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Enhancing Savonius Rotor Performance with Zigzag in Concave Surface-CFD Investigation

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ABSTRACT

Savonius, a type of vertical-axis wind turbine (VAWT), is suitable as an appropriate small-scale energy conversion apparatus for regions with relatively low wind speeds, such as Indonesia; however, it exhibits sub-optimal efficiency. One potential approach to improving the efficiency of Savonius turbines is to increase the drag force on the concave surface of the blades. In this case, the dissimilarity in the forces experienced by the two blades can be increased, resulting in a corresponding increase in torque. This investigation aims to assess and compare the power coefficient (Cp), torque and drag coefficient (C_d) of the conventional Savonius rotor with the zigzag pattern implemented in the middle area of the concave surface of the blades at low wind speeds. The efficiency can be achieved by implementing the k-ω shear stress transfer (SST) turbulent model and 3D computational fluid dynamics simulation at tip speed ratio (λ) 0.4-1 with a velocity inlet of 4, 5, and 6 m/s. The study results show that using the zigzag pattern on the concave surface led to an 18.8% boosted in Cp of at $\lambda = 0.8$ and an inlet velocity (U) = 5 m/s compared to the standard Savonius rotor model. In this case, the efficiency of the Savonius wind turbine may be enhanced by incorporating a zigzag pattern in the middle of the concave surface of the Savonius rotor.

1. Introduction

The community's primary energy sources mostly depend on fossil fuels, resulting in a significant negative impact on environmental contamination. The utilization of fossil fuels results in the release of emissions, thereby amplifying air pollution levels which contribute to the 60 percent mortality rate [1]. Transitioning to renewable energy sources is an efficacious approach to solving the issue of excessive dependence on fossil fuels and reducing greenhouse gas emissions. Wind energy is recognized as a natural sustainable energy source and environment. In the practical implementation of wind energy, the utilization of this sustainable source does not lead to pollution of the environment [2]. Using a turbine, which converts the kinetic energy of the wind to mechanical energy, is necessary to harvest this energy.

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Selecting the appropriate wind turbine is paramount for optimizing wind energy utilization, particularly within urban locales characterized by low wind speeds, such as those encountered in Indonesia. According to Triyogi, Y. *et al.,* [3] . Indonesia experiences a relatively low average wind speed, typically ranging between 4-7 m/s. Indonesia's strategic planning indicates an average annual wind speed range of 3-6 m/s, which is comparatively lower than many other countries due to its equatorial location with warm air and low pressure [4]. Base on standart IEC 61400-2 is the global standard for Small Wind Turbine (SWT), categorizing sites into four classes based on wind speed and turbulence, detailed in Table 1 [5, 6].

Table 1
Application Site Classes for SWT given by IEC 61400-2 Standard [6]

SWT Class	I (High wind)	II (Medium wind)	III (Low wind)	IV (Very low wind)
Reference wind speed	50 m/s	42.5 m/s	37.5 m/s	30 m/s
Annual Average wind speed (max)	10 m/s	8.5 m/s	7.5 m/s	6 m/s

Based on several references for low-speed areas suitable for urban use, the appropriate wind turbine is the Savonius type [7-9], but the Savonius rotor has low efficiency. It is necessary to improve the geometric aerodynamics of the Savonius rotor to increase efficiency. To maximize the Savonius rotor's efficiency, experts have suggested numerous modifications and refinements to the design. They examined the effects of diverse design characteristics, such as modification of blade shape [10-13], variation of overlap ratio [14-17], endplates [18, 19], aspect ratio [20], number of stage rotors [20], number of blades [16], and augmentation component [21, 22]. The primary focus of all studies revolves around examining the impact of various parameters on its performance. A previous study reported a noteworthy improvement in the effectiveness of the Savonius turbine by approximately 62.83% when the overlap ratio was established at 0.2 [23]. The Savonius turbine with two blades exhibited the most significant Cp compared to the configurations with three, four, five, and six blades [16] . The performance of the Savonius is also affected by the number of blades. The number of blades augments their area of curvature, which confronts the wind at an angle. Consequently, the curved area's amplification diminishes the torque disparity between the concave and convex sides, thereby influencing Cp [24]. The 2-stage rotor, featuring elliptical profiles, displays the potential for efficiently harnessing wind power [25].

