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Abstract. The energy demand, which relies on fossil fuels, is increasing while their availability is decreasing. As a result, alternative energy sources like wind energy are necessary to decrease the reliance on fossil fuels. The recent study focused on enhancing the performance of Darrieus H rotor type by attaching Vortex Generators (VGs) to harvest wind energy more efficiently. The study examined a three-blade Darrieus H rotor turbine with rectangular straight VGs under a wind velocity of 8 m/s. The fluid flow characteristics were analyzed using the Unsteady Reynolds Averaged Navier Stokes (URANS) model, and the performance was evaluated using the Coefficient of Power (Cp). The rectangular straight-type VGs were positioned at different chordwise (x/c) locations of 10%, 15%, 20%, 25%, and 30%. The findings indicated that VGs could significantly enhance the turbine's performance, with the most optimal position for the VGs being at x/c of 30%. This positioning produced the highest Cp value of 0.452 at a tip speed ratio (TSR) 1.5. The average Cp improved by approximately 30% compared to a wind turbine without VGs. Visualization of turbulent kinetic energy illustrated how VGs disrupted the flow around the airfoil, acting as flow control to diminish separation. These findings offer valuable insight into using VGs for designing airfoils and utilizing geometric VG parameters for optimal design. Although the improved performance shows potential for harvesting wind energy in low wind speed environments, it's essential to acknowledge that the flow field details may be constrained due to the rotating nature of the turbines.

Keywords: Darrieus Turbine; Vortex; Rectangular; Performance; Tip Speed Ratio (TSR).

1. Introduction

The human need for energy, particularly for electricity, is increasing daily. However, the energy sources that mostly came from fossil energy were constantly growing. This energy issue has led researchers and engineers to explore renewable energy as an alternative to fossil energy. Indeed, the system's renewable energy performance could not be compared later to fossil energy. Some researchers are trying to develop a system that uses different renewable energy sources to produce electricity. Jessam[1)] utilized the exhaust air from air conditioning to drive the wind turbine. They found that energy results can be used to power small devices such as LED lights. Warjito et al.[2)] numerically investigated a vortex hydro turbine by analyzing the effect of blade size and depth on turbine efficiency. They found the efficiency was high when the turbine position at the upper top with the larger blade size was 500 mm. A banki hydro-turbine was assessed using the combination of CFD and FDA by modifying the angle and number of blades[3)]. They found that both parameters strongly affect the coefficient of power (Cp). Javaid et al.[4)] propose predicting photovoltaic-wind hybrid system energy using an artificial intelligence (AI) tool for an urban environment. Their forecasting, considering the analysis of wind direction as well as the storage capacity of the battery, found that the hybrid system could provide sustainable and green energy in the future. Chen et al.[5)] provide a study on stabilizing the wind turbine under high-speed conditions by optimizing the pitch control. Evolutionary structural optimization (ESO) and nonlinear optimal control were combined to demonstrate wind turbines' dynamic performance effectiveness, indicated by electrical power production against the disturbances.

Not only are wind and solar energy considered and potentially developed to produce electricity, but also wave energy, such as a review by Santoso et al.[6]. Another form of renewable energy that has to be developed is geothermal, that have been investigated by Muslihudin et al.[7]. They are trying to find the constraints for developing geothermal power plants in Indonesia related to the environmental conditions. Besides the environmental conditions, the people's understanding of geothermal potency is also essential, as explained by Pambudi et al.[8]. The last but not least is tidal energy. Wang and Ng[9] provide the technique to improve the power generation electricity production based on a closely-interconnected tidal array and improve it using a tandem hydrofoil. Besides the tidal array, Wu et al.[10] also propose a technique to enhance the performance of tidal system utilization. Wu et al.[10] investigated the direction of the impeller and their geometry with flow velocity variation and evaluated the coefficient of power (Cp).

