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Design and CFD simulation of guide vane for multistage Savonius wind turbine

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Abstract

This study proposes improving the performance of a fixed-axis multistage Savonius wind turbine by integrating a six-bladed guide vane. Guide vanes aim to direct the incoming wind towards the blades of the Savonius wind turbine so that it can increase the performance value of the turbine itself. There are two methods, the first method is computational fluid dynamics (CFD) simulation to evaluate the best performance guide vane angle variations. The second method is implementing real conditions using 3 m/s until 4.2 m/s wind speed. The implementation of the guide vane to the wind turbine will consider four (4) variants of angles (0°, 20°, 40°, and 60°). The purpose of testing with four kinds of guide vane angles is to find out which guide vane angle can provide the best results among other guide vane angles. This research proposed the initial design of the guide vane addition to the multistage Savonius wind turbine with a fixed rotary axis. From the CFD simulation, the implementation of a guide vane can improve the performance of the multistage Savonius wind turbine with a fixed rotary axis. On the other hand, for the proposed initial design in this research, the 20° angle of guide vane gives the best result compared to the 0°, 40°, 60°, and without guide vane.

Keywords: multistage Savonius wind turbine; guide vane; power coefficient; torque coefficient; CFD simulation.

I. Introduction

In Indonesia, the use of electrical energy is expected to increase every year by as much as 3.2 % from 2018 to 2050 which will dominate in the sector of households around 58 % in 2050 [1]. To meet the national electricity demand, coal power plants dominate besides power plants other areas are made from gas, fuel, and renewable energy [2]. Although Indonesia has coal energy reserves which are abundant, over time these fossil resources will be exhausted. Therefore, a solution is needed to overcome the resource limitations of energy [3]. Wind energy is one of the renewable energy that converts wind kinetic energy to produce electricity [4].

The utilization of wind power generation in 2020 (Indonesia is at 0.21 % of the total generating capacity at 72,750.72 MW), which is still few [5]. This is due to the wind speed in Indonesia ranging from 2 m/s to 6 m/s which is classified as a low-speed wind based on the Beaufort scale [6][7]. This research was conducted at Parahyangan Catholic University, Indonesia, which has wind speeds ranging from 2 m/s to 5 m/s [8]. Considering the wind speed, the wind turbine referred to in this research is the Savonius vertical axis wind turbine which can rotate at wind speeds of 3 m/s [9]. To improve the performance of the multi-level Savonius wind turbine with a fixed rotational axis, this research will discuss the addition of the guide vane to the wind turbine, specifically the design and the computational fluid dynamics (CFD) simulation. The Savonius wind turbine has several characterizations that are swept area (As), tip speed ratio (TSR), power coefficient (Cp), and torque coefficient (Ct) [10].

Research [11] focuses on exploring the power-producing mechanism of Savonius turbines through flow field visualization and experiments.

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Additionally, [12] conducted research related to three-level Savonius turbines with variations in air gaps, which contributes to understanding the performance characteristics of these turbines. Furthermore, [13] described the experimental study of the effect of Savonius blade height on the performance of a hybrid Darrieus-Savonius wind turbine, highlighting the relevance of airflow and torque. These studies provide valuable insights into the performance and augmentation techniques of Savonius wind turbines. On the other hand, Savonius wind turbine testing on research [14] is based on the addition of a guide vane with four (4) pieces of guide vane design in the form of 4, 5, and 6 guide blades which have different angles in the form of 0°, 20°, 40°, and 60°. Research [15] is based on the addition of variation in the number of guide vanes against an angle of 45°. Also, the research [16] investigates the impact of varying the number of guide vanes on the performance of a pump used as a turbine, focusing on aspects such as turbulence, impeller design, and the optimization of turbine stator and rotor parts. The Savonius wind turbine testing conducted in the study [17] is based on a simulated analysis of computational fluid dynamics (CFDs) for studying the behavior of Savonius wind turbines to airflow.

The Savonius wind turbine which is the main review consists of three blade levels. The addition of a guide vane to the multistage Savonius wind turbine [8] with a fixed rotary axis will apply a total of guide vanes 6 fins with four (4) reviewed angles in the form of 0°, 20°, 40°, and 60°. The application of the guide vane based on research [14] can increase the power generated by the Savonius wind turbine because the utilization of guide vanes can affect the incoming airflow so that it can block the flow of air towards convex that can cause negative forces and direct flow the air went straight to the concave. The objective and contribution are to prove the results of previous research that the addition of several guide vanes provides an effect in which the angle of this guide vane is narrowed, so that the thrust of the wind from the guide vane gap increase, making the thin stronger and propelling the blades more forcefully.

II. Materials and Methods

A. Multistage Savonius wind turbine with fixed rotary axis

The design of multistage Savonius wind turbine with fixed rotary axis has a blade height (H) of each level is 200 mm, blade radius (R) of 290 mm, plate thickness (h) of 10 mm, plate diameter (Do) of 600 mm, and shaft diameter (d) 20 mm which is showed in Figure 1 is the considered wind turbine that has been made in the previous research [5] which exploring the best configuration for Savonious wind turbine.

On a multistage Savonius wind turbine with a fixed rotary axis in Figure 1 the turbine blade parts are made of 3D printing material because it can regulate density as well as have lightweight material. The base section utilizes an aluminum plate with a size of 1 m × 0.4 m × 0.4 m because aluminum material has a lightweight and anti-rust structure.

B. Design of guide vane

1) Parameters

The mechanical power $P\omega$ (Watt) obtained from the rotor is determined by equation (1) [6].

$$P\omega = T.\omega \tag{1}$$

where T is the torque of the rotor (Nm) and ω is the angular velocity from the rotor (rad/sec).

Torque is defined as the tangential force of the rotor blade acting along the radius of the rotor from the central point of the rotor. By definition of that to get the torque can be defined as equation (2) which expresses that torque (T), measured in Newton-meters (Nm), is the product of an object's moment of inertia (I), measured in kilogram-square meters (kg.m²), and its angular acceleration (α), measured in radians per second squared (rad/s²).

$$T = I.\alpha \tag{2}$$

Meanwhile to get the actual torque from the Savonius wind turbine, one can use equation (3).

