Prediction of the Hydrodynamic Performance of an Elliptical Blade Savonius Turbine using Computational Fluid Dynamics

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Abstract. Electricity is a renewable energy source that can be generated from natural energy resources. Savonius rotor is a type of turbine which produces small-capacity electrical energy using the kinetic energy obtained in the water flow. The main driving force in this paper is to predict the hydrodynamic performance of elliptical blade savonius hydro turbines with computational fluid dynamics (CFD). A 3D unsteady simulation will be conducted using ANSYS-CFX 19. The elliptical blade profiles with vertical axis turbines are performed at different blade numbers of 2, 3, and 4 blades. The performance analysis results show an improvement in the coefficient performance value of the elliptical blade compared to the conventional semi-circular blade. Based on the results, the more appropriate results obtained at TSR 1.069 for three elliptical blades with a power coefficient value of 0.738.

Keywords: Savonius, Simulation, Performance, Elliptical blade.

1. Introduction
Green energy has become a hot topic of environmental discussion nowadays. Many research performs more effort to generate environmentally friendly energy, thereby reducing dependence on fossil energy or possibly eliminate. Thus, there is considerable need to improve the source of renewable energy. Savonius turbine is the conventional type of turbine which transforms the fluid flow to rotate the blades attach to the shaft. The preliminary design of the savonius turbine is aimed at the wind turbine. Nevertheless, few researchers have proven that savonius turbine can be applied as the water turbine [1]. However, the efficiency of savonius turbine regarding a study reported being inferior as compared to other types of turbines [2]. The current researcher conducts a study to improve the performance of the turbine, which will achieve higher electrical energy. Although high progress has been achieved for the wind turbine, it needs to predict the performance value for hydro turbine applications qualitatively. Therefore, it has become necessary to develop a suitable configuration of savonius hydro turbine to absorb the energy contained in water flow. With the advancement of computer capabilities, allows the researcher to perform an investigation by numerical simulation faster and more complexity of the case. It allows us to get more detailed information and to be closer to the real conditions.

Alom et al. [3] had performed an unsteady 2D numerical simulation to optimize the performance of savonius wind turbine with an elliptical blade using ANSYS Fluent. Based on their configuration of the elliptical curve, the velocity inlet was set for \( v = 6.2 \) m/s and aspect ratio, \( \alpha = 0.7 \), and overlap ratio, \( \beta = 0.2 \). The result shows that the performance gained by 18.18 % can be obtained for the
elliptical curve compared to the semi-circular blades at TSR, $\lambda = 0.8$, and $\theta = 47.5^\circ$. Similar research also performed by Banarjee et al. [4]. They conducted an unsteady numerical simulation to calculate the performance of savonius elliptical turbine in 2D operating as a wind turbine. Depend on their numerical setup and turbine configuration with different scale factors, the performance gain of 10.7% was attained compared to the semi-circular savonius turbine. Hassan et al. [5] had modified classical blades design of the savonius wind turbine to improve the efficiency. Several modified blade curves were performed and also conducted a comparison between two and three blades. A 2D unsteady Reynolds-Averaged Navier Stokes equation (URANS) was applied to investigate the performance. The results that can be obtained shows that three blades are reducing the $C_p$ by 17.2%. Wenehenubun et al. [6] had observed an experimental study on wind tunnel to investigate the performance characteristic of savonius wind turbines in a various number of blades. At the three blades, the turbine will operate higher rotational speed and higher tip speed ratio compared to the two and four blades. Besides, at the four blades, the turbine produces the highest torque than two and three blades.

Sarma et al. [1] had performed an experimental and numerical investigation to observe the performance of savonius hydrokinetic turbine. The results were compared to savonius wind turbines with the same input power. It has an improvement (for the same input power) for the maximum power that can be extracted by savonius hydrokinetic turbine. In this regard, the power increased by 61.32% of the same size of the turbine. Based on the results, Sarma et al. stated that improvement in the power produced due to a higher density of water might result in a higher drag force. So, it could drive the turbine to generate more torque and hence power in the water. Hadi et al. and Hamzah et al. [7,8] had been conducted an experimental observation with applied savonis rotor into the water pipe to utilize the energy contained on water flow. From the results of their experiments, it can be concluded that savonius turbine is the applicative turbine type. It was able to be operated in several conditions.