Considering the small review above, Indonesia has an advantage as one of the countries with the highest possibility of developing almost all renewable energy. However, some constraints exist in the application and building of the system using renewable energy[11-13]. Klimenko et al.[11] explained that primary material resources can limit the growth of renewable energy applications. Material incompatibility selection may reduce the stability and quality of the power system. Basit et al.[12] proposed research on a renewable energy grid integration system to ensure power sustainability. They provide some methods to enhance the performance, including the power density. Bremer et al.[13] conducted an optimization for controlling the problem when applying renewable energy. In the case of wind energy, they include the data for the wind energy distribution, particularly on wind speed data. Based on the wind speed data[14], Indonesia has a high potential to harvest wind energy. It is not only in Indonesia but may also be one of the most considerable power sources globally. Their sustainability and environmentally friendly energy source would minimize the impact of disrupting the environment. The only disadvantage of wind energy is the variation in wind velocity and direction. The pattern of the wind varies randomly with time. The wind pattern depends on the season and location and may change yearly.

Wind energy is harvested using a wind turbine. Many wind turbine system types depend on the wind speed and location conditions. A large wind farm usually uses a horizontal axis wind turbine (HAWT) because it can produce high power and is also very efficient. However, in urban areas, the HAWT is not suitable to be installed. The wind turbine in a metropolitan area should be able to operate at low wind speeds and be omnidirectional. The right design for the condition is a vertical-axis wind turbine (VAWT). This turbine can operate in urban, mountainous, and sandy areas[15].

Although it has some advantages, most VAWT types have lower power performance than the HAWT. However, the VAWT may still have the potential to be developed in design and performance and will be a severe competitor to the HAWT type[16]. Therefore, research activities for developing the VAWT performance have become attractive over the last decades. Among the VAWTs, the Darrieus H rotor wind turbine performs at the highest level compared to the other turbines. The Darrieus H rotor is a lift system wind turbine that works mainly based on the generated lift force on the blades[17].

Some blade modifications were proposed to enhance the lift system aerodynamics performance of the wind turbine[17–20]. Even then, when designing the blade, it must be carefully assessed to ensure the blades will not fail. The blade can be damaged due to lightning, icing, fatigue, and erosion in the leading edge[21]. The optimization of blade deflector shape was conducted by Marinić-Kragić et al.[18] by counting wind directions factor. They found that adding the deflector will improve the turbine's performance coefficient. Another attempt to improve the Cp was made by Marinić-Kragić et al.[19] by adding a multi-blade combined with optimizing the aspect and tip-speed ratios. The improvement was about 12% compared to the classical one. Shape modification was also done by Ma et al.[20]. Not only did the shape modification, but they also considered the effect of twist angle and chords in their research. Porto et al.[22] investigated how the turbine blade number would affect their performance. The blade number was modified to three and five-bladed. Under low velocity, the five-bladed turbine could reach a 25% higher performance than the three-bladed turbine.

Instead of the blade models, the blade surface flow characteristics influence their performance. The aerodynamic performance will be enhanced due to stream-wise vortices generation[17,23], flow separation field affect[17,24], and stall field delay[25,26]. This phenomenon can be found by adding a small fin called a vortex generator (VG). Since it is small, VG was normally installed on the object's surface. The vortex generator can generate vortices to modify airflow into turbulent flow, delay flow separation, and, as a result, delay the stall[27].

The VGs bring the concept of controlling the flow by suppressing or delaying the separation while increasing the lift-to-drag ratio. The development of wind turbines using VGs was researched by Zhao et al.[28], Lee and Kwon[29], Zhu et al.[30], and Chen et al.[31]. Zhao et al.[28] used five models of VGs with triangular shapes. The model was investigated under four angles of attack from 5° to 20°. They found that VG's presence effectively controlled the flow separation and altered the stalling conditions. A simulation was done by Lee and Kwon[29] to analyze the effect of triangular VGs on the inboard rotor blades of NREL 5 MW. The VGs generate strong vortices, leading to a 1.04% performance improvement. Zhu et al.[30] control the dynamic stall of the NREL S809 airfoil using single and double-row VGs. A simulation was performed, and the results were compared with those without VGs. They found by using VG, a 40% improvement was revealed. The best position of VG was on 15% of the chord length.