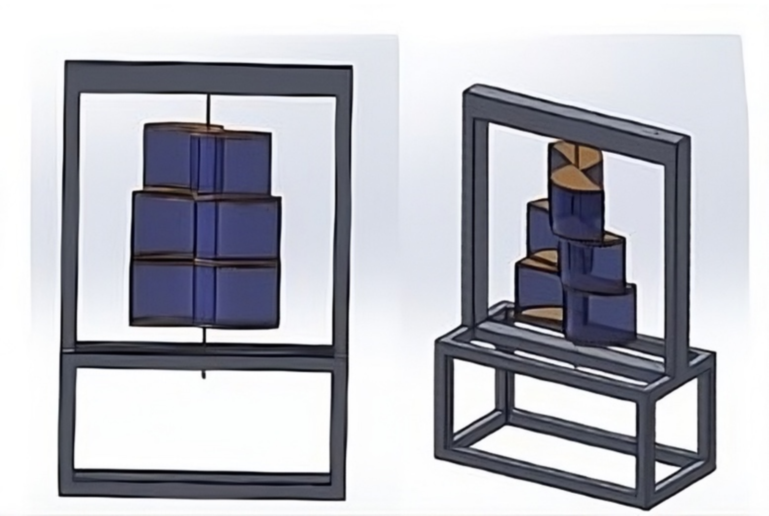

Figure 1. Multistage Savonius wind turbine with fixed rotary axis [8]

$$T = \frac{1}{4}\rho A d V^2 \tag{3}$$

The variable ρ represents air density (1.2 kg/m^3), A is the swept area in the units of m^2, d represents the diameter, and V is the value of wind velocity. The tip speed ratio is the ratio of the product of blade radius and angular speed of the rotor to the wind velocity. Angular velocity ωR is defined as the angular mechanical velocity of the wind turbine rotor (rad/sec). Angular velocity is obtained from the rotational speed of each minute (n) (rev/min). Then the angular velocity in the turbine is defined with the calculation of equation (4).

$$\omega R = \frac{2\pi n}{60} \tag{4}$$

To obtain the calculation of tip speed ratio (TSR) can use the calculation in equation (5)

$$\lambda = \omega R / V \tag{5}$$

Then by the tip speed ratio as equation (6) as follows, the rotor rotational speed can be developed by the calculation of the rotor rotational speed is

$$rpm = 60\lambda V / \pi D \tag{6}$$

Power efficiency (Cp) is the ratio of the maximum power obtained from the mechanical power in the rotor to the available power from the wind [7]. The actual power of the wind (Pa) is obtained from the equation (7).

$$Cp = \frac{P\omega}{P\,a} = \frac{T.\omega}{\frac{1}{2}\rho H.D.V^3} \tag{7}$$

where H is the blade height (m), D is the blade diameter (m), ρ is the air density (kg/m^3) and V is the wind velocity (m/s). The torque coefficient (Ct) is the ratio between the actual torque coming from the rotor (T) and theoretical torque derived from wind ($T\omega$) with equation (8).

$$Ct = \frac{T}{T.\omega} \tag{8}$$

2) Computational fluid dynamics simulation

Computational fluid dynamics (CFD) is a branch of mechanics fluids in which number methods and algorithms are used to solve fluid flow problems [18]. In this study, CFD simulation was carried out to find out the effect of airflow on the behavior of wind turbines Savonius with the implementation of four (4) angular variations. CFD Simulation also provides additional benefits in the form of time and cost savings over using real experiments, although in the end simulations should still be tested with experiments [19]. Figure 2 illustrates the CFD simulation process for the multistage Savonius wind turbine, which was carried out using ANSYS software. On the other hand, shows the simulation framework, covering key phases such as mesh development and boundary condition application.

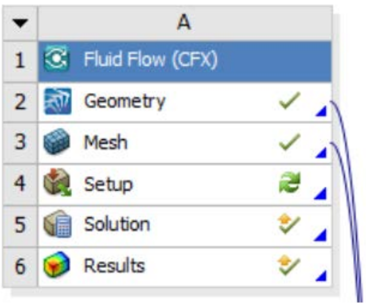

Figure 2. CFD simulation framework on ANSYS software

III. Results and Discussions

A. Design of guide vane addition

The multistage Savonius wind turbine with a fixed rotary axis implemented a guide vane that is placed around the rotor from the Savonius wind turbine. The guide vane used consists of four (4) kinds of variants. Guide vane each guide vane consists of six (6) blades guide vane placed outside around the rotor of the Savonius wind turbine stratified with a fixed rotary axis. The specifications of the guide vane are shown in Table 1. The outer diameter size of the guide vane is 850 mm to be able to cover the size of the blade diameter of the multistage Savonius wind turbine with a fixed rotary axis. The inner diameter of the guide vane is 535 mm, so the blade can rotate properly.

The height of the guide vane is 735 mm to cover the height of the turbine. The length of the guide vane is 150 mm by the blade radius of a multistage Savonius wind turbine with a fixed rotary axis. The top and bottom plates of the multistage Savonius wind turbine with a fixed rotary axis are designed with a width of 20 mm. From the CFD simulation, the output values are power, torque, and rotational speed of the multistage Savonius wind turbine with a fixed rotary axis by implementing the guide vane. Figure 3 illustrates the structural configurations of guide vanes for a multistage Savonius wind turbine at four steering angles: 0°, 20°, 40°, and 60° which serves as a visual representation, highlighting the distinct design variations considered.

B. CFD simulation results

Figure 4 shows the result of the geometry part of the multistage Savonius wind turbine with fixed rotary axis by the implementation of guide vane on ANSYS Workbench. Figure 4 illustrates a critical step in the simulation process: the transfer of the rotor and CFD domain from SolidWorks to ANSYS Workbench. This import is critical for preserving the geometrical integrity of the design in the CFD analysis, ensuring that the simulations accurately reflect the turbine's physical characteristics. This step emphasizes the significance of precise model integration in this study for reliable aerodynamic

Table 1.
Specification of guide vane on Savonius wind turbine

Symbol	Parameters	Size (mm)
D	Outer diameter	850
Do	Inner diameter	535
H	Height guide vane	735
h	Plate thickness	20
p	Length guide vane	150