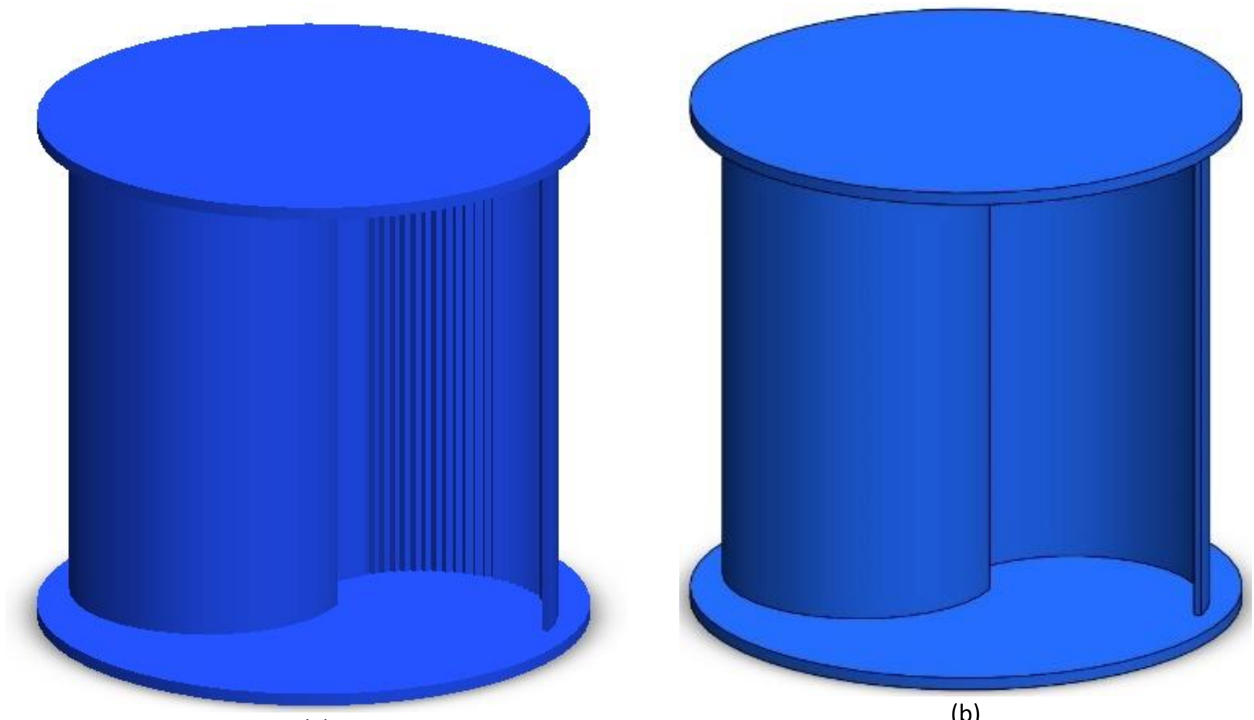
The disparity in the drag forces generated by the convex and concave blades creates a mechanical torque that ensures the rotation of the turbine around its axis [26]. To achieve optimum performance, the drag force on the concave blade surface must be greater than that on the convex blade [3]. To enhance the drag coefficient on the concave side, one can employ a wave pattern [7, 27,28], multiple blades [29-31], and a pin implemented in the concave side of the rotor [32]. Based on Al-Ghriybah *et al.,* [27] research the findings suggest that the full wavy geometry in the concave area of the rotor with outward overlap type demonstrates enhanced power characteristics compared to the conventional rotor. At $\lambda = 0.4$, the maximum Cp observed is approximately 0.18. The testing conditions were set with an inlet velocity of 9 m/s. The research findings by Salih Meri Al Absi *et al.,* [33] indicate that the wave in the middle on the concave elliptical Savonius turbine can increase the Cp value to 0.292, as tested experimentally at a wind speed of 9 m/s. Based on Nurmutia Syahreen's research [34] on the 3D numerical testing of Savonius turbines at wind speeds of 6, 8, and 9 m/s, it is demonstrated that Savonius turbines exhibit a 20 percent increase in Cp when equipped with a wavy surface in the middle concave model compared to the conventional Savonius. The results of the Sumiati, R. *et al.,* [35] experiments' indicate that incorporating a tiered-height zigzag pattern into a concave surface may result in Cp that is 16% higher than that of a conventional rotor. The research indicates that providing a wavy concave blade surface can enhance the efficiency of the Savonius rotor.

Numerous prior studies have been conducted to improve the performance of the Savonius turbine through unique designs. However, the effect of the zigzag pattern in the middle of the concave on the efficiency of the Savonius rotor has not been studied so far, especially regarding drag coefficient (C_d), moment, and Cp under varying low wind speed conditions. This research aims to analyze the efficiency of Savonius turbines by comparing the performance of standard Savonius turbines with modified ones in concave blades. The comparison is based on parameters such as drag coefficient, torque, and power coefficient, using a 3D numerical technique.

2. Methodology

2.1 Design of Purpose Model

In this study, the models were designed using the ZW3D CAD software. Both models have the same dimensions, with the exception of a 2 mm-high zigzag on the blade's concave surface and an overlap ratio of 0.2. Danardono Dominicus DPT. *et al.,* [16] state that Savonius turbines exhibit optimal performance when using OR 20%. Figure 1 shows a 3D geometry under investigation, while Figure 2 and Figure 3 shows a detailed description of the model geometry. Table 2 shows the geometric parameters of the model investigated.



(a) (b)

