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# CFD-OPTIMIZED SAVONIUS WIND TURBINE PERFORMANCE DESIGN FOR PSA ANALYSIS

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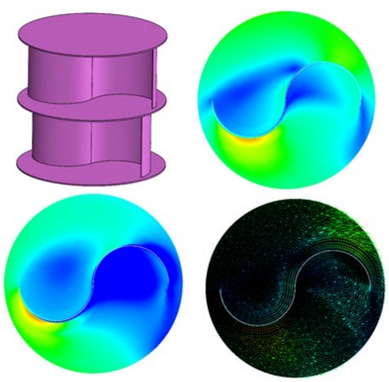
**Graphical abstract**



**Abstract**

The primary aim of this research is to enhance the accessibility of clean energy by advancing technology in energy conversion. Specifically, the focus is on optimizing the design of wind turbines equipped with Savonius rotors to maximize the generation of renewable energy. The Savonius rotor is a cross-flow rotor characterized by its uncomplicated design and ease of implementation. The performance of Savonius is significantly influenced by geometric considerations. The performance enhancement of the Savonius multi-stage is contingent upon the phase-shift angle (PSA). The present study employed three-dimensional modeling techniques with Ansys software, specifically utilizing the CFX solver. An optimization of the Savonius rotor design was conducted on a two-stage rotor, utilizing PSA variations of 0˚, 15˚, 30˚, 45˚, 60˚, 75˚ and 90˚. The technology employed in this study is computational fluid dynamics (CFD), which is performed assuming steady-state boundary conditions. The turbulent behavior of fluid flow is effectively captured by the SST turbulence model. The velocity of the fluid entrance is established at 6 m/s, while the pressure of the output is consistently maintained at 1 atm. The Savonius rotor variant, including a pitch angle angle (PSA) of 15°, demonstrates a coefficient of power of 0.32, which is widely regarded as the most ideal. The performance of the two-stage Savonius design can be further evaluated by considering its performance at angles of 0° and 30°, as it exhibits commendable performance.

*Keywords*: Savonius; Renewable Energy; Phase-Shift Angle; Computational Fluid Dynamics



## 1.0 INTRODUCTION

In the last ten years, electrical energy consumption in Indonesia has shown an increasing trend every year. Increase in average electricity consumption by 4%. In 2021, electrical energy consumption will increase by 5%; the highest growth was 8% in 2013 [1]. In general, the need for electrical energy is shown in the graph shown in Figure 1. The increase in electrical energy consumption also spurred a rise in electricity generation in Indonesia, where the capacity of electricity generation in Indonesia in the 2012-2021 period increased by an average of 6%. In 2021, electricity generation capacity increased by 3%; the highest increase was in 2013 at 18% [1]. This increase is a new problem because electricity generation from new and renewable energy is only 15% of the total capacity. This phenomenon shows Indonesia's dependence on nonrenewable energy sources for electrical power.

The Sustainable Development Goals, as determined by the United Nations, include a specific objective pertaining to the provision of clean and affordable energy. This objective remains inconsistent with the prevailing circumstance that the electricity provision in Indonesia is currently sourced from non renewable energy (NRE) at only 15%. Conversely, the geographical positioning of Indonesia presents a favorable circumstance wherein an abundance of clean energy resources, including water, wind, geothermal power, bioenergy, and solar, are abundantly available [2]. The advancement of research related to renewable energy sources is a crucial step in augmenting the processing of such energy. This can be achieved through the progression of both modeling based research [3] and experimental research [4]. Wind energy is a significant energy source in Indonesia, boasting a substantial potential capacity of 60,647 MW [5]. The potential of wind energy is considerable. The current installed capacity stands at a mere 154 MW, indicating a substantial disparity between the potential capacity and the actual installations. One effort to mitigate this disparity involves researching wind turbines, with a particular focus on vertical axis wind turbines. The turbine is the principal mechanism for converting wind energy into electrical energy.

The Savonius rotor is a type of wind turbine rotor that can be used in vertical axis wind turbines. Savonius rotors are cross-flow rotors in which the fluid flow attacks perpendicular to the turbine rotor [6]. Many factors influence the performance of the Savonius rotor, including geometry [7] and material [8]. Aspect ratio [9], number of blades [10], blade shape [11], and phase-shift angle (PSA) [12] are all geometric factors. The two factors that have received the most attention in the research are multi-stage and PSA. Previous research found that the two-stage Savonius rotor improved Savonius performance to a higher Coefficient of power (CP) value than the single-stage [13] .