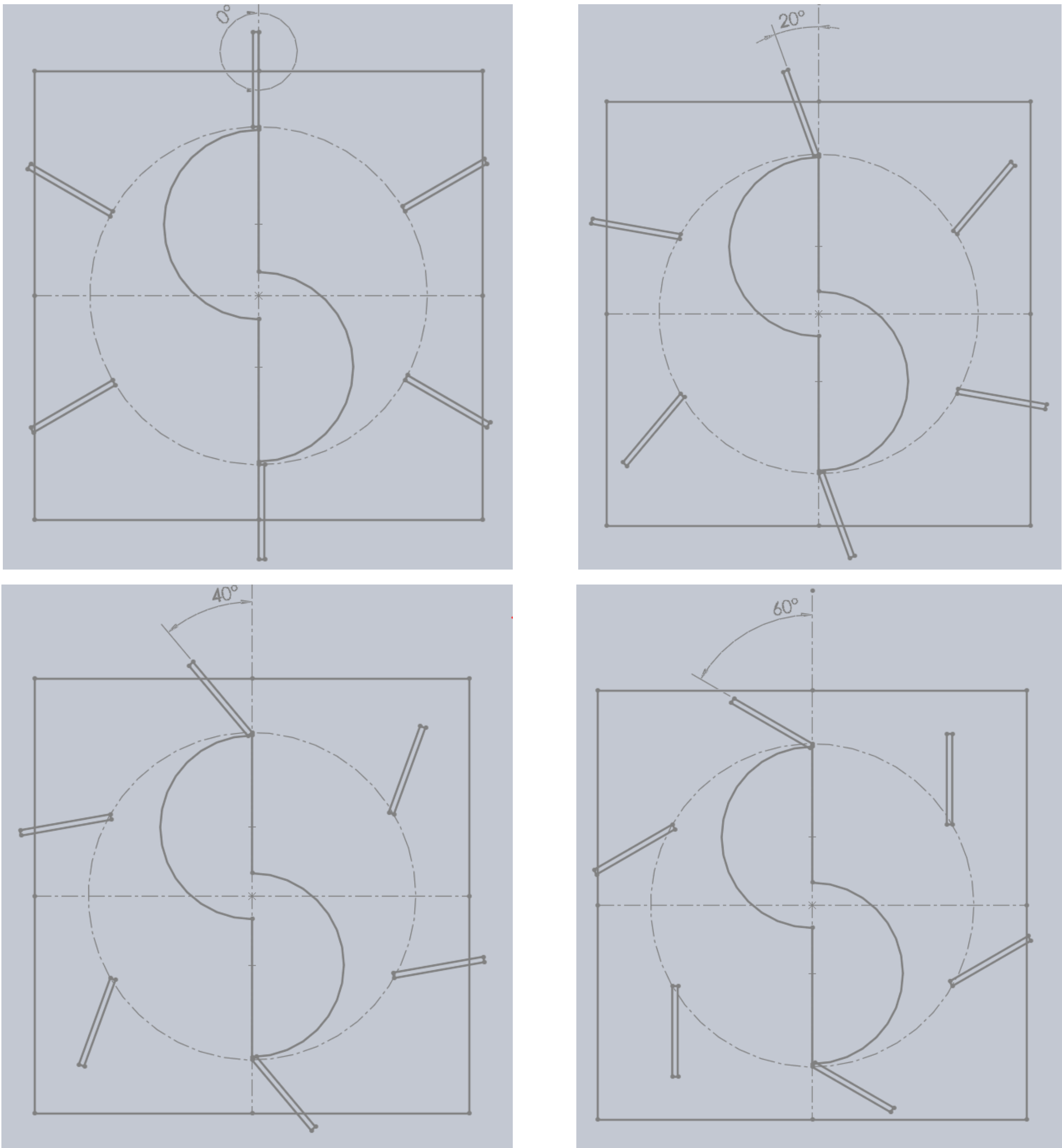

Figure 3. Guide vane design with 4 variations of angle steering

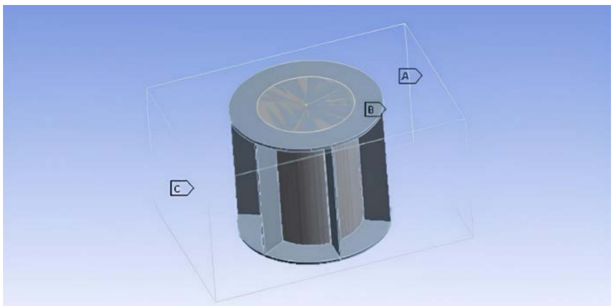

Figure 4. Imported geometry results

evaluations. The domain is defined as the area work from the rotor.

On the other hand, the imported geometry of a multistage Savonius wind turbine with a fixed rotary axis and a 0° guide vane is shown in Figure 5, ready for CFD analysis in ANSYS Workbench. This step is critical for ensuring that the simulations accurately represent the turbine's design and for evaluating the aerodynamic impact of the guide vane on turbine performance.

Figure 6 is the result of the meshed geometry of each multistage Savonius wind turbine with a fixed rotary axis by the implementation of four variants of guide vane. In the meshed geometry, the rotor and

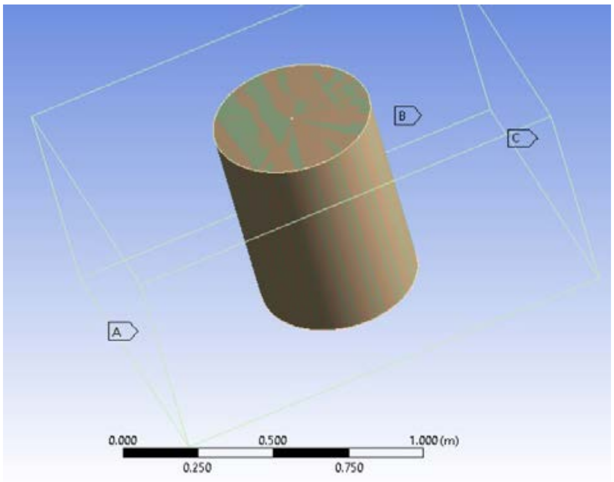

Figure 5. Imported geometry results of multistage Savonius wind turbine with fixed rotary axis by implementation of guide vane