Fig. 1. (a) Modified model (b) Conventional model

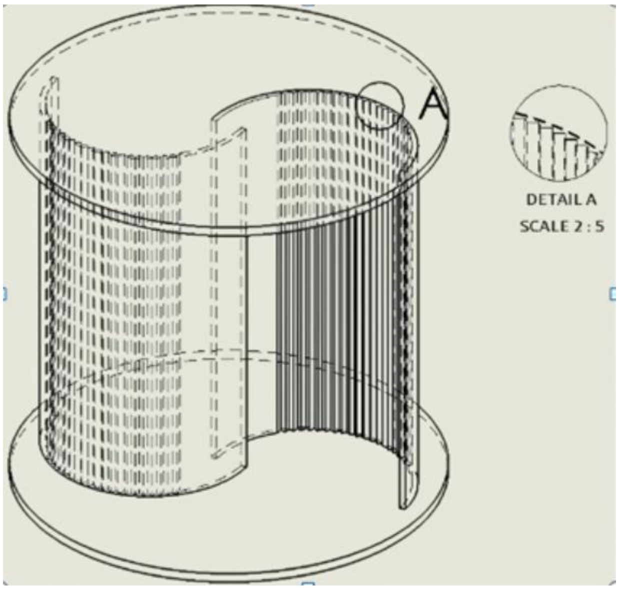


Fig. 2. Sketch 3D of zigzag model

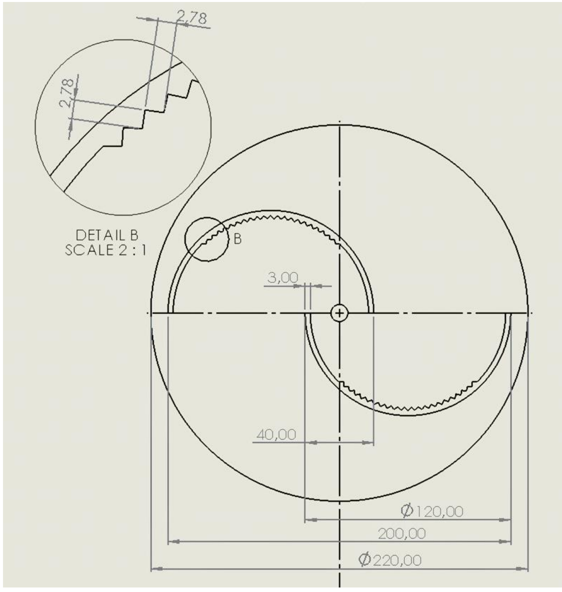


Fig. 3. Geometry detail of the zigzag pattern on the concave surface

Table 2
Geometric parameter of the model under investigation

Parameter	Value
Blade Diameter	200 mm
Endplate	220 mm
Overlab ratio	0.2
Height of blade	200 mm
Number of blade	2
Number of stage	1
Aspect Ratio	1
Zigzag height (t)	2 mm

2.2 Numerical Method

This study employs the Computational Fluid Dynamics (CFD). Using unstructured triangular grids, the 3D computational domains have been discretized. Figure 4 depicts the computational domain, which has dimensions of 30R x 10R x 10R. The domain is divided into two distinct regions: a stationary and a rotating section. The two components are separated by an interface. Fine grids are often used for spinning components, including up to 15 layers and a 1.2 growth ratio rate. Blade inflations are included to get precise data from the test item, namely the blades. In general, inflation layers are also a meshing component and are utilized when it is necessary to capture the turbulent flow wall-bounded in the boundary layer. The mesh of the rotating sub domain and the surface of the blade are shown in Figure 5.

