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TAGUCHI OPTIMIZATION OF WATER SAVONIUS TURBINE FOR LOW-VELOCITY INLETS USING CFD APPROACH

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Abstract

One of the renewable energy technologies for producing electricity from moving water is the Savonius turbine. This paper optimizes the Savonius turbine performance by conducting several CFD simulations and utilizing the mixed-level Taguchi method to improve the poor performance of Savonius turbine. The quality function was first created, and then the levels and factors were determined. After analyzing the mesh and the boundary conditions, the orthogonal array was built and the CFD simulation was executed for each run. The diameter is the parameter that has the greatest influence on the hydrodynamic performance, according to the Taguchi analys is, which demonstrated the optimal combinations of the parameters in low-speed streams. The main finding was that the modified water turbine's power coefficient (Cp) had a 15% improvement over the original design.

Keywords: Savonius turbine; CFD; Taguchi analysis; Vertical turbines; Optimization.

1.0 INTRODUCTION

Energy demands are mainly fulfilled by burning fossil fuels, such as coal, oil and natural gas [1]. The most significant issue is that fossil fuel resources are limited. Climate change and other alarming environmental problems are tied to the use of non-sustainable resources [2]. Renewable energy has grown in importance as a component of global energy development plans to help minimize these problems [3, 4]. Due to its availability, sustainability, and non-toxicity, hydrokinetic energy is one of the potential sources of clean energy. It has recently attracted a lot of attention. In addition, tidal and river turbines have increasingly become more and more in use [5].

Water turbines generate electricity from the kinetic energy of moving water [6]. Hydropower turbines can be divided into horizontal and vertical axis turbines (HAT and VAT respectively) [7]. VATs are more favoured in small and medium-scale water turbines since they can operate in water streams from different directions, and maintenance cost is relatively inexpensive [8, 9]. Savonius turbine is one of the vertical turbines, on which this study focuses.

Many regions in Malaysia, East Malaysia in particular, have serious issues with electricity due to their remote location [10, 11]. These remote places depend on fossil fuel power generators. Pulau Perhentian, Tioman Island, Pulau Redang, Pulau Layang-layang and Kampung Opar are prime examples of areas that do not have enough electricity, and they are dependent on fossil fuel generators [10, 12, 13]. In addition, operation and maintenance costs for fossil fuel generators over the long run are costly [10]. In addition, the cost of fuel can be around four times higher than in other places due to the expense of transportation [14-16]. Therefore, tidal and river energy could offer a good solution to mitigate these issues. However, there are several challenges associated with VATs, like poor performance, poor rotation, low stream inlets, and problems associated with self-starting [17, 18].

These issues have motivated many scientists and engineers to propose different solutions and optimize the existing turbines. For example, Al-Quraishi et al. have proposed a novel deflector surrounding the Savonius turbine to improve its poor performance, and the deflector improved the performance to reach 0.4 CP at 1.3 TSR, while, without the use of a deflector, the power of coefficient was only 0.1 CP [19]. Another study developed a new concept of deflectors by employing a rotating cylinder to improve the generated power of the drag-type turbine and to reduce the negative torque created by the returning blade, causing poor performance. Their method achieved more efficiency, up to 14%

improvement than the turbine without the deflector [20].

Chen et al. improved the efficiency of the vertical turbine by optimizing a deflector by using the Taguchi method in conjunction with a modified additive model, and the researchers found that one of their proposed deflectors achieved a 12% enhancement in the efficiency of the vertical turbine[21]. Different researchers used the Taguchi method to study the interactions between a Savonius wind turbine and moving vehicles, and it was found the optimal combination of factors for maximising the efficiency was d = 0.4m, α = 30°, and VC =30m/s, increasing the extracted power by 26%[22].