Based on these parameters discusses, it needs to improve the rotor efficiency to extract the power available in the water stream. So, the modification of the conventional turbine with new blades curve have to calculate qualitatively how much the increased efficiency can be obtained, or even reduce its efficiency. Therefore, this paper focuses on the discussion of elliptical savonius performance if operated on the canal. The performance will be generated by numerical simulation using ANSYS CFX 19.0. Three different models will be applied as the variation of the study to understand the effect of blades number. The simulation has an assumption that the water flow is uniform at an ambient temperature of 25℃. Approximation with Multiple reference frame (MRF) approach is applied to calculate the torque generating at one rotation or 360°. Then, the performance parameter will be presented, and the efficiency change will discuss further.

2. Conceptual application

Savonius turbine has gained much attention for the wind turbine application. However, savonius turbine concept is not much attempted as a hydrokinetic turbine. Savonius turbine has several advantages, such as: easy to manufacture and suitable for the river stream or canal water flow, which has a low fluid stream. This paper will give attention to apply the savonius turbine as the small power plant on the canal. Figure 1 shows the conceptual design to operate savonius turbine in the canal.
Figure 1. (1) Water flow, (2) Canal wall (3) Electric generator (4) Turbine rotor (5) Turbine vane, (6) Direction of water flow [9]

3. Performance calculation
The relationship between the hydrodynamics coefficient is represented by equation 3. Which, it is used to calculate the dimensionless hydrodynamic performance of the rotor. Another nondimensional parameter, such as aspect ratio ($\alpha$) and overlap ratio ($\beta$), is also presented in this section. The performance of the savonius turbine is often calculated in term of power coefficient ($C_p$) and torque coefficient ($C_T$) [8].

$$\alpha = \frac{H}{D} \quad (1)$$

$$\beta = \frac{e}{d} \quad (2)$$

$$C_p = \frac{P_{turbine}}{P_{available}} = \frac{T \omega}{1/2 \ \rho \ A_r v_0^3} = \frac{T}{1/2 \ \rho \ A_r v_0^3} \cdot \frac{r \ \omega}{v_0} = C_T \lambda \quad (3)$$

where, $P_{turbine}$ is the actual power produced by the turbine, $P_{available}$ is the power contained in the water flow. $T$ is the torque produced by the turbine, $A_r$ is the projected area of the turbine perpendicular to the flow direction, $\omega$ and $v_0$ representing by the angular velocity and linear velocity, respectively. $P$ is the fluid density, $r$ is the radius of the rotor, and $\lambda$ is the nondimensional parameter called with tip speed ratio or TSR.

4. Numerical setup
4.1. Geometry modeling
The objective of the current paper is to adapt the elliptical blade shape that has been performed by alom et al. [3]. The more appropriate design with the sectional cut angle at $\theta = 47.5$ is chosen and applied to the current research. Figure 2 shows the dimension and pattern of the ellipse with the sectional cutting angle $\theta$. The $\theta$ is made by the line intersecting the major axis AA’ at M. The point M is at 54% of AO from O to get the required chord length ($d$) of the blade.
Figure 2. Elliptical profile and turbine geometry [3]

The report of simulation is the performances over a range of tip speed ratio (TSR) by comparing the power and torque coefficient of the elliptical blade profile at $\theta = 47.5^\circ$. While varying the TSR, both the aspect ratio and overlap ratio are kept constant.

Figure 3. 3D model for 2, 3, and 4 blades

Detailed dimension of the turbine are, $H = 370$ mm and $D = 0.245$. In this regard, the aspect ratio $a = 1.5$ with the $D/D_o = 1.1$, the endplate diameter, $D_o = 269.5$. The overlap ratio of each couple blades is 20% of the chord length. Which this model has chord length, $d = 135.8$ mm. Moreover, the thickness of the blades is set by 2 mm.

4.2. Computational domain and Meshing

In the present study, ANSYS design modeler is used to design the 3d model of the elliptical blade and the conventional semi-circular blades. For every simulation under consideration, the rotating domain is a cylinder, placed at $5D$ form the inlet and $7D$ to the outlet. Then, the square surface on the inlet and the outlet sides are $6D$, respectively. To predict the turbine performance by numerically, a method known as a multiple reference frame (MRF) approach is applied [10]. This method divides the domain of fluid into two different domains: rotating domain and fixed domain.