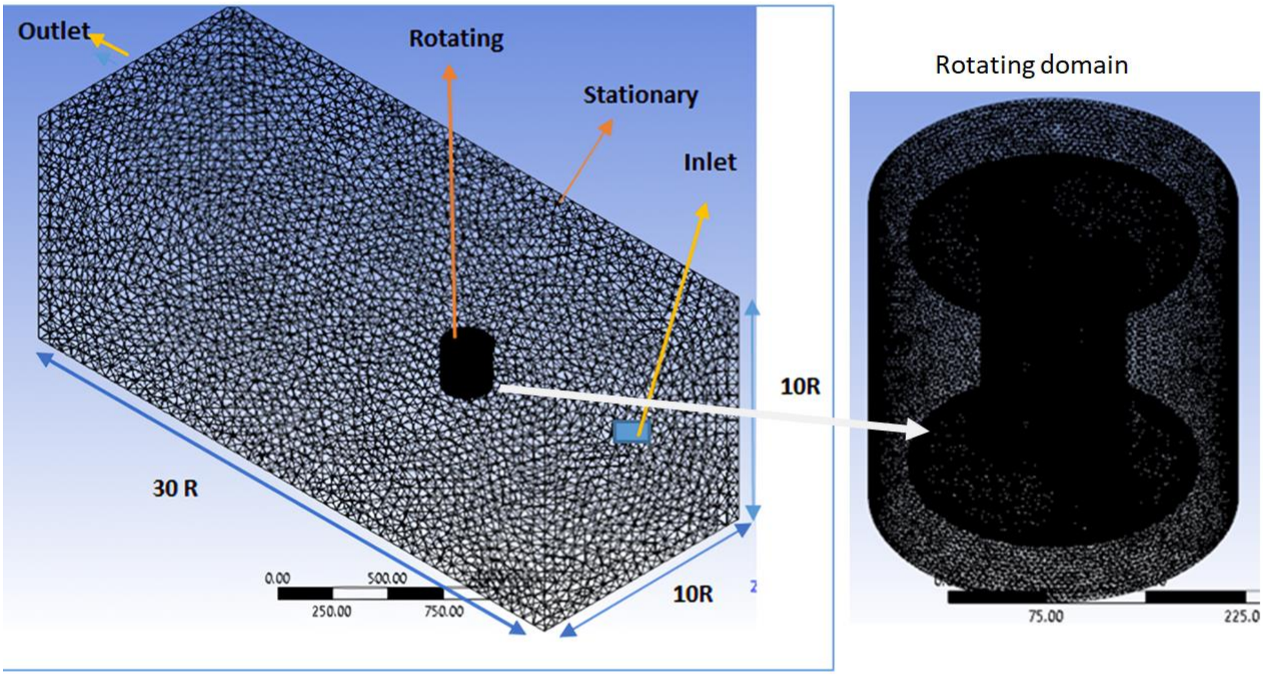


Fig. 4. Computational domain

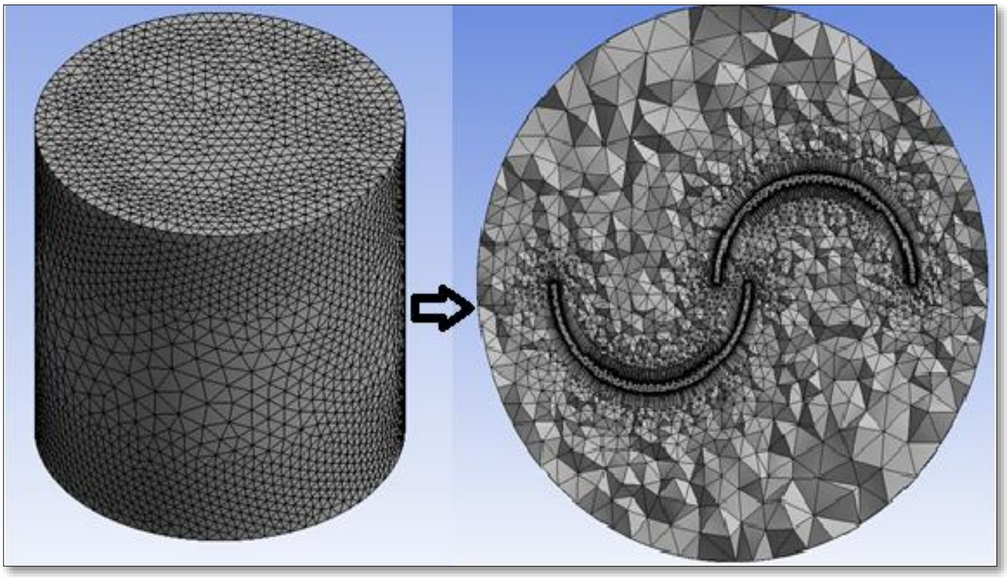


Fig. 5. Mesh of rotating subdomain and around the blade

The commercial CFD program Ansys Fluent academic version was used to simulate the flow field around the blade, employing the Unsteady Reynolds Averaged Navier-Stokes (URANS) equations. Additionally, the k-ω shear stress transfer (SST) model was used to represent the turbulent viscosity. Jin *et al.,* [36] stated that the SST k-ω and realizable k-ε models were compared to the experimental results, and it was concluded that the SST k-ω model exhibited positive characteristics. The cell zone condition sets a mesh motion in the rotating sub domain with a varying TSR value at TSR 0.4 – 1.

The boundary conditions contain an inlet with a variable velocity of 4, 5, and 6 m/s, a turbulence intensity of 5%, and a pressure outlet of 0 Pa. The interfaces are designated as the overlapping edges between the rotating and stationary domains, and the blades are subject to no-slip wall conditions at their surfaces. The sliding mesh technique can be employed to dynamically simulate a turbine's rotation to generate electricity from the input stream. Applying a SIMPLE scheme for pressure-velocity coupling improves stability and is least squares cell-based for the spatial discretization gradient. Spatial discretization of pressure and momentum is set up at second-order upwind.

2.3 Performance of Savonius Rotor Parameter

Torque coefficient (C_T) and power coefficient (Cp) are the two main parameters that affect the Savonious' performance [9]. Cp measures the turbine's performance in generating kinetic energy into the mechanical energy [33], which is calculated using Eq. 1, the ratio between the actual power of the turbine (P) and the available power in the wind (PA). The C_T value compares the actual torque produced with the torque available in the wind, as expressed by Eq. (2). TSR (λ) is the ratio between the speed of the rotor tip and the wind speed expressed by Eq. (3).

$$C_p = \frac{P}{P_A} = \frac{T.\omega}{\frac{1}{2}\rho\, A\, U^3} \tag{1}$$

$$C_T = \frac{T}{T_A} = \frac{T}{\frac{1}{2}\rho\, A\, U^2 R} \tag{2}$$

$$TSR\ (\lambda) = \frac{\omega\, R}{U} \tag{3}$$

Where ρ is the density of air measured in kg/m^3, U is the speed of the wind in the free stream measured in m/s, A is the swept area of the turbine measured in square meters (m^2), equal to the height multiplied by the rotor diameter (m^2), R is the radius of the turbine measured in meters, and ω is the rotational speed of the turbine measured in rad /s.

2.4 Grid Independence Test

Grid-independent tests (GIT) have been conducted to improve the grid sensitivity in this study. The appropriate mesh size is achieved through a degree of remeshing adaptation into smaller element sizes. GIT was conducted in this simulation using a range of mesh elements from 370,441 up to 6,431,216 elements at TSR 0.5 and U = 5 m/s. The findings observed pertain to the moment (Nm) of every grid size (Figure 6). An element size of 1,549,697 was used for the simulation based on the GIT results.

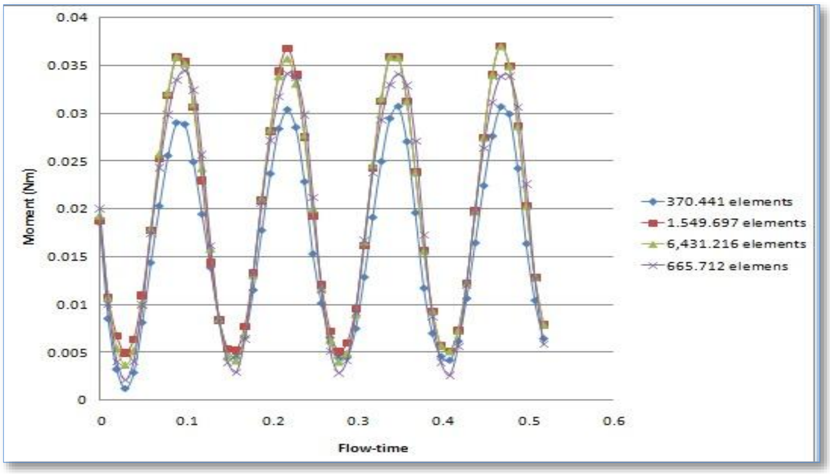


Fig. 6. Comparison of mesh convergence for verification

3. Results and Discussion

3.1 Drag Coefficient

3.1.1 Validation data

The computational simulation technique commences by undergoing a process of verification, where in the parameters of the current simulation analysis are compared to those of previous work. The simulation result is illustrated in Figure 7. Unsteady simulations are performed with the SST k-ω turbulence model at TSR 0.6 and U = 6.2 m/s for all models. However, the present study uses a 3D numerical simulation.