Ma et al. utilized the Taguchi method to optimize the airfoil, pitch angle, enwinding ratio, solidity ratio, and small shaft position of the H-type turbine, and it was found that the optimization process improved the performance by around 17%[23]. Other researchers used the Taguchi method and a neural network model depending on CFD data to optimize the mean of tip speed ratios for vertical wind turbines while using a deflector. It was found that the power of coefficient value from CFD can be enhanced by more than 3.58 folds under the optimal mean of tip speed ratio[21]. There are many factors controlling the performance of the vertical Savonius turbines, such as aspect ratio, diameter, height, overlap ratio, etc. Many researchers investigated each factor individually, like Patel et al. who studied the effect of overlap ratio and aspect ratio on hydrokinetic Savonius in low velocities[24], but no researcher has optimized all the parameters together to acquire the highest efficiency in law speed water streams. Therefore, the study aims to optimize all the factors affecting the Savonius turbine to reach its highest coefficient of power (Cp) in low-velocity water inlets by using the Taguchi method.

2.0 METHODOLOGY

Taguchi technique offers an effective method to determine the optimum geometries with a minimum number of experiments[25]. The steps taken to find the best combination are illustrated in Figure 1. To find the objective function, which is the required output of VAT, a Quality Loss (QL) function should be calculated as equation 1. QL is utilized to assess the parameter deviation from the quality output, which is the maximum value that could be acquired[26].

$$\mathrm{QL} = \mathrm{K}(\mathrm{V_e} - \mathrm{V_t})^2 \qquad (1)$$

where K is the quality loss factor, V_e is the calculated response and Vt is the target quality.

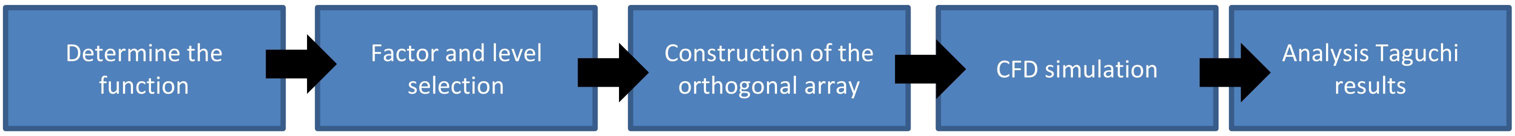


Figure 1. The study methodology

The quality target for this study is the highest harnessed power (Cp) from VAT, which is 0.59-the maximum amount of power generated from a turbine in an open stream, according to Betz Limit. The Taguchi optimization approach evaluates the optimization objective's output using the signal-to-noise ratio (S/N)[27]. The formula to calculate the S/N ratio for each category is found[28]:

$$\text{Larger} - \text{the} - \text{better}: S/N_{LTB} = -10\log \frac{1}{n}\sum_{i=1}^{n} \frac{1}{(Y_i)^2} \qquad (2)$$

$$\text{Nominal} - \text{the} - \text{better}: S/N_{NTB} = 10\log \frac{Y_m}{S^2} \qquad (3)$$

$$\text{Smaller} - \text{the} - \text{better}: S/N_{STB} = -10\log \frac{1}{n}\sum_{i=1}^{n} (Y_i)^2 \qquad (4)$$

where Y is the observed response, Y_m is the mean of the observed responses, S^2 is the variance, and n is the number of observed responses.

The QL function is considered a ‘smaller-the-better problem type, and it is transformed into the S/N ratio to assess the Savonius turbine efficiency[29].

$$S/N_{STB} = -10\log\,(V_e - V_t)^2 \qquad (5)$$

From equation 5, the difference between the maximum and optimum response should be smaller the better to maximize the S/N ratio. Therefore, maximizing V_e is equivalent to minimizing the QL in the equation, making the noise sensitivity minimum[30]. When changing Cp and target quality, the objective function is given by:

$$S/N = -10\log\left(C_p - 16/27\right)^2 \tag{6}$$

By selecting the factors' levels with the highest S/N ratio, the optimal value of each factor is calculated. In this study, the aim is to determine the best combination of the controlling factors. As Table 1 shows, the factors and levels. For this paper, the factors are the deflector, the number of blades, the diameter (d), the overlap between the paddle (e) and the gap ratio(e').

