser it decreased by 7.359%, while it increased by 2.504% on the shroud. At a yaw angle of 25 degrees, the average Cp value on the blade decreased significantly by 23.476%, on the diffuser it decreased by 20.150%, while it increased by 1.392% on the shroud. Based on these results, it can be seen that a yaw angle of 5 degrees shows the best performance for all turbines with an increase in average Cp values on the blade and shroud, while a yaw angle of 25 degrees results in a significant decrease in Cp values for the blade and diffuser.

3.3 Interpretation of Results

Causes of the increase and decrease of the Coefficient of Power (Cp) at a certain yaw angle can be influenced by several factors. Firstly, changes in the yaw angle of a water turbine can have an effect on the fluid flow velocity around the blade, diffuser, and shroud angles of the turbine. When the yaw angle increases, the incoming fluid flow to the blade angle will experience a change in direction and velocity, which can affect the performance of the water turbine [21]. In addition, changes in the yaw angle can also alter the position of the rotor of the water turbine, thus also affecting its performance [22]. Secondly, changes in the Cp value of a water turbine are also influenced by the design of the shroud, as the shroud design plays an important role in maximizing the energy generated by the turbine when there is a change in the yaw angle. According to previous research conducted by Gish et al. [23], changes in the yaw angle of a water turbine can affect the value of Cp of the water turbine. The results of the research show that when the yaw angle increases, the Cp value of the water turbine decreases. However, excessive changes in the yaw angle can also cause a reduction in the fluid flow velocity entering the water turbine, resulting in a decrease in the Cp value of the water turbine.

4. Conclusion

This research is a quantitative study that used descriptive statistical methods to analyze the performance of a hydrokinetic turbine under yaw misalignment conditions. The data used in this study consisted of the coefficient of power (Cp) values obtained from a 19.8 cm diameter hydrokinetic turbine with a horizontal shaft, operated under yaw misalignment conditions. Tests were conducted at water

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velocities of 0.7, 0.9, and 1.1 m/s for three types of turbine casings, which included a casing-less turbine and two different types of casings. Experiments were conducted for yaw angles ranging from 0° to 25° with 5° intervals. The following conclusions can be drawn from the results of this study:

- The performance of each turbine type was significantly influenced by the combination of water flow velocity and yaw angle. The Diffuser type had the highest Cp value at every yaw angle, but its performance decreased with every increase in yaw angle. The Blade type had a poorer performance compared to the Diffuser at every yaw angle and had its best performance at the combination of 1.1 m/s water velocity and 5° yaw angle. Meanwhile, the Shroud type had a more stable performance and was less affected by variations in velocity and yaw angle. The average Cp values showed that the Shroud type had the best performance at the combination of 0.9 m/s water velocity and 15° yaw angle.
- Based on the analysis of the changes in the average Cp value with respect to changes in yaw angle at a velocity of 0.7 m/s, all three turbine types experienced an increase in Cp value at a yaw angle of 5°, where the Blade type increased by 2.895%, the Diffuser increased by 7.838%, and the Shroud increased by 16.633%. Both Blade and Diffuser types experienced a significant decrease at a yaw angle of 25°, but the Shroud type was able to maintain a consistent Cp value at this angle. A velocity of 0.9 m/s was able to maintain the average Cp value at every yaw angle for the Diffuser and Shroud types, but the Blade type experienced a decrease at every increase in yaw angle and a significant decrease at a yaw angle of 25°. At a velocity of 1.1 m/s, the results obtained were not significantly different from those at 0.7 m/s, where both the Diffuser and Blade types experienced a decrease in performance at every increase in yaw angle, but the Shroud type was able to maintain a consistent Cp value and even experienced a significant increase at a yaw angle of 5°, by 7.3%.

Based on the results of the research that has been conducted, it can be known that changes in yaw angle and shroud are factors that can affect the value of Cp in hydrokinetic turbines. Among the three types of shrouds, the Shroud type can provide more stable performance and smaller changes in Cp values compared to Blade and Diffuser types.

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