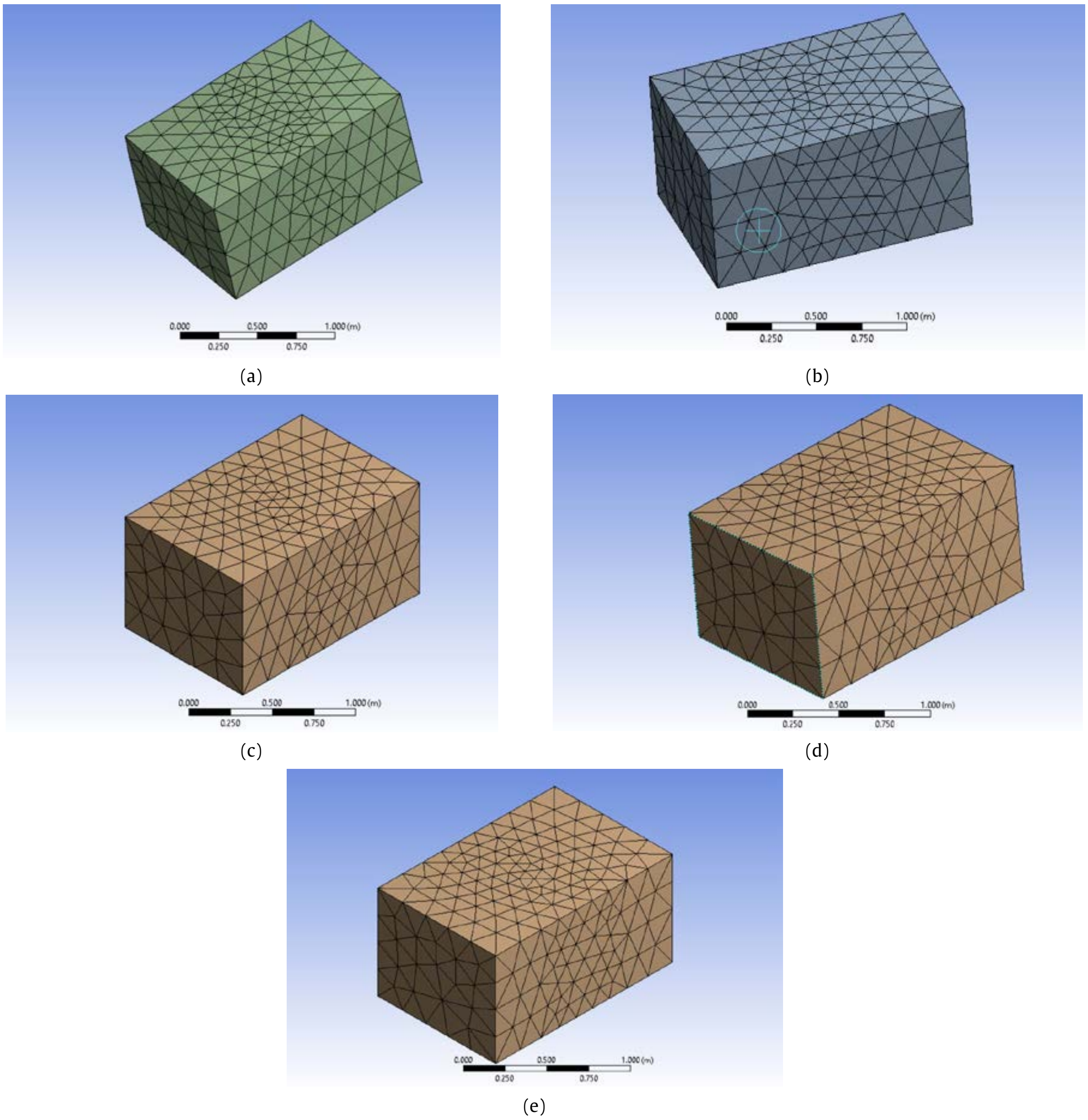

Figure 6. Results meshed geometry of multistage Savonius wind turbine with fixed rotary axis by the implementation of four variants angle guide vane: (a) without a guide vane; (b) with 0° angle guide vane; (c) with 20° angle guide vane; (d) with 40° angle guide vane; (e) with 60° angle guide vane

CFD domain merged into one part. Meshed geometry results from the Savonius wind turbine paired with four (4) variations of guide vane have the same similarities with each other because the parameters

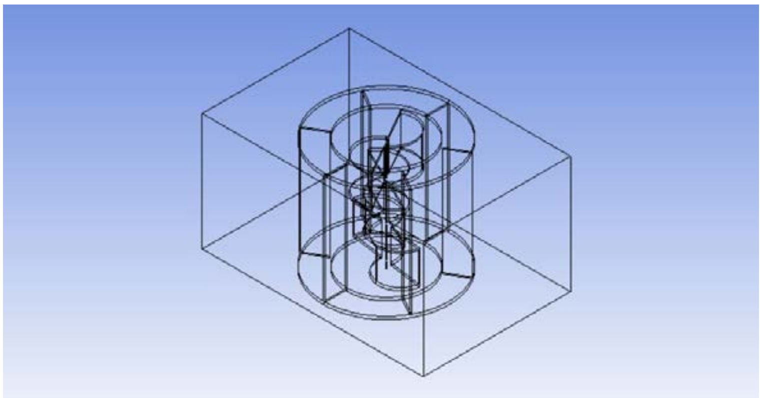

Figure 7. CFD domain simulation result

in the meshed geometry are also the same as the other Savonius wind turbine on simulation in ANSYS software.

In Figure 6, the CFD domain, wind turbine, and the guide vane are merged into one part of one body Figure 7 shows the CFD domain results from the multistage Savonius wind turbine with fixed rotary axis by the implementation of a guide vane 0° angle for the rest of 20°, 40°, and 60° has the same shape as the results of Figure 7 which illustrates the combined CFD domain for the simulation of a multistage Savonius wind turbine with an integrated 0° guide vane. This unified setup is used to analyze the aerodynamic impact of guide vanes at different angles, ensuring consistent and comparable results across all simulations.

Figure 8 shows the result of the airfield design that uses 5 m/s wind speed in the simulation. On the airfield, static pressure is determined to be 1 atm, and the air temperature specified to 25°C is assumed to be ideal conditions for the environment. On the airfield continue by determining the inlet, outlet, and opening parts The inlet is the part where the wind comes to the airfield area. While the outlet and opening sections are the parts where the wind will come out. Figure 9 shows the inlet and outlet sections of the airfield design within the CFD simulation, which is required for modeling wind flow at a speed of 5 m/s. The inlet directs wind into the domain of the turbine, while the outlet defines the flow's exit path.

In this research, the effectiveness of the proposed guide vane design in improving the performance of a multistage Savonius wind turbine with a fixed rotary axis is observed. To assess the impact of guide vane implementation, the research is divided into five distinct simulation scenarios. The first scenario investigates the turbine's performance in the absence of guide vanes, establishing a baseline for comparison. Notably, the simulation reveals distinct wind speed behaviors at three levels, influencing the turbine's functionality. This analysis not only provides a scientific interpretation of each result but also sets the stage for comparing this research's findings to existing literature and determining whether the findings corroborate or contradict previous findings.