Table 1. Factors and levels

Factors	L1	L2	L3	L4
Deflector	Non	2		
Blade	2	4		
d	3.6	1.2	0.6	0.36
e	0	0.24	0.18	0.15
e'	0	0.01	0.02	0.03

These factors are chosen because they control the other important design aspects, like the aspect ratio and the overlap ratio, which are directly affecting the power output of the turbine. The design parameters for Savonius turbines can be found in Figure 2. To construct the orthogonal array (OA), the Taguchi method allows testing a certain number of experiments to find the best combination of the parameters instead of testing all the possible models. The optimization approach requires a parameter matrix with multiple levels to be analyzed. The number of runs in the Taguchi method is specified concerning the degree of freedom (DOF)[31]. The orthogonal array is modified in the design to test two factors at 2 levels and three factors at 4 levels. The feasible OA with these variables is L16($4^3 * 2^2$), which is a mixed-level OA built as shown in Table 2. Therefore, there will be 16 cases, instead of 256 runs, that will be tested to acquire the optimum turbine performance (Cp), depending on the OA.

A 2D-CFD analysis was conducted by utilizing Ansys Fluent to determine the output power of the turbine. A grid independence study was conducted to ensure the reliability of the simulation[32]. The tested number of mesh elements was approximately 200,000. The used turbulent model was K-omega SST because it provides a very high rate of accuracy for transient cases, like turbomachines[33]. The performance in all the runs was found at the same TSR, which is 0.8 since it is the peak performance value for Savonius turbines. The main method chosen for this simulation is PISO (The Pressure-Implicit with Splitting of Operators) because it provides more stable solutions for all transient cases[34, 35]. All the simulations were conducted at the lowest velocity stream in Malaysia, which accounts for 0.56 m/s[36]. A CFD analysis was conducted on the turbine with the optimized parameters at the full TSR range later. The maximum power from the turbine is determined by the equations:

$$P_{max} = \frac{1}{2}\rho A v^3 \tag{7}$$

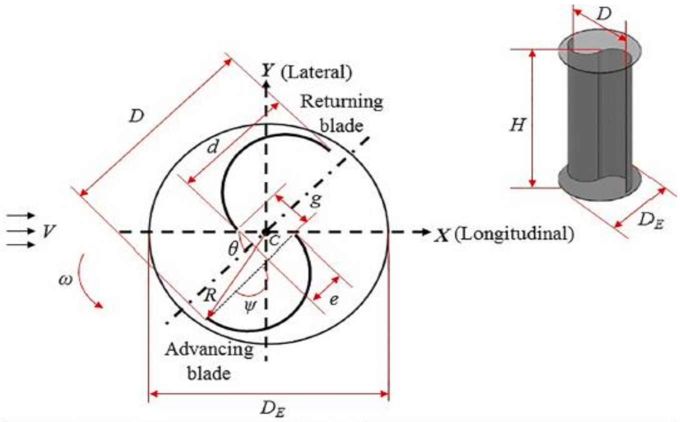
Where P_{max} is the maximum power in watts, ρ is the density of the fluid and the inlet velocity of water is defined by v in m/s. The cross-sectional area in equation 7 is defined by A in meters, which is defined as diameter (D) × height (H).

To calculate the power generated by the rotor, the following equation is used:

$$P_{rotor} = T\omega \tag{8}$$

Where T is the torque generated by the Savonius turbine in *N.m*, and ω is the angular velocity of the turbine in *rad/s*. From equations 7 and 8, the coefficient of power for the turbine is defined as:

$$C_p = \frac{P_{rotor}}{P_{max}} \tag{9}$$



C	Center of turbine	V	Freestream velocity (m/s)
D	Diameter of turbine (m)	θ	Turbine rotor angle (°)
D_E	End plate diameter (m)	ω	Angular velocity of turbine (rad/s)
d	Diameter of blade (m)	ψ	Blade arc angle (°)
e	Overlap distance (m)	AR	Aspect ratio [H/D]
g	Gap distance (m)	ER	End plate ratio [D_E/D]
H	Height of turbine (m)	GR	Gap ratio [g/d]
R	Radius of turbine (m)	OR	Overlap ratio [e/d]