The findings of the study indicate that the performance of hydro turbines equipped with cross-flow rotors is influenced by the number of blades. Studies conducted on different blade counts (3–12) have shown that the 3-blade configuration yields the most performance, with a coefficient of performance (CP) of 0.07. [14]. The effect of the PSA on the Savonius wind turbine has been tested at an aspect ratio of 2:1. The results show that the 45° angle has the best performance, where the variations of the tested PSA are 0°, 45° and 90° [12].

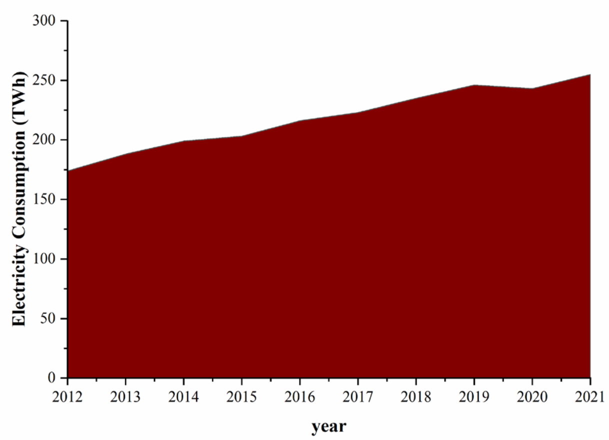



**Figure 1** Indonesian electricity consumption graph [1].

The study involved an examination of the Savonius rotor in a vertical wind turbine, employing three-dimensional modeling on Ansys software with the CFX solver. This study was conducted on a multiple-stage Savonius rotor. The term "multistage" refers to having multiple levels of construction, and this study focused on Savonius' two stages. This is a variation of the traditional form, which only has a single stage. The main focus of this study is to examine the Phase-Shift Angle (PSA) factor. The angles being examined in this study are 0˚, 15˚, 30˚, 45˚, 60˚, 75˚, and 90˚, with respect to the PSA. The objective of this study is to devise a two-stage Savonius configuration featuring an optimal PSA. This design will function as a financially efficient substitute for the production of clean energy.

## 2.0 METHODOLOGY

The Savonius turbine rotor is characterized by its uncomplicated design, comprising an endplate, a convex blade, a concave blade, and a shaft. The schematic diagrams presented in Figure 2 illustrate the operational principle of the Savonius turbine. When comparing the moment exerted on the convex blade of the Savonius rotor to the moment exerted on the concave blade, it appears that the former is lower due to the varying resistance coefficients of the surfaces. The counterclockwise torque has a positive value as depicted in schematic Figure 2. Due to this rationale, the Savonius wind rotor exhibits rotation in the positive direction [15]. The Savonius wind turbine, which is utilized in wind energy applications, is characterized by its vertical axis configuration. Vertical wind turbines possess several advantages in comparison to other types of wind turbines. Firstly, they are capable of functioning efficiently even at low wind velocities. Additionally, they have the ability to operate effectively regardless of the wind direction. Moreover, vertical wind turbines exhibit a lower starting torque, which contributes to their enhanced performance. Lastly, their construction is characterized by simplicity, further enhancing their appeal [16].

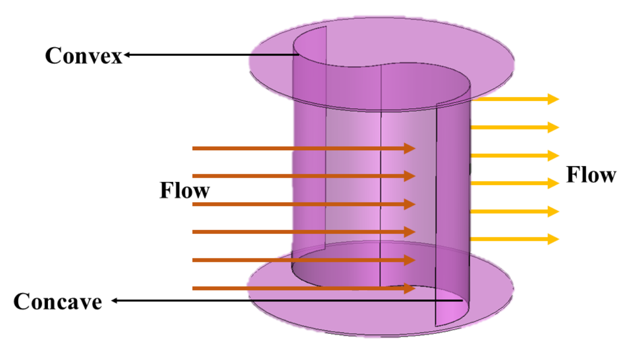



**Figure 2** The functioning principle of the Savonius rotor.

Turbine performance is indicated by aerodynamic parameters such as coefficient of power (CP) and coefficient of torque (CT). The coefficient of power of the turbine is obtained from equation 1 [17], which shows the relationship between turbine power (PT) and available power (PA). Equation 2 shows PT, which is the relationship between torque (T) and angular velocity (ω) [18]. PA is shown by equation 3 [17], where available power is the relationship between fluid density (ρ), fluid velocity (V), and projected area (A). The relationship between CP, CT, and TSR is shown by equation 4 [18]. Tip Speed Ratio (TSR) is a comparison between angular velocity (ω), blade radius (R), and inlet fluid velocity (V), which is expressed in equation 5 [18].