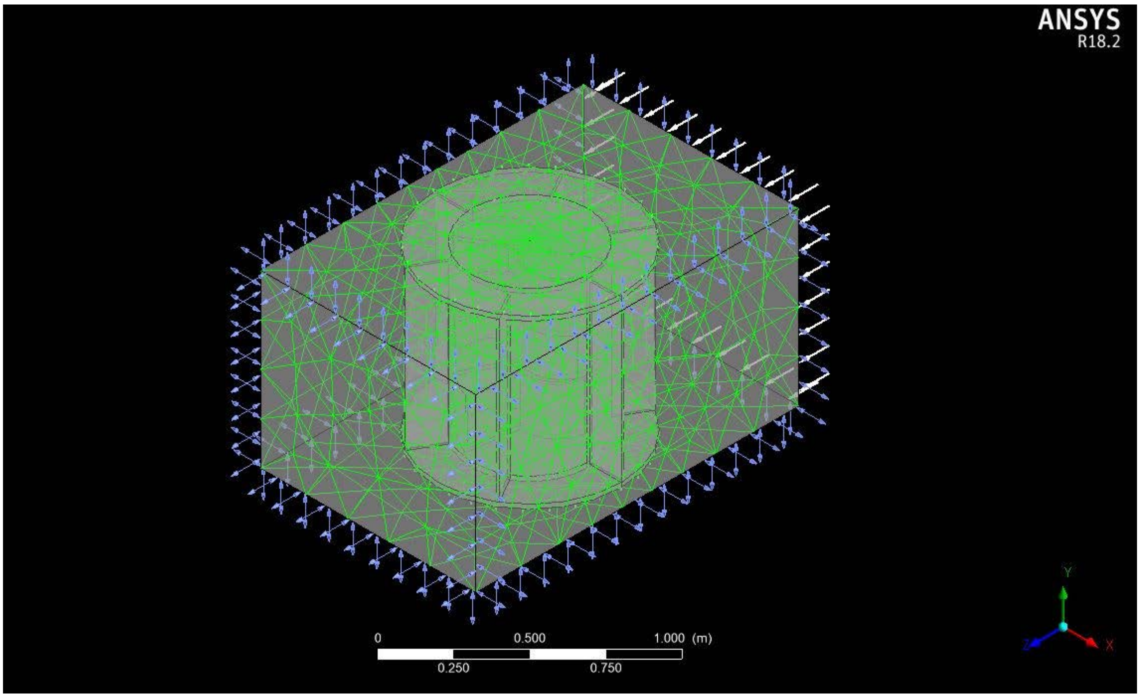

Figure 8. Airfield simulation result

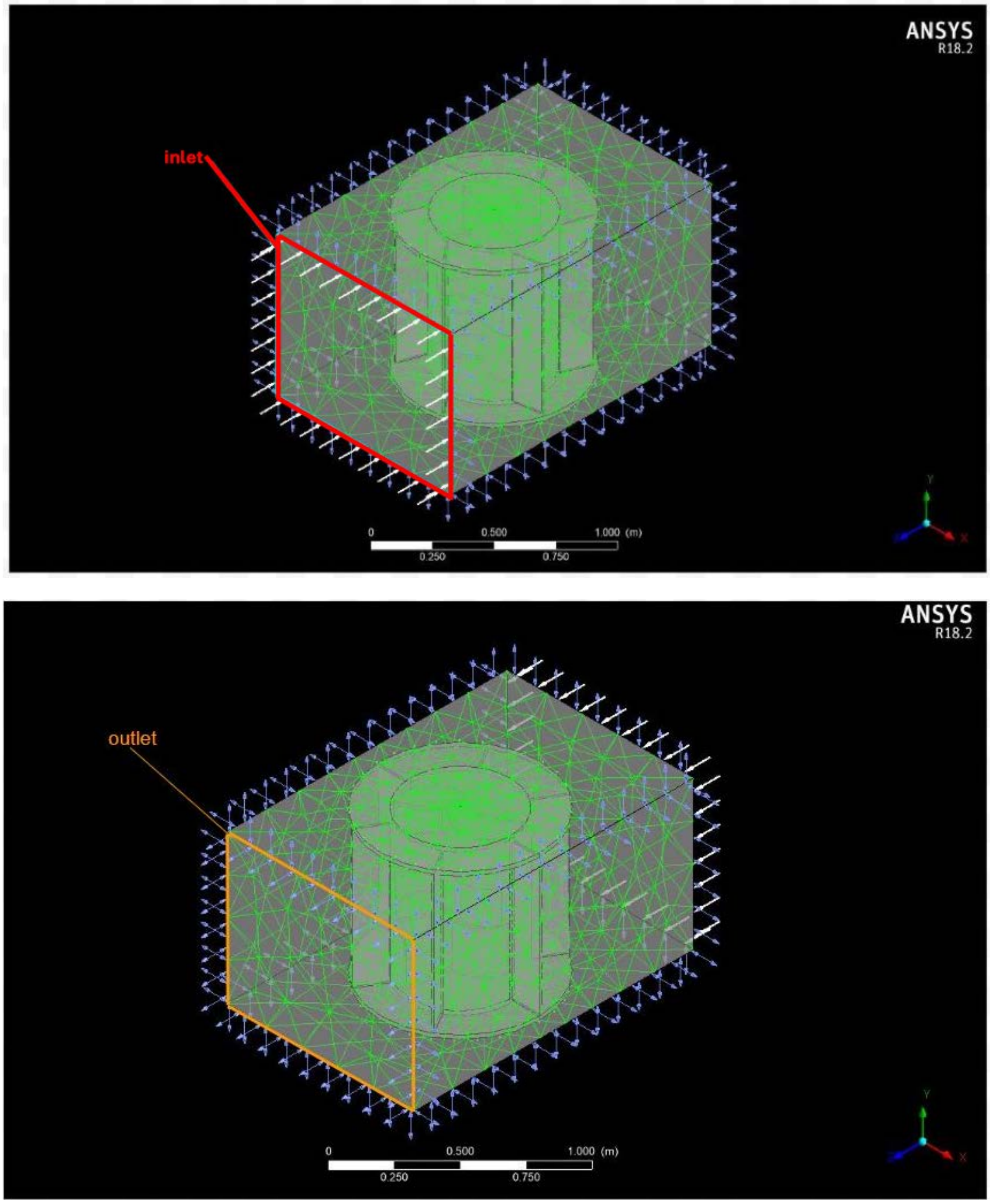

Figure 9. Inlet (top) and outlet (bottom) section for airfield design

Figure 10 until Figure 14 show the result of the CFD simulation from a multistage Savonius wind turbine with a fixed rotary axis by the implementation of no guide vane, 0°, 20°, 40°, and 60° angle guide vane respectively.

Figure 10, which shows the scenario without guide vanes, sets a baseline for airflow patterns around the turbine. Figure 11 through 14 then show the effects of guide vanes set at 0°, 20°, 40°, and 60°. The wind flow behavior changes noticeably as the angle increases, implying an effect of variations in guide vane angle and aerodynamic efficiency. The 20° angle (Figure 12) demonstrates promising flow redirection, whereas the 40° and 60° angles (Figure 13 and Figure 14) provide insight into the relationship between guide vane angle and effective wind energy capture.

Further, the results of the multistage Savonius wind turbine with a fixed rotary axis by the implementation without a guide vane the power coefficient (Cp) and Torque Coefficient (Ct) can be determined. On the other hand, Figure 15 shows the vector of airflow against the wind turbine with no guide vane, 0°, 20°, 40°, and 60° angle guide vane.

Figure 15(a) without guide vanes establishes a baseline of performance. Figure 15(b), using a 0° guide vane, demonstrates how even minor angle changes can affect the power and torque. Figures 15(c) and 15(d) investigate the effects of 20° and 40° guide vane angles, with the airflow vectors indicating a more optimal wind engagement at 20°

Table 2.
Parameters result

Parameters	Savonius without Guide Vane	Savonius with 0° Guide Vane	Savonius with 20° Guide Vane	Savonius with 40° Guide Vane	Savonius with 60° Guide Vane
Pω (Watt)	1.11	0.95	1.49	0.19	0.73
T (Nm)	0.1	0.09	0.13	0.106	0.06
ω (rpm)	105.9	100.745	109.43	107.37	106.37

Table 3.
Power coefficient and torque coefficient

Parameters	Savonius without Guide Vane	Savonius with 0° Guide Vane	Savonius with 20° Guide Vane	Savonius with 40° Guide Vane	Savonius with 60° Guide Vane
Cp	0.042	0.036	0.057	0.045	0.028
Ct	0.133	0.12	0.182	0.14	0.087

compared to the increased turbulence at 40°. These figures highlight the delicate balance between guide vane angulation and efficient wind energy capture.