Figure 1. Savonius geometrical parameters [37]

Table 2. The OA for the Taguchi design with the responses

Factors	d	e	e′	n-deflector	n-blades	CP
Run-1	3.60 (1)	0.00 (1)	0.0 (1)	non (1)	2 (1)	0.169
Run-2	3.60 (1)	0.24 (2)	0.01 (2)	non (1)	2 (1)	0.195
Run-3	3.60 (1)	0.18 (3)	0.02 (3)	2 (2)	4 (2)	0.246
Run-4	3.60 (1)	0.15 (4)	0.03 (4)	2 (2)	4 (2)	0.223
Run-5	1.20 (2)	0.00 (1)	0.01 (2)	2 (2)	4 (2)	0.16
Run-6	1.20 (2)	0.24 (2)	0.0 (1)	2 (2)	4 (2)	0.1922
Run-7	1.20 (2)	0.18 (3)	0.03 (4)	non (1)	2 (1)	0.11
Run-8	1.20 (2)	0.15 (4)	0.02 (3)	non (1)	2 (1)	0.102
Run-9	0.60 (3)	0.00 (1)	0.2 (3)	non (1)	4 (2)	0.13
Run-10	0.60 (3)	0.24 (2)	0.03 (4)	non (1)	4 (2)	0.15
Run-11	0.60 (3)	0.18 (3)	0.0 (1)	2 (2)	2 (1)	0.14
Run-12	0.60 (3)	0.15 (4)	0.01 (2)	2 (2)	2 (1)	0.12
Run-13	0.36 (4)	0.00 (1)	0.03 (4)	2 (2)	2 (1)	0.13
Run-14	0.36 (4)	0.24 (2)	0.02 (3)	2 (2)	2 (1)	0.1399
Run-15	0.36 (4)	0.18 (3)	0.01 (2)	non (1)	4 (2)	0.11
Run-16	0.36 (4)	0.15 (4)	0.0 (1)	non (1)	4 (2)	0.10

3.0 RESULTS AND DISCUSSION

The CFD analysis was conducted on all the runs in the OA at 0.8 TSR, and Run-3 acquired the highest performance as seen in Table 2. Figure 3 displays the velocity contour, streamline graph and velocity vector for Run-3, whereas Run-8 and 16 showed the lowest response among the tests. To optimize the turbine's performance, numerous simulations are conducted across a broad spectrum of Tip Speed Ratios (TSRs).