The domain initialization for rotating is set with an automatic meshing method, and the fixed domain is established as the tetrahedron meshing method. For the interface of rotating and fixed, CFX solver is capable of joining the meshing approach using a generalized grid interface (GGI). To minimize the number of mesh elements and increase the mesh density, we applied the mesh sizing with the body of influence selection. It may allow more accuracy for calculating the critical section. Then, to obtain the viscous effect as the turbulent boundary layer, we placed seven layers with inflation on the propeller surface. All simulation meshes had the same value of $y+ \approx 50-100$ for all blades surfaces. After convergence, the element mesh for each blade is different due to the larger surface are every addition of the blades. But, the number of elements for a fixed domain
keep remain constant for each run. For two blades, the number of elements of the rotating domain is 3,227,549, and the number of nodes is 966,064. Besides, for the fixed domain, the number of elements of the rotating domain is 757,721, and the number of nodes is 132,240.

![Computational domain](image1)

**Figure 4.** Computational domain

![Element mesh](image2)

**Figure 5.** Element mesh for two elliptical blades

### 4.3. CFX-Pre

The simulation is performed in 3D, assuming unsteady. The water flow in a homogenous uniform inflow and open water conditions. With the MRF Approach, the rotational speed is varied at 30 – 90 rpm. The inlet velocity is always constant at 0.6 m/s, and the outlet pressure is set with static pressure by 1 atm. The rotor, as the solid boundary, the no-slip condition is applied to approach the real conditions. Besides the outer boundary, free slip conditions are used. The transient analysis type the total time is set by 1 s with time step 0.001, and the automatic initial time is applied. To catch the turbulent flow around the solid body, a turbulent model SST is applied and used for all simulation with automatic wall function.

| Parameters          | Type                  | Setting         |
|---------------------|-----------------------|-----------------|
| Inlet domain        | Normal speed          | 0.6 m/s         |
| Outlet domain       | Static Pressure       | 1 atm           |
| Rotating domain     | Angular velocity      | 30-120 rpm      |
| Turbulent model     | Shear Stress Transport| Automatic wall function |
5. Verification and validation method

5.1. Verification and validation
In this study, the role model of geometry design and the performance value of the savonius hydrokinetic turbine is validated with the numerical study by Patel et al. [11]. In this study, a conventional semi-circular blade is generated, and then, the torque value is compared to the torque value of the reference paper. All simulations are performed at constant water velocity for $v = 0.6$ m/s. Based on the numerical setup that we have obtained, the performance and the torque error percentage are presented in Table 2, as follows.

Table 2. Verification and validation parameters

| $\omega$ (rad/s) | $T$ (N.m) | $\lambda$ | $C_T$ | $C_P$ | $T$ (Patel et al.) | $T$ (Error) |
|-----------------|-----------|----------|-------|-------|-------------------|-------------|
| 3.140           | 1.398     | 0.641    | 0.701 | 0.449 | 1.378             | 1.451%      |
| 4.189           | 1.105     | 0.855    | 0.554 | 0.474 | 1.078             | 2.505%      |
| 5.236           | 0.936     | 1.069    | 0.469 | 0.502 | 0.909             | 2.970%      |
| 6.283           | 0.798     | 1.283    | 0.400 | 0.513 | 0.782             | 2.046%      |

Figure 6. Verification and validation of $C_p$ and $\lambda$ compared to the research of Patel et al. [11]

5.2. Mesh dependent study
In this step of research, mesh study performs to achieve the optimum elements of simulations. It will give more primacy, lower requirements of computer capability, and shorter time needed to complete
the simulations. Mesh study is done with adding the element of mesh, in this regard, understated the mesh size at the same boundary. Prabowoputra et al. [13] have performed meshing studies for nine different mesh. They stated that the effective mesh is at the number of elements of 2.7 million depend on their numerical setup and the size of the design. But, it can be the judge that these values are valid for every condition. In this paper, the optimal number of element mesh is determined based on the torque value, which is close to the torque value in the reference paper, or in this case, has the smallest error and least number of elements. This study only performs at \( v = 0.6 \text{ m/s} \), \( \omega = 30 \text{ rpm} \) for semi-circular blade. The number of element mesh is used as the comparison study, presented in Table 3. After the mesh setting has obtained, it applied to all blade profiles.

| Setting | Rotating | Fixed | Torque | Error |
|---------|----------|-------|--------|-------|
| 1       | 996,127  | 966,064| 1.267  | -8.055%|
| 2       | 3,227,549| 966,064| 1.398  | 1.451% |
| 3       | 5,378,182| 966,064| 1.421  | 3.120% |

6. Results and discussion
The savonius wind turbine can operate due to the pressure drag and lift force acting on their curve. The force can different for every angle of attack, and each shape has its own force coefficient. Therefore, the moment pushes the blades to turn at a certain angle. It can happen because of the variations of the force during the device rotation. Based on the previous study, the highest torque extracted by the turbine is at the angle of attack 90° or when the flow perpendicular to the chord line of the bucked.