Modeling using counter-rotating VGs on DU91-W2-250 wind turbine blades was done by Chen et al.[31]. Considering the size of the VGs, which was smaller than the wind turbine blades size, Chen et al.[31] provided a parametric model to improve numerical research. They compared the results with the experimental data. In conclusion, they found that their model could represent the VG parameters program and be used to improve VG arrangements efficiency research. Their findings would be beneficial for the development of wind turbine technology.

In the present research, the turbine blade for the Darrieus H rotor turbine was designed as NACA 0015 airfoil. Their effect was investigated by a numerical study using ANSYS FLUENT. A rectangular type of VG was employed in the current research. VG was mounted at the point before the flow separation on the turbine blades. As described above, adding a VG in the turbine is expected to delay the occurrence of stalls and increase the lift force; hence, the aerodynamic performance would be enhanced. Some geometrical parameters were investigated to see how their changes could affect the wind turbine performance. Jiang et al. [32] placed VGs on the blade of HAWT. The presence of VGs delayed the flow separation and increased the lift coefficient of the rotating blade. VGs are also indicated as devices that could affect stall behavior[33]. VGs could delay the stall when the angle of attack was high. As a result, the blade's performance will be enhanced. Another geometrical factor of VGs, such as height and surface mounting position, also influences the performance of the blade[34]. Yan et al.[35] modeled the influence of a micro vortex generator (MVG) on an H-rotor Darrieus turbine with airfoil NACA 0018 for the blade. It was found that MVG had the highest effect when the tip speed ratio (TSR) was set as three, leading to an increase in the power coefficient by more than 50%.

Many researchers have investigated the influence of adding VGs on the blade of HAWT. Conversely, very few studies provide research on VWAT using VGs. Therefore, this study analyzes the performance improvement of the Darrieus H-rotor by adding VGs to the turbine blades.

2. Methods

2.1 The Model of Wind Turbine

The Darrieus H-rotor type turbine is modeled as three-dimensional (3D) using Ansys Fluent software, as shown in Fig. 1. The parameters and dimensions of the turbine are using the geometry from Song et al.[36]. The airfoil type used in this study is NACA 0015. Turbine modeling consists of two parts: rotating and non-rotating. The rotating part contains the turbine blades, which are the turbine's moving parts. The non-rotating part represents the fluid (air) domain of the model. The turbine has 3 blades number (N), with chord length (c) of 375 mm. The rotor diameter (D) and height (H) were 1,650 mm and 1,000 mm, respectively. The wind velocity (V) used in this study was 8 m/s.

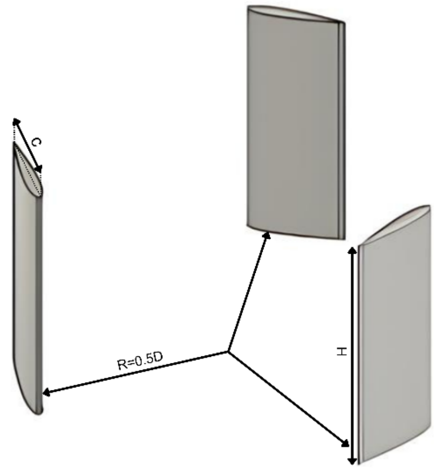


Fig. 1: 3D model of the turbine

2.2 Vortex Generator addition

The VGs attached to the turbine are the straight rectangular type. Figure 2 depicts the VG dimensions based on Herdiana's research[37].