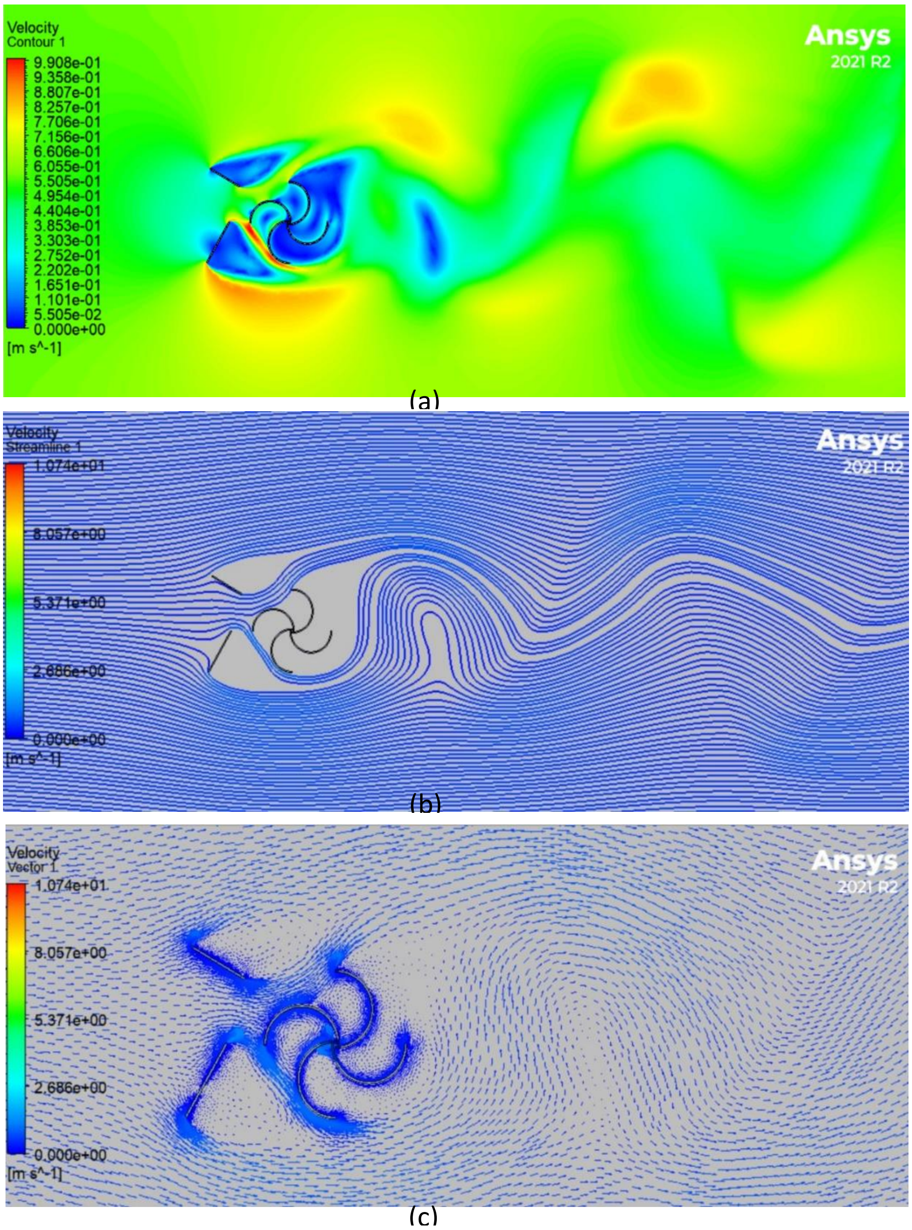


Figure 2. (a) velocity contour (b) streamlines graph (c) velocity vector at 0.8 TSR Run 3

According to Table 3, the analysis showed that the diameter is the most significant factor that impacts the power coefficient, as can be seen from its ranking. This is because the aspect and overlap ratios are strongly affected by the change in the diameter. This finding is in line with the theoretical principle of the design. As equation 7 shows, the bigger the area is, the more maximum power can be extracted. The torque is also expected to increase when the diameter increases because the turbine will be exposed to more energy from the water, increasing the overall performance. However, e' is the factor that has the lowest effect on the Cp. Therefore, it is recommended to be kept around zero.

From the main effects plot for means and SN ratios, as Figure 4 displays, the best combination for the optimized turbine is the higher in the plot, as the following d=3.6m, e=0.24, e'=0.03, the number of deflectors =2, and the number of blades =4. The turbine showed a better performance when deflectors were placed near the rotor.

Table 3.(a)Response table SN ratio (b) Response table for means

(a)

Level	d	e	edah	Deflector	blades
1	-18.47	-16.59	-16.58	-17.67	-17.22
2	-17.08	-17.66	-16.73	-15.58	-16.03
3	-17.24	-16.72	-16.77		
4	-13.71	-15.55	-16.44		
Delta	4.76	2.10	0.33	2.09	1.19
Rank	1	2	5	3	4

(b)

Level	d	e	edah	Deflector	blades
1	0.1202	0.1490	0.1526	0.1344	0.1404
2	0.1403	0.1386	0.1490	0.1710	0.1651
3	0.1421	0.1542	0.1535		
4	0.2082	0.1690	0.1557		
Delta	0.0881	0.0304	0.0068	0.0366	0.0247
Rank	1	3	5	2	4

The performance of the optimized turbine in different TSRs can be shown in Figure 5, and it can be seen that the performance has improved by a factor of around 15% compared to the typical Savonius turbine with the same diameter adapted from [36, 38]. The percentage increase was calculated by Equation 10 for each TSR, and the average value is determined.

$$Precentage\ increase = \frac{(final\ value - intial\ value)}{intial\ value} \times 100 \tag{10}$$

The typical design of a Savonius turbine involves two half-cylinder-shaped blades or scoops that are placed parallel to each other, creating an S-shaped configuration. This S-shaped rotor design allows the turbine to capture water from any direction, making it suitable for areas with turbulent or changing water patterns.