$$C_P = \frac{P_T}{P_A} \quad (1)$$

$$P_T = T.\omega \quad (2)$$

$$P_A = \frac{1}{2}\rho.A.V_\infty^3 \quad (3)$$

$$C_T = \frac{C_P}{TSR} \quad (4)$$

$$TSR = \frac{R.\omega}{V_\infty} \quad (5)$$

Completion of the modeling uses the Computational fluid dynamics method based on the Navier-Stokes equation. The Navier-Stokes equation for the x-axis direction is expressed in equation 6, the y-axis direction is defined in equation 7, and the z-axis direction is expressed in equation 8 [19].

$$\rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = \rho\frac{du}{dt} \quad (6)$$

$$\rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = \rho\frac{dv}{dt} \quad (7)$$

$$\rho g_y - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = \rho\frac{dw}{dt} \quad (8)$$

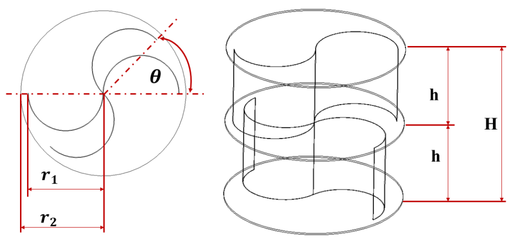



**Figure 3** Rotor design dimensions.

Modeling is generally carried out in four stages: geometry design, meshing, setup/process, and solution. Geometry is created in three dimensions. The dimensions of the rotor variations are shown in Figure 3 and Table 1, and the three-dimensional design of all variations is shown in Figure 4. The rotor variations are made based on the phase-shift angle, equal to 0˚, 15˚, 30˚, 45˚, 60˚, 75 ˚ and 90˚. Apart from creating a rotor design, the simulation domain is also made in two domains [20]. The modeling domain is divided into the rotary and stationary domains[21, 22]. The modeling domain is shown in Figure 5.

**Table 1** Dimention of Savonius

| Symbol | Name | Dimension |
|---|---|---|
| $r_1$ | Radius of blade | 105 mm |
| $r_2$ | Radius of endplate | 115 mm |
| h | High of stages | 102 mm |
| H | High of rotor | 210 mm |
| ɵ | Phase-Shift Angle | 0˚, 15˚, 30˚, 45˚, 60˚, 75˚ and 90˚ |

Meshing comes after designing the rotor geometry and domain. The tetrahedral inflation method was used with five layers along the blade [23], yielding an average skewness of 0.28. In turbine modeling, the tetrahedral approach is often utilized [24]. The meshing produces good results because the average skewness value presented is 0.72, which is smaller than the typical skewness value of 0.8 [25]. Figure 6 depicts the meshing results.

The process after meshing is to enter boundary conditions in the modeling domain. The schematic of the modeling is shown in Figure 7. The boundary conditions in the modeling consist of an inlet, outlet, wall, and interface. The modeling uses steady-state [26] and shear stress transport (SST) turbulence type [27]. The SST turbulence type accurately displays modeling results, a combination of the advantages of K-epsilon and K-Omega [28]. The inlet has a wind fluid speed of 6 m/s. The boundary condition on the wall domain is symmetry, assuming the rotor is in a wide system. The outlet boundary condition uses an outlet pressure of 1 atm. The interface uses fluid to fluid as a link between the rotary and stationary domains.