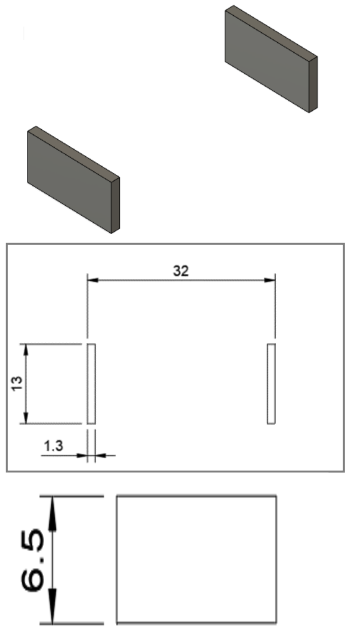


Fig. 2: Rectangular straight Vortex Generator dimension (all are in mm).

The VGs are placed along the outer side of the turbine blades. In this study, the VG position varied in terms of the ratio of x to c, where x is the position of VG to the airfoil chord length (c). The nomenclature of x and c can be seen in Fig. 3.

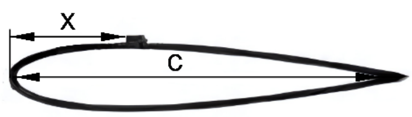


Fig. 3: The nomenclature of x and c.

The x/c position variations were 10%, 15%, 20%, and 25% of the chord length. The VG position used in the current study is depicted in Fig. 4.

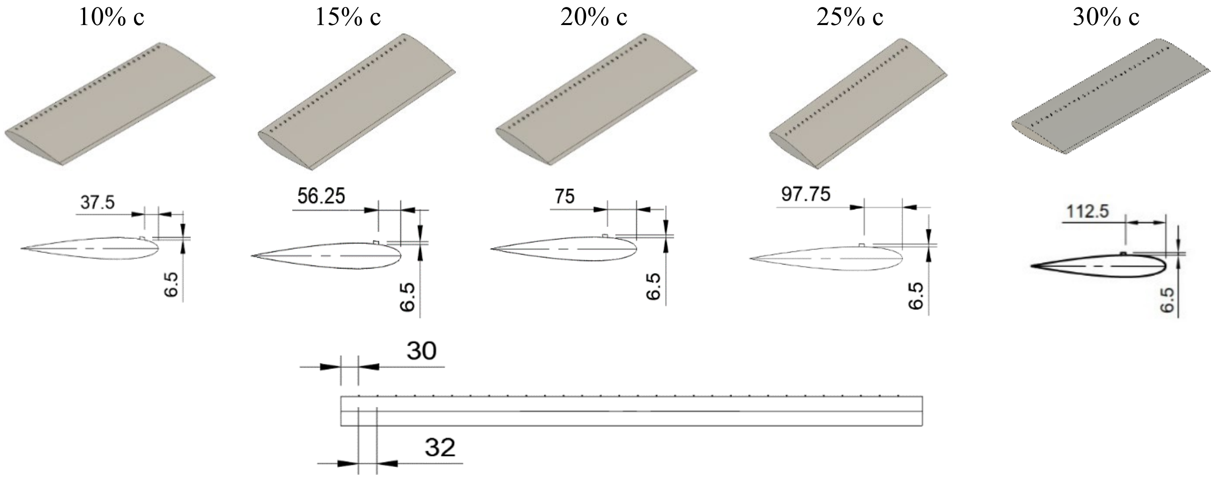


Fig. 4: The VG position variation. (all dimensions are in mm).

2.3 Setup for Computational Fluid Dynamic (CFD)

The CFD domain of the model was determined based on the turbine radius (R). The distance was set at 5R for the inlet turbine to the center. The exact value was also used to define the distance between the top and bottom walls of the turbine to the center[38]. Meanwhile, the distance was set at 15R from the center and turbine outlet. The domain height was equal to the turbine height. Therefore, the overall dimension of the domain is 8.25m x 15m x 1m. Figure 5 shows the turbine model.