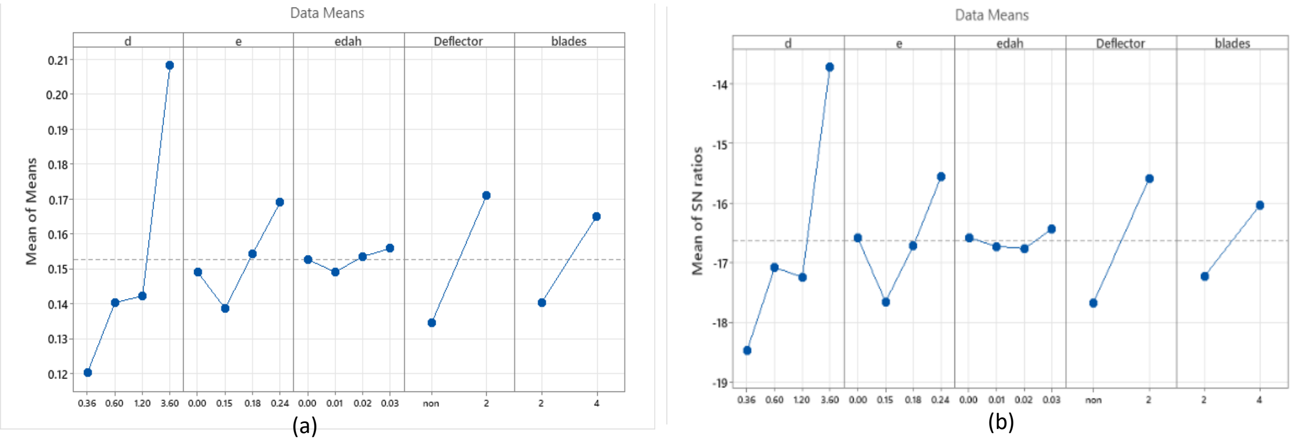


Figure 3. (a) Main effect plot for means (b)Main effect plot for SN ratios

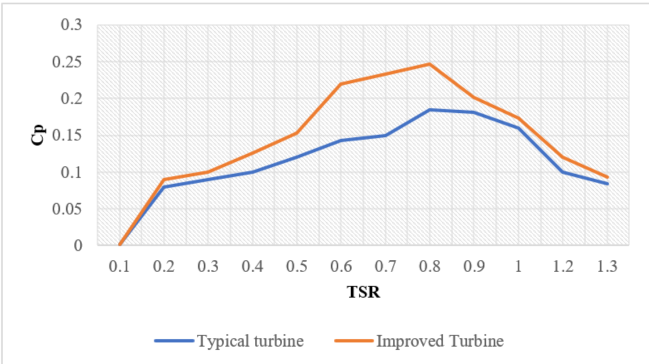


Figure 4. The performance curve for a typical turbine adapted from [36, 38] and the improved turbine

4.0 CONCLUSION

This study optimized the Savionus turbine at low-speed water inlets by conducting several CFD simulations. This study used a mixed-level Taguchi approach and investigated the influence of several factors on the Savionus turbine operating at law velocity streams. At first, the quality function was created, and the levels and factors were selected. An orthogonal array with $L16(4^3 * 2^2)$ was constructed to undergo the CFD analysis. The Taguchi analysis concluded that the optimal design parameters for the Savionus turbine in low-speed streams are: d=3.6m, e=0.24, e'=0.03, the number of deflectors =2, and the number of blades =4. In addition, it also concluded that the most significant factor is the diameter of the turbine. A full simulation was also conducted for the optimized turbine, and it has a better performance by a factor of 15% compared to a typical turbine from the literature.

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