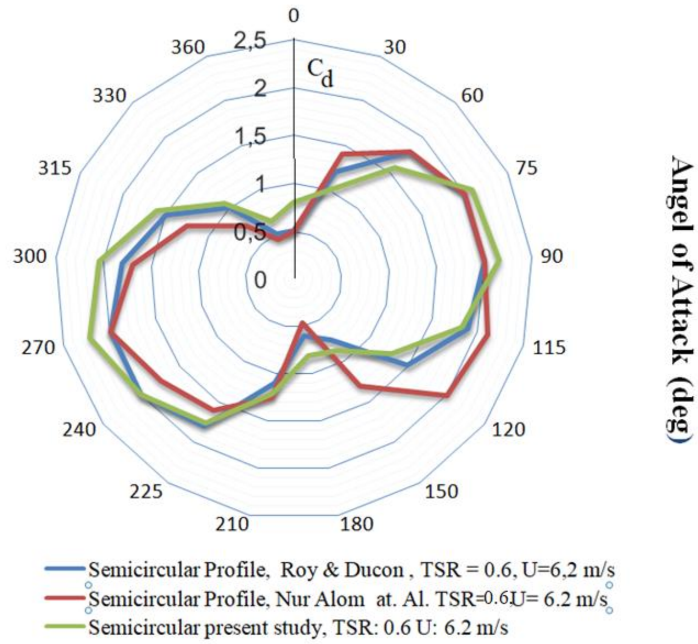


Fig. 7. Validation of the Drag Coefficient using the previously collected data

The current analysis exhibits a similar graphical pattern in C_d value to the two prior investigations conducted by Nur Alom [37] and Roy & Ducoin [38]. Their studies used a 2D numerical simulation method, whereas this research adopts a 3D simulation. Consequently, there is a slight discrepancy in the coefficient drag results. The current investigation exhibits a slightly higher drag coefficient (C_d) when compared to the two preceding models. Although the C_d value is not exactly the same, it has approached the pattern of data values in previous studies

3.1.2 Drag coefficient of the modified model

Figure 8 shows the drag coefficients for a zigzag in the middle of a concave surface and a conventional Savonius rotor with different angles of attack.

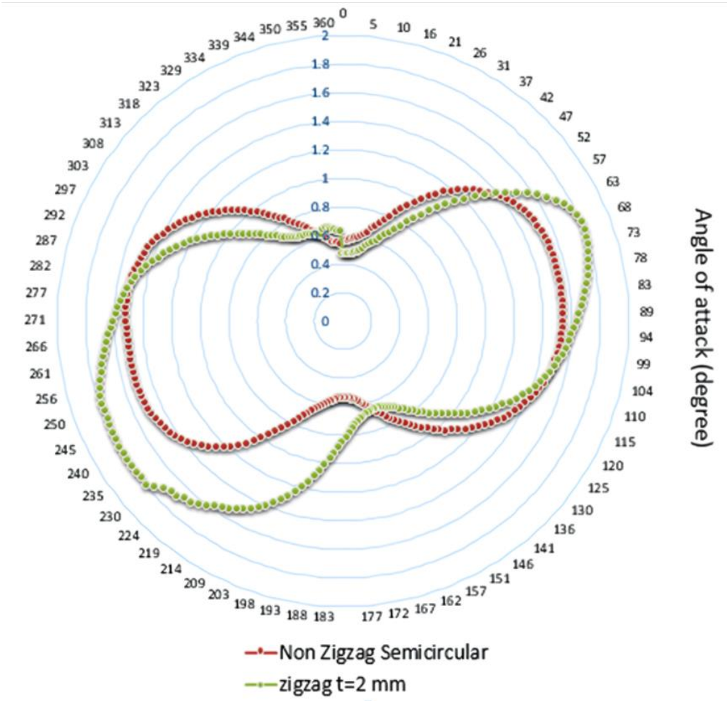


Fig. 8. Comparison of C_d of the model at TSR 0.6 & U=5 m/s

Compared to the conventional rotor of the Savonius, the zigzag model achieves a higher C_d. Figure 8 shows the maximum C_d values for the zigzag model are observed at α = 68° and 256°. The conventional model's maximum C_d occurs at α = 82° and 277°. As depicted in Figure 9, the maximum drag coefficient for the conventional model is 1.547, while the zigzag model measures 1.810. The average C_d value of the Savonius rotor, utilizing the zigzag model, is 1.182, in comparison to an average C_d value of 1.104 for the conventional rotor. Upon examining both models, it can be inferred that the Savonius rotor model, with a zigzag configuration on the concave surface, has a higher C_d than the conventional rotor. The average C_d increased by 6.59% from the conventional rotor.

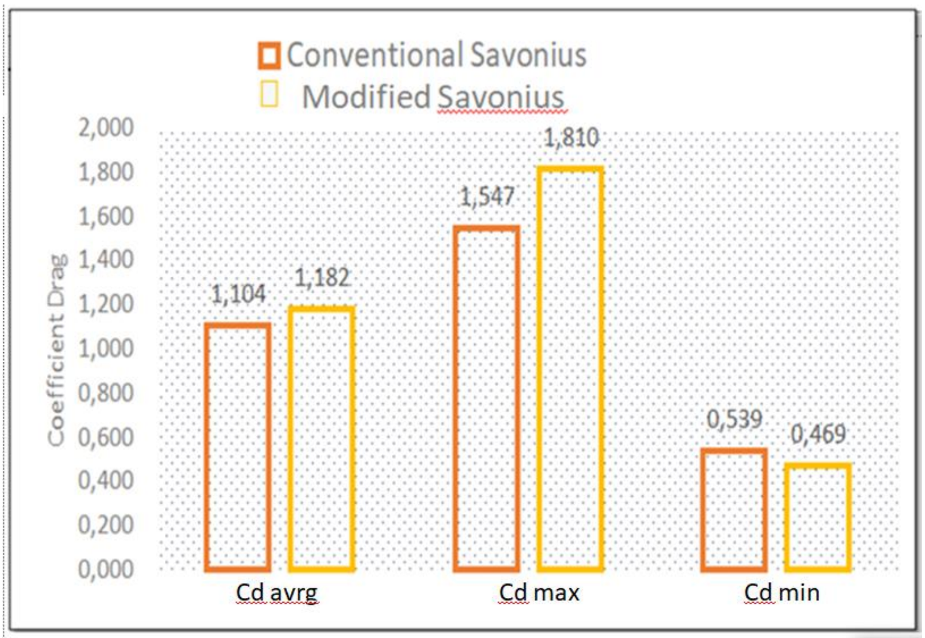


Fig. 9. Comparison C_d max, C_c Avrg & C_d min

Nur Alom's research [37] on drag force suggests that an increase in drag value has a beneficial effect on the efficiency of the Savonius rotor. This discovery substantiates earlier scholarly findings [27, 34], which suggest that augmenting the surface roughness on the concave side of the Savonius turbine results in a heightened efficiency level. In other words, the proposed model's drag value has been increased, leading to a boost in its efficiency.