The number of blades plays a critical role in the performance of the savonius turbine. It also has unique behavior depending upon the operating conditions. Increasing the number of blades can reduce the fluctuations of the dynamic and static moment of a savonius rotor along the angular position of the advancing bucked. To understand the effect of the number of blades, we perform a numerical simulation with a variation of blades number. 2, 3, and 4 blades are applied to our case study. Based on the results, we found that with the increase of the blades number, the performance of the turbine is drop due to a cascade effect. It makes the performance of two blades is highest compared to other turbines. But, the starting static torque characteristics are better in line with the increase of blades number. Form Figure 8 and Figure 10, it can be observed that the surface area of downwind pressure for two blades is larger than other blades at the same angle of attack. Meanwhile, the upwind pressure surface of three and four blades is greater because of the following blades exiting. So, both the larger downwind surface and the smallest upwind surface lead to better rotor performance.

![Figure 8. Velocity contour for semi-circular and elliptical blade](image-url)
Tip speed ratio (TSR) is the fundamental parameter to assess the savonius rotor performance. The construction and design of the turbine with the number of blades and aspect ratio of the turbine are the keys factor which affects the optimal tip speed ratio. If the turbine rotates too slowly, the turbine has not the capability to extract the energy contained in water, and less amount of water passes through the turbine. Nevertheless, if the turbine rotates too fast, it will produce turbulent water. There must be sufficient time lapse between the blades traveling through the same location so that the nearby water can move in, and the power can be harnessed from it, not use turbulent water.

Figure 9 shows the comparison of the power coefficient that can be obtained by each blades type. For elliptical curve with two blades, the maximum power coefficient value, $C_p = 0.738$, can be achieved at tip speed ratio, $\lambda = 1.069$. Besides, the semi-circular blades can achieve the maximum power coefficient, $C_p = 0.513$, at tip speed ratio approximately $\lambda = 1.2$.

Figure 10. Velocity contour for 2, 3, and 4 blades

Figure 11. Coefficient of power values of each blade
Figure 12. Torque coefficient value for each blade

Figure 10 also shows the comparison of the power coefficient that can be obtained by each blades type. For elliptical profile with three blades, the maximum power coefficient value, $C_p = 0.337$, can be achieved at tip speed ratio about $\lambda = 1.069$. Besides, the elliptical profile with four blades can achieve the maximum power coefficient, $C_p = 0.624$, at tip speed ratio approximately at $\lambda = 1.2$.

7. Conclusion
The present paper attempts to optimize the semi-circular blades numerically and adapt the elliptical blade's profile that has been performed in previous research for the wind turbine to the water turbine. 3D unsteady simulation is carried out with the same velocity of water flow at 0.6 m/s. the torque and the power coefficient are calculated. The performance analysis shows an improvement in the power coefficient ($C_p$) of the elliptical profile. With $\theta = 47.5^\circ$, $\alpha = 1.5$ and at tip speed ratio 0.641, the maximum of $C_p$ of 2 blades has an improvement. The power coefficient value increase by 17.68% compared to the power coefficient of semi-circular blades. Finally, the highest power coefficient of our study that can reach is at two blades, then four blades, and at last is three blades.

Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| $A_r$  | Projected area (m$^2$)       |
| $C_p$  | Power coefficient            |
| $C_T$  | Torque coefficient           |
| $d$    | Chord length (m)             |
| $D$    | Diameter of the rotor (m)    |
| $D_o$  | Endplate diameter (m)        |
| $e$    | Overlap distance (m)         |
| $H$    | Turbine height (m)           |
| $r$    | Radius of the turbine (m)    |
| $T$    | Torque (Nm)                  |
| $v$    | Water velocity (m/s)         |

Greek symbols

| Symbol | Description                  |
|--------|------------------------------|
| $\alpha$ | Aspect ratio                |
| $\beta$ | Overlap ratio                |
| $\lambda$ | Tip speed ratio             |
| $\omega$ | Rotational speed (rad/s$^{-1}$) |
| $\rho$  | Water density (kg/m$^3$)    |
| $\theta$ | Sectional cutting angle     |
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