Table 2 shows the extracted power ($P\omega$) and torque (T) of the rotor without guide vanes, with P at 1.11 Watts and T at 0.1 Nm. This baseline is essential for assessing the efficacy of guide vanes at different angles.

Using the calculation in [6] the ω value is 105.9. Then convert to the rpm value by using the equation (9).

$$1\,rpm = \frac{2\pi}{60} rad/sec \tag{9}$$

From equation (9) the rotational speed of the multistage Savonius wind turbine without guide vane is 1007.745 rpm. For the multistage Savonius wind turbine with the four variants guide vane uses the same equation from the power that the rotor can extract and torque are obtain the ω value. Using equation (9) can obtain the rotational speed in rpm.

Table 3 shows the power coefficient (Cp) and torque coefficient (Ct). Using equation (7) the Cp

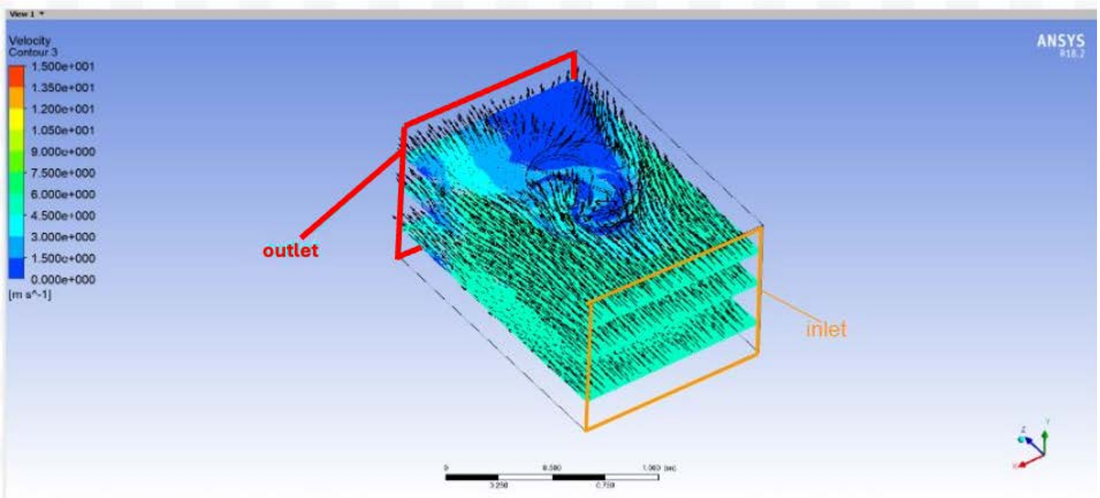

Figure 10. CFD simulation results on ansys workbench without a guide vane

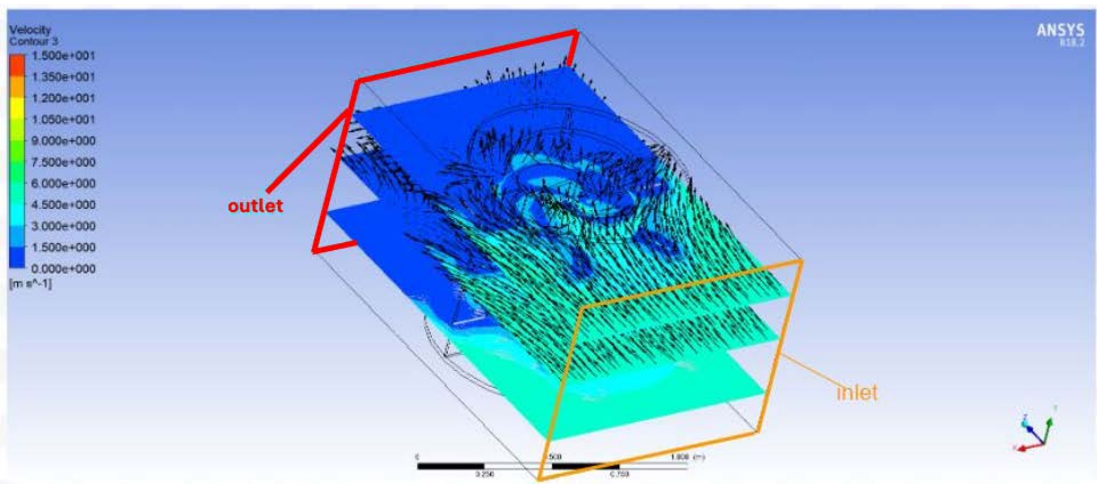

Figure 11. CFD simulation results with 0° angle guide vane

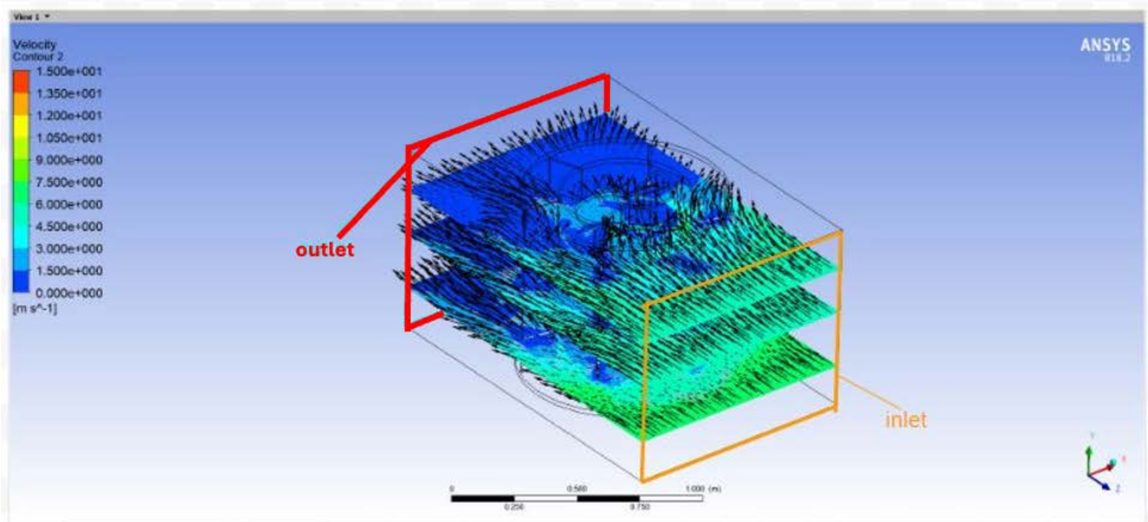

Figure 12. CFD simulation results with 20° angle guide vane

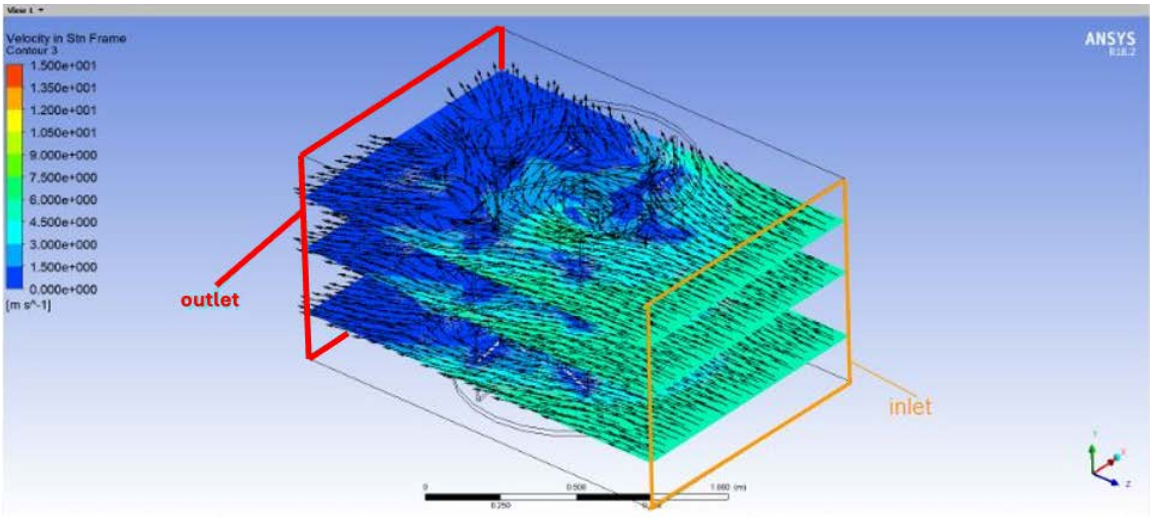

Figure 13. CFD simulation results with 40° angle guide vane

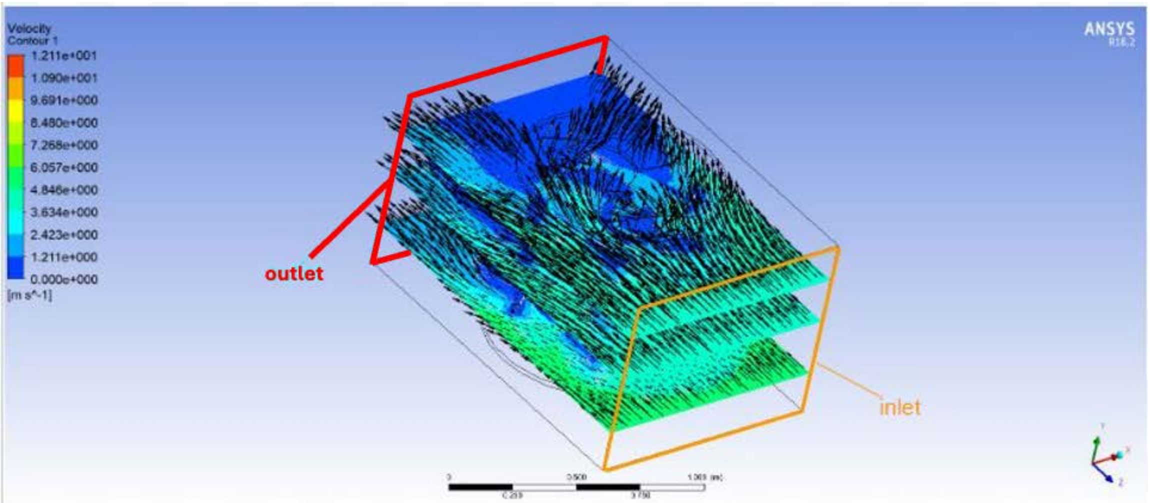

Figure 14. CFD simulation results with 60° angle guide vane

value of the multistage Savonius wind turbine is 0.042 and the Ct value is 0.133. Then, utilizing equation (7) to obtain the Cp and Ct for the multistage Savonius wind turbine with four variants of guide vane.