3.2 Comparison of Performance

The impact of the applied zigzag pattern in the center of the Savonius blade's concave surface on the Savonius turbine's performance has been studied by numerical simulation using Ansys Academic 2023. The simulation findings demonstrate that the torque value in the zigzag model exceeds that of the conventional one at speeds ranging from 4 to 6 m/s, as shown in Figure 10 – Figure 12, the torque values against the rotor rotation angle. The investigation was done at TSR 0.6.

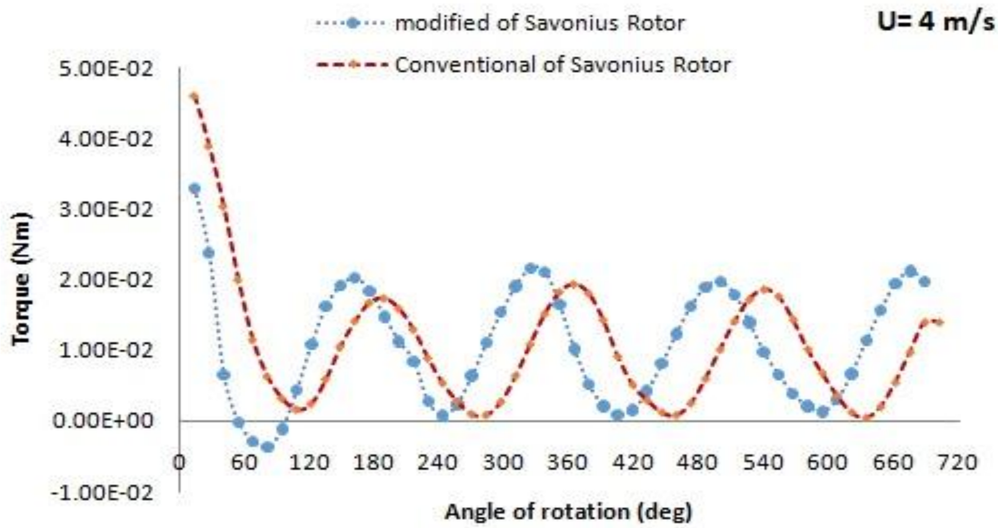


Fig. 10. Value of the rotor torque at the variation of the rotation angle at U = 4 m/s

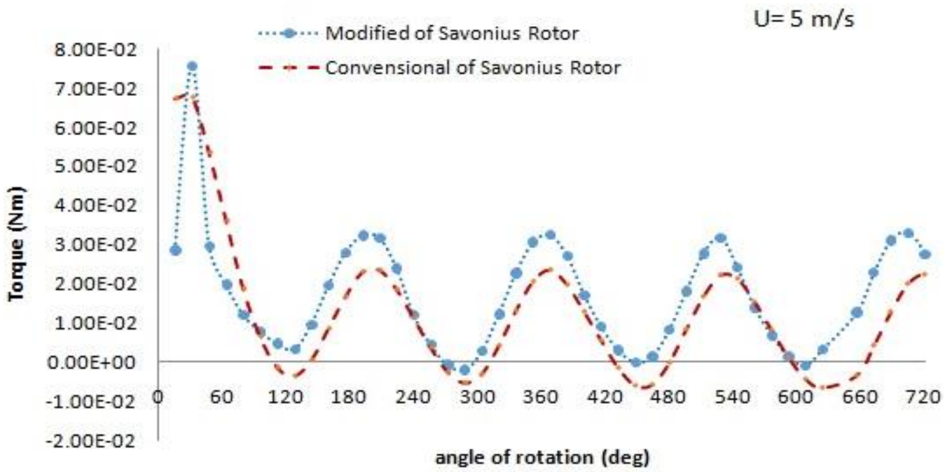


Fig. 11. Value of the rotor torque at the variation of the rotation angle at U = 5 m/s

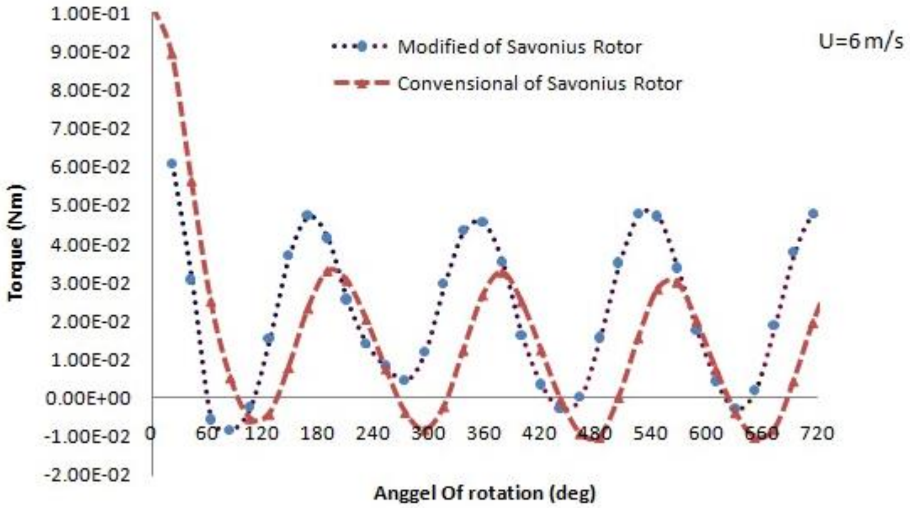


Fig. 12. Value of the rotor torque at the variation of the rotation angle at U = 6 m/s