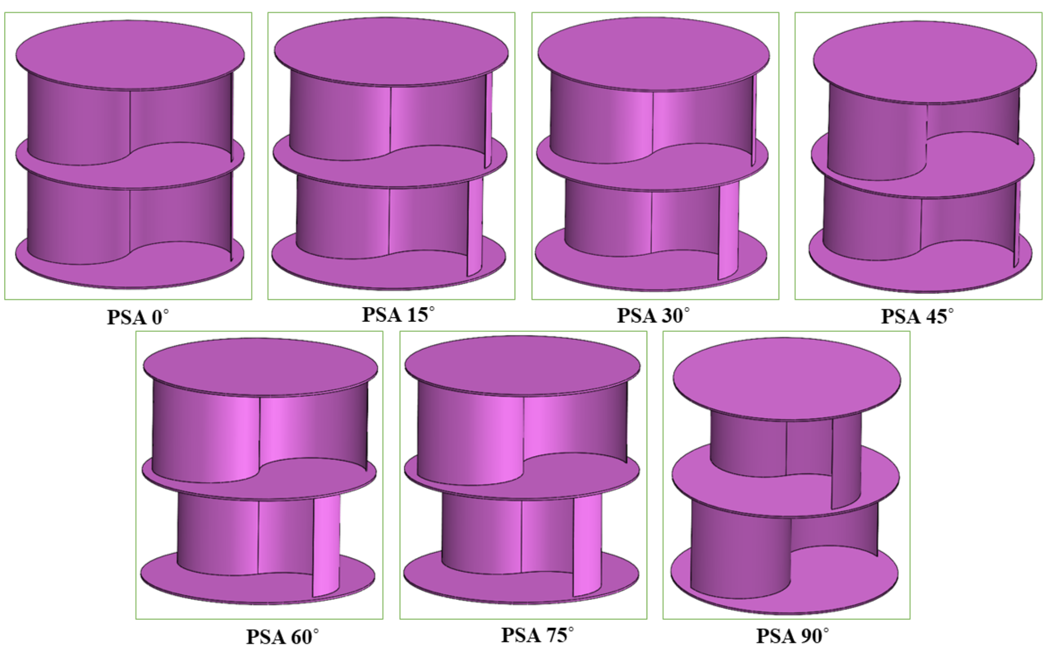



**Figure 4** The design of a Savonius rotor variant.

A mesh study is one form of validation. Mesh study is the process of determining the best mesh at a convergent point. This study used a mesh of three sizes for its mesh study [29]. If the discrepancy between results is smaller than 3%, a mesh study is said to be convergent [30]. The mesh study procedure is depicted in the graph in Figure 8. The difference results show that the resulting difference is 0.4%, indicating that the mesh study's results are acceptable. The mesh used is a mesh with the third setting and three million elements.