The simulation of four variants of the angle of the guide vane is a method to improve the multistage Savonius wind turbine. The guide vanes aim to direct the wind towards the concave blades, allowing for increased power generation while minimizing the effects on the convex blades. Figure 15(c) and 15(d) depicts a simulation with 20° and 40° angle guide vanes that results in optimal wind redirection. This angle appears to efficiently harness wind energy by directing the flow onto the concave blades and reducing wind impact on the convex blades, implying an effective balance between force redirection and drag minimization. On the other hand, the simulations in Figure 15(e), which show guide vane angles of 60°, demonstrate the complexity of wind flow management at higher angles. While these steeper angles aim to capture more wind, they also run the risk of causing flow separation and turbulence, as seen in the 60° configuration. The comparison of these figures highlights the effect of the guide vane angle on turbine performance, with the 20° angle guide vane demonstrating a potential design optimization for optimizing energy extraction efficiency.

The CFD simulation results from the ANSYS software show the effect of the implementation of a guide vane and without a guide vane. For the multistage Savonius wind turbine without a guide vane, the CFD simulation shows that the incoming wind hit the concave blade and convex blade so, the power that the rotor can extract could not be obtained properly because there is negative torque from the convex blade. Notably, the 20° guide vane configuration produces the highest values in both power and torque, implying that this angle achieves