The highest torque values were obtained at an input velocity of 6 m/s, which were 0.0478 Nm for the modified rotor and 0.032 Nm for the conventional rotor. Implementing a zigzag pattern on the concave side of the blade generates an increase in drag, which in response results in an increase in torque in the modified model. This results in a greater difference in force between the two blades, leading to an increase in torque value. In addition, the zigzag shape expands the surface area in contact with the wind force, enabling it to absorb a greater amount of wind energy compared to a conventional rotor. This is in line with prior research indicating that increasing the surface area enhances the turbine's ability to capture the wind's available energy, thereby improving its performance [28, 30]. Figure 10 – Figure 12 demonstrate that an increase in wind speed results in an enhancement of torque for both models. Although the torque amplitude values of both models are nearly identical and the peaks (minimum and maximum) have different values, this is because the conventional Savonius rotor model exhibits negative torque as wind speed increases, whereas the modified Savonius rotor model can mitigate this negative torque. Therefore, the application of a zigzag pattern on the concave surface can reduce the negative torque on the Savonius turbine.

Figure 13 depicts the performance of the numerically tested Savonius rotor. They were analyzed at an inlet velocity of 5 m/s and a TSR range of 0.4 - 1. Based on the numerical analysis results, the data indicates that the modified Savonius has a higher Cp value compared to the conventional Savonius rotor. The maximum Cp is reached at TSR 0.8, with values of 0.223 and 0.18 for the modified Savonius and conventional Savonius rotor, respectively

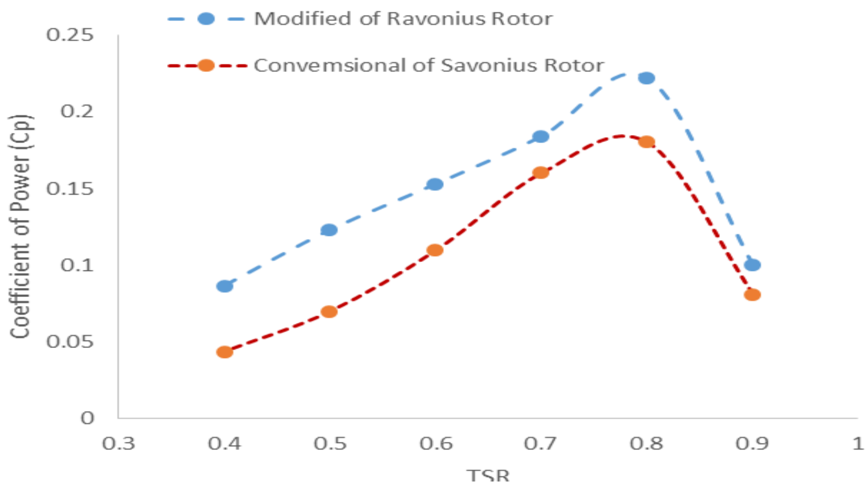


Fig. 13. Comparison of Cp for both models

3.3 Pressure Contours Visualization

The contour plots predict the pressure variations in different regions around the blades across the flow domain. As the rotor rotates, the pressure contours display a drop from the upstream to the downstream region. The noticeable pressure reduction results from the mechanical energy expended by the rotor to produce its rotation. Figure 14 presents a comparison of the pressure contour of the Savonius turbine studied.

Once there is a pressure differential between the concave and convex surfaces, the rotor will rotate [32]. By visualizing the pressure contours in both models, the pressure in the zigzag model has a higher pressure on the concave side compared to the convex side, which results in a higher torque to drive the rotor compared to the conventional model. The modified rotor has a pressure value of 19.26 Pa at the concave side with a large area, while the conventional rotor model has the highest pressure at the concave side of 13.55 Pa with a relatively small area. We observed the two models from the same angle of attack. The visualization of pressure contour infers that the modified Savonius turbine has a greater pressure difference than the conventional Savonius turbine, resulting in greater torque and improved performance for the modified turbine.