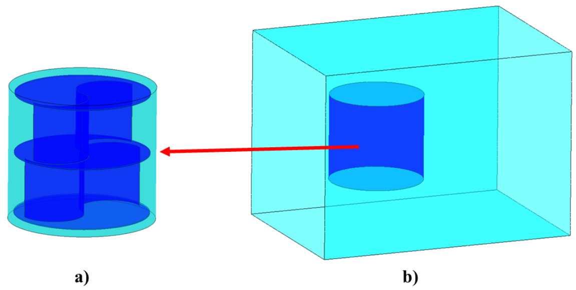



**Figure 5** Domain modeling: a) rotary domain and b) stationary domain.

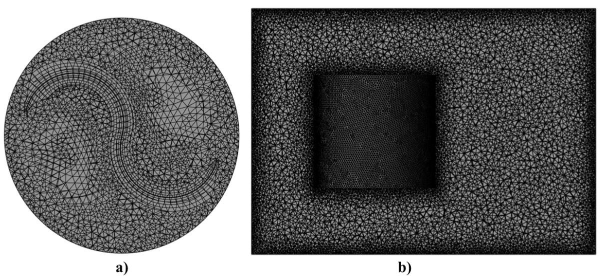



**Figure 6** Meshing results in a) rotational domain and b) stationary domain

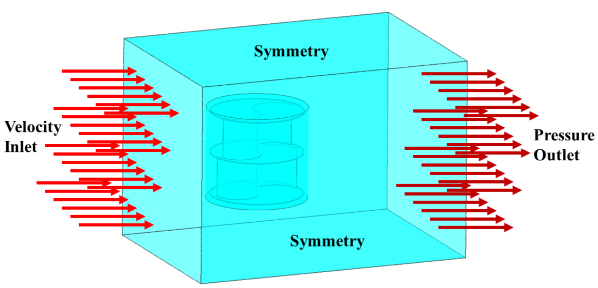



**Figure 7** Savonius Turbine Modeling Schematic.

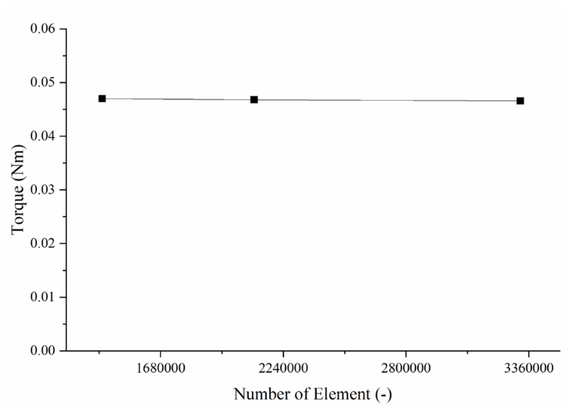



**Figure 8** Graph Mesh Study.

Validation was carried out by comparing the modeling results with experimental research by Saha et al [31]. Benchmarking results show an average error difference of 3%. Where the error value is searched using equation 6 [10]. The error value obtained is below the modeling error limit, where the maximum acceptable modeling error limit is 10% [32]. The results of the benchmarking are shown in the graph in Figure 9. These results indicate that modeling can be used to continue solving the modeling case.

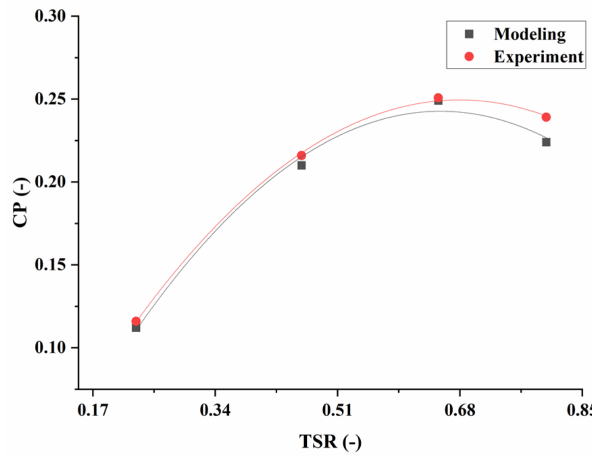



**Figure 9** Comparison of experimental [30] and modeling findings.

## 3.0 RESULTS AND DISCUSSION

The computational fluid dynamics method was used to investigate the Savonius rotor. Three-dimensional modeling was completed using Ansys software and the CFX solver. The influence of PSA on the Savonius rotor applied to a vertical axis wind turbine yields the findings displayed in Figure 10. Using Equations 1 and 4, the modeling outputs are torque values transformed into CP and CT. Because $CP_{max}$ in turbine modeling is typically in the TSR, modeling is done at TSR 0.7. The modeling findings demonstrate that PSA 0˚, 15˚ and 30˚ produce CP greater than 0.2, but PSA 45˚, 60˚, 75˚ and 90˚ produce CP less than 0.2. PSA 15˚ produced the highest CP of 0.32, while PSA 90˚ provided the lowest CP of 0.16. CT in PSA variants exhibits the same phenomenon as CP, with CT produced by PSA 0˚, 15˚ and 30˚ having a value greater than 0.3 and CP produced by PSA 45˚, 60˚, 75˚ and 90˚ having a value less than 0.3.