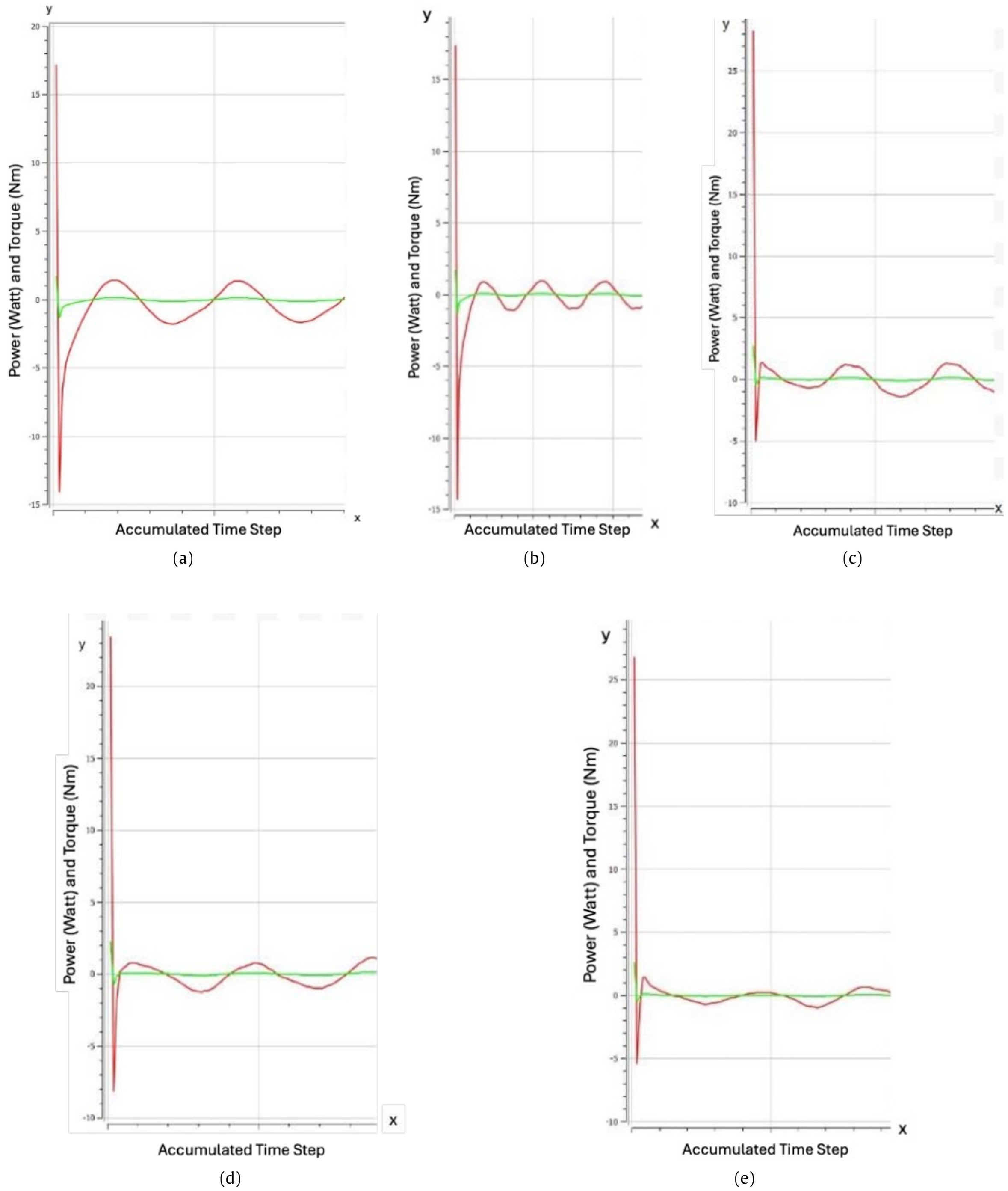

Figure 15. Extracted power and torque from rotor: (a) without guide vane; (b) with 0° angle guide vane; (c) with 20° angle guide vane; (d) with 40° angle guide vane; (e) with 60° angle guide vane

the best balance between wind capture and flow redirection. The corresponding rotational speeds (ω) support this, revealing a consistent and favorable conversion of aerodynamic forces into rotational energy. With a notable rpm of 100.745, the value calculated using equation (6) from the referenced study and converted to rpm using equation (9), confirms the superior performance of the 20° guide vane.

On the other hand, Table 3 examines the aerodynamic coefficients, revealing that the 20° angle guide vane has the highest power coefficient (Cp) at 0.057 and the highest torque coefficient (Ct) at 0.182. These coefficients are more than just numbers; they reflect the turbine's ability to effectively harness wind energy. The higher Cp and Ct values indicate a more efficient energy conversion process, as the 20° guide vanes enhance wind interaction with the concave blades while minimizing negative effects on the convex blades.

The highest power coefficient (Cp) is produced by the multistage Savonius wind turbine with a 20° angle of guide vane because the implementation of the number of guide vanes by 6 blades can influence turbine performance improvement due to more kinetic energy in the wind that is converted to mechanical energy [14]. Besides the number of guide vanes, the angle of 20° produces the best improvement than the other guide vane and without a guide vane because this angle could direct the airflow into the blade and direct airflow outside the blade of the turbine that the angled entry for the wind are bigger and have the best angle so the rotor can rotate properly.

CFD simulations in this research indicate power efficiency (Cp) increases in multistage Savonius wind turbines due to improved direction vane design. This is consistent with the findings of [20] and [21], who both observed improvements in turbine output and the benefits of guide vanes in vertical-axis wind turbines. While [21] concentrated on omni-direction-guide-vane angles without giving exact numerical gains, this research provides concrete efficiency percentages, allowing for a more precise assessment of guide-vane efficacy.

The impact of guide vane design on turbine performance, as demonstrated by the results of this study, is consistent with the findings of [22] and [23]. In [22] investigated the effect of guide vane design on airflow, whereas [23] investigated performance differences in Savonius-type turbines with and without guide vanes. This research expands on these findings by providing quantitative data on power efficiency, which is not extensively documented in previous investigations. Furthermore, despite focusing on a different turbine type, in the research [24], the examination of the split sliding guide vane for variable nozzle turbines provides a methodological parallel in terms of CFD modeling methodologies.

The research's utilization of advanced CFD techniques for modeling the aerodynamics and efficiency of multistage Savonius wind turbines is a significant aspect of this research. This method is similar to that utilized by [24] which explored the split sliding guide vane for variable nozzle turbines, and [21], which focused on the impacts of omni-direction-guide-vane angles. Both studies emphasize the importance of accurate and detailed simulations in understanding turbine performance, similar to this research. Furthermore, the thorough simulations in this study can be compared with the wind tunnel testing approach of [12], providing insight into how simulated data correlates with physical testing.

Overall, this research contributes to the field of wind turbines, specifically in the context of multistage Savonius wind turbines, where the research stands out for its extensive and quantifiable analysis. This research adds to this understanding by providing precise numerical data on power efficiency increases. This depth of quantitative detail, which is less provided in the previous research, expands the knowledge base by offering benchmarks for evaluating guide vane effectiveness. However, it is critical to acknowledge that each piece of study adds something unique to the industry, and this research builds on these basic studies to further the aim of optimizing wind turbine technology.

IV. Conclusion

In this research, a new guide vane design for multistage Savonius wind turbines that incorporates six fins and a fixed rotary is proposed. Through extensive simulation, it is demonstrated that employing this guide vane design significantly improves the turbine's performance. According to the simulations in this research, a 20° angle for the guide vanes generated the greatest results, outperforming other configurations such as 0°, 40°, and 60° angles, as well as scenarios without a guide vane. The finding highlights the significance of precise guide vane angle in enhancing wind turbine efficiency, as well as providing helpful insights into the design and operation of renewable energy technology.

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Declarations

Author contribution

D. Devin: Writing - Original Draft, Conceptualization, Formal analysis, Investigation, Visualization, Software, Investigation, Data Curation. L. Halim: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Validation, Supervision. B. Arthaya: Formal analysis, Investigation, Resources, Visualization, Supervision. J. Chandra: Resources, Software.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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