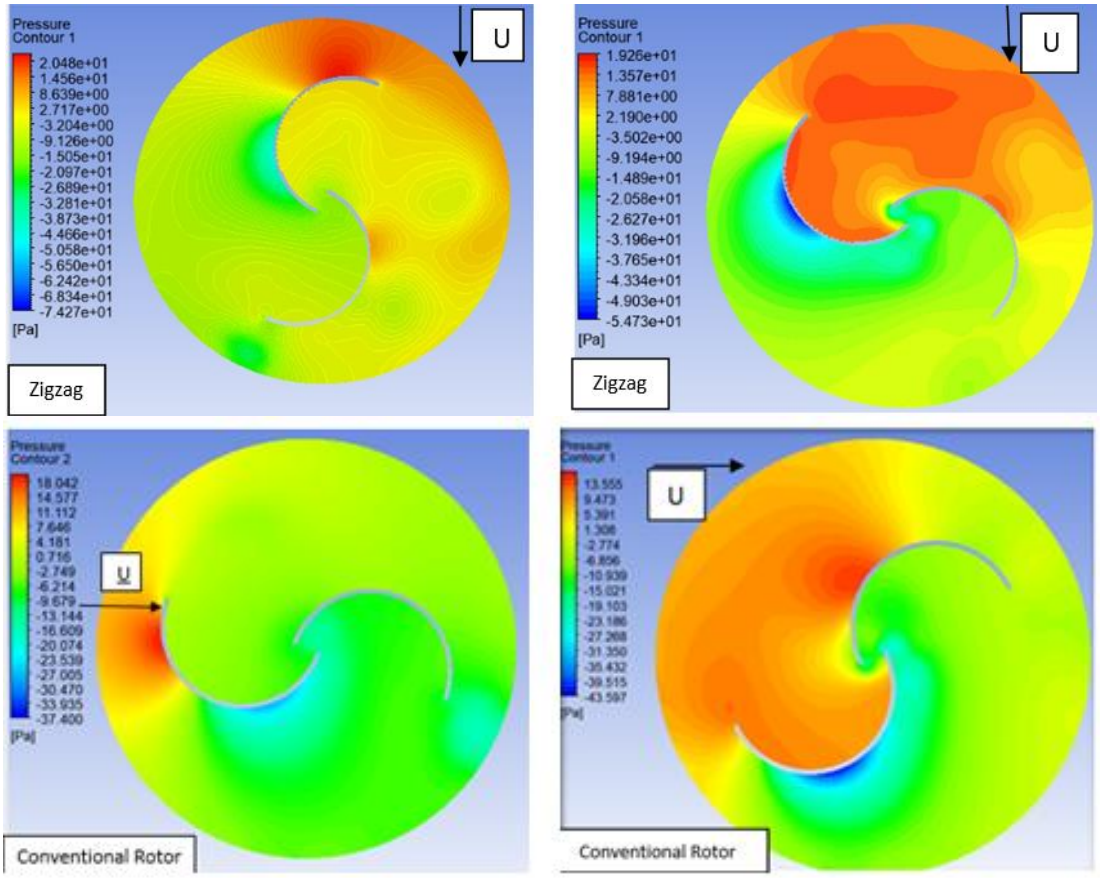


Fig. 14. Pressure contour

3.4 Velocity Contours Visualization

The velocity contours of the both Savonius rotor were analyzed at an inlet velocity of 5 m/s, TSR 0.6. Figure 15 presents a comparison of the velocity contour of the Savonius rotor studied. The velocity energy contacting the concave wall is converted into kinetic energy, which reduces the speed at the concave.

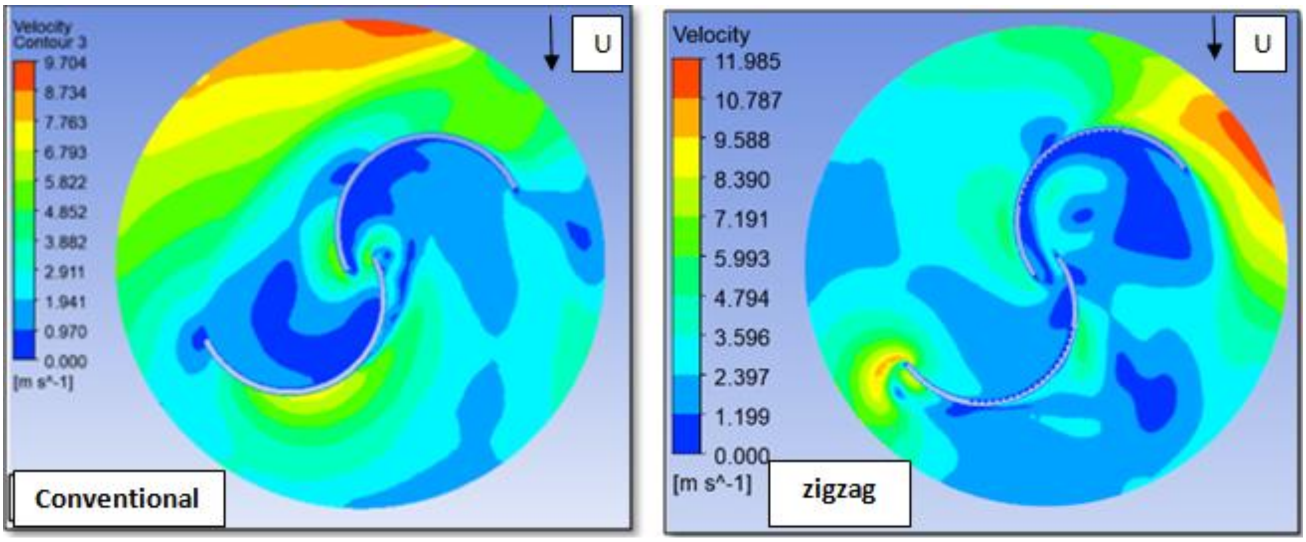


Fig. 15. Velocity contour

The formation of an overlap jet is observed in both model types. However, it is most pronounced in the case of the modified Savonius rotor. This overlab jet is responsible for reducing the negative torque of the returning blade of the Savonius rotor [39].

The research that has been done is limited because it only talks about 3D simulations using Ansys Academic 2023 with a speed input of 4-6 m/s, a TSR of 0.4–0.8, and the Reynolds-averaged Navier-Stokes (RANS) k-ω shear stress transfer (SST) model equations. Furthermore, the research has not been tested or implemented using an experimental method.

4.Conclusion

This study investigated the impact of a zigzag pattern on the concave surface of a Savonius rotor, focusing on drag coefficient and performance coefficient using 3D CFD methode. The results show a 6.59% increase in average drag and an 18.8% rise in Cp with the zigzag design. The maximum Cp is reached at TSR 0.8, with values of 0.223 and 0.18 for the modified Savonius and conventional Savonius rotor, respectively. The application of a zigzag pattern on the concave surface can reduce the negative torque on the Savonius rotor. The research attributes this improvement to increased drag in the concave section, leading to faster turbine rotation and greater wind power absorption compared to the conventional model.

In future studies, investigations will be conducted to examine the impact of the zigzag pattern on the concave surface of the blade through the use of experimental methods.

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