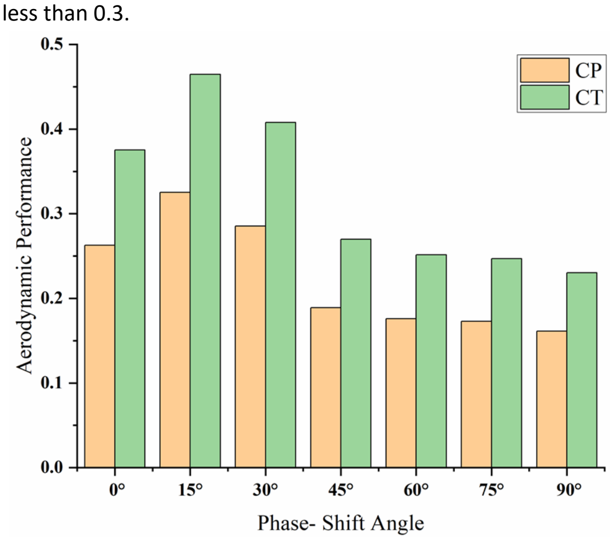



**Figure 10** Aerodynamic performance results on the Savonius rotor with PSA variations.

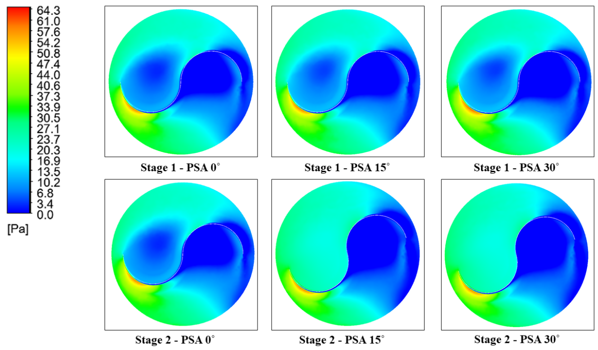



**Figure 11** Pressure contours on the Savonius rotor with PSA variations.

Modeling carried out on the Savonius rotor produces pressure contours in the fluid. Figure 11 shows the results of the pressure contour in modeling. The rotor modeling displays the pressure contour with good CP results, namely PSA 0˚, 15˚, and 30˚. In stage 1, each rotor shows the same contour, position, and wake zone area. The contour indicates that at stage 1, the three types of rotors have different convex and concave pressures with similar values. The differences between the PSA variations are visible in Stage 2, where the position and extent of the wake zone look different.

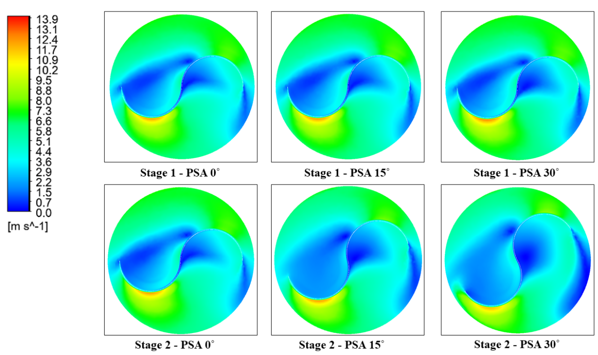



**Figure 12** Velocity contours on the Savonius rotor with PSA variations.

Figure 12 illustrates the contour representation of the wind velocity in the modeling process, whereas Figure 13 provides a vector depiction of the same velocity of the wind. In the PSA changes of 0˚, 15˚, and 30˚, it is observed that Stage 1 exhibits identical speed contour and speed vector shapes, a pattern that is also evident in the pressure contour. The observed homogeneity in contour can be attributed to the identical shape and position of all PSA changes throughout stage 1. The speed contour in stage 2 reveals that PSA 0˚ exhibits the largest speed region near the outer edge of the convex blade, characterized by a velocity vector that opposes the direction of rotor rotation. The overall speed in the direction of rotor rotation at PSA 0˚ is comparatively reduced when compared to PSA 15˚ and 30˚, leading to a decrease in the torque generated by PSA 0˚ in comparison to PSA 15˚ and 30˚.

There are no variations seen in stage 1 of Figures 12 and 13. This phenomenon occurs due to the fact that during stage 1, the rotor's whole variation remains in a fixed place. Stage 2 exhibits disparities among the many variants of the angle. At an angle of 30°, the wake-zone region is quite vast, particularly on the right side. A concave blade with an angle of 15° exhibits a greater high-speed region along its edge in comparison to both the 0° angle and the 30° angle.

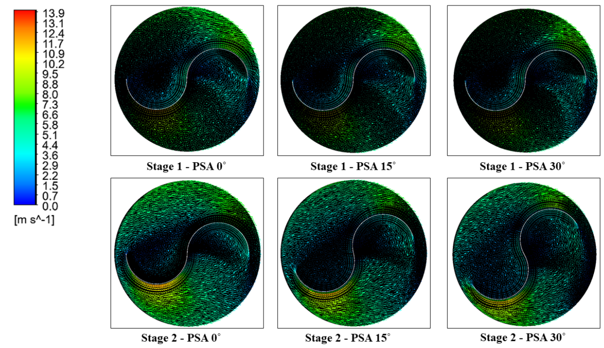



**Figure 13** Vector velocity on the Savonius rotor with PSA variations.

## 4.0 CONCLUSION

Modeling research has been carried out using the computational fluid dynamics method of Ansys and Solver CFX software. Modeling has been carried out with convergence in the mesh study of 0.4% and error in validation with Saha et al.'s experimental research of 3%, so the modeling is acceptable. This research resulted in the highest CP value achieved in the PSA 15˚ variation with a value of 0.32 and the smallest CP value achieved by PSA 90˚ with a value of 0.16. The optimal design for the PSA factor can be obtained at a PSA of 0˚ to 30˚. The optimal PSA recommendation for a two-stage Savonius is 15˚, where this design can be used as an alternative in the clean energy conversion sourced from wind energy.

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## Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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