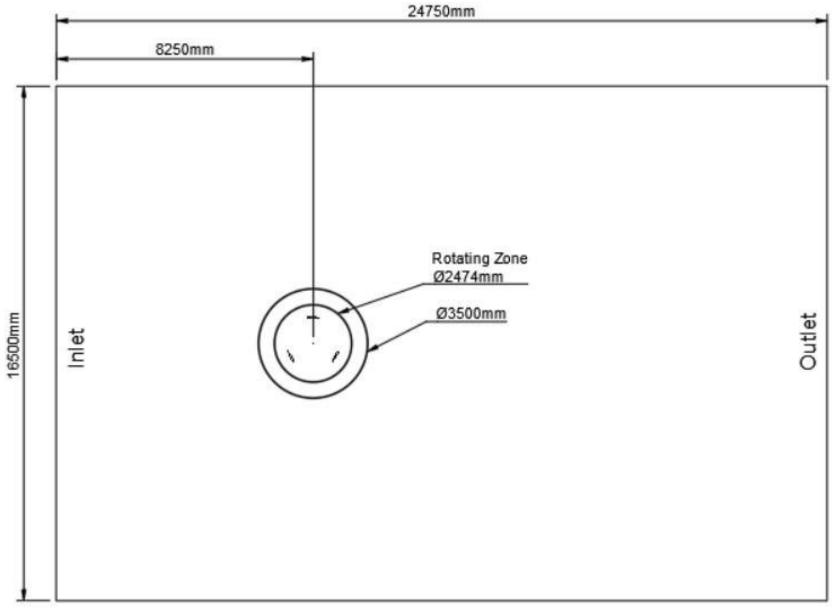
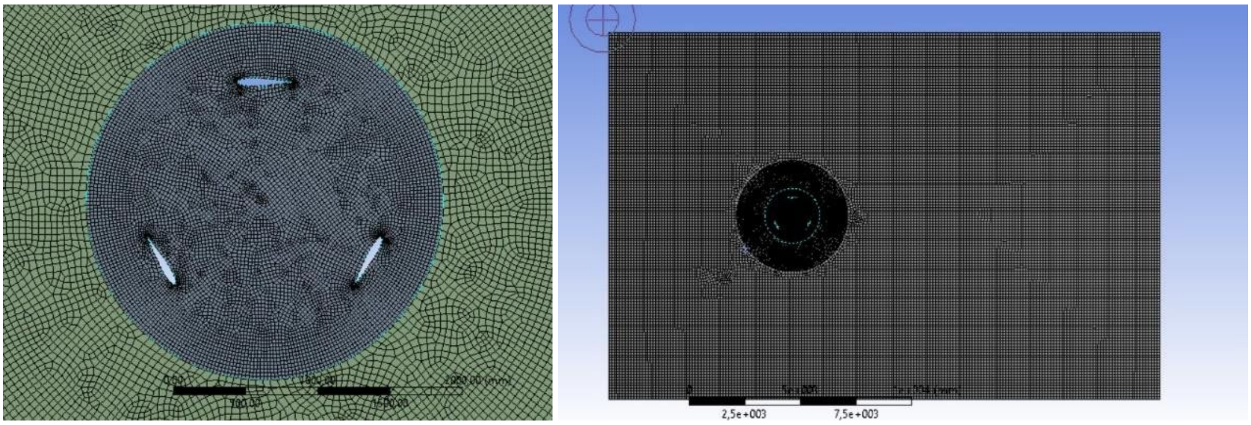


Fig. 5: The domain of the turbine model.

The meshing type used in the current simulation was tetrahedral, as shown in Fig. 6.a and b. Figure 6. a shows the turbine model meshing for the rotating domain, while Figure 6.b. was for the domain far-field. The proximity and curvature functions were used to make a good mesh quality for the area of curvature for the rotating domain and airfoil. Darrieus H-rotor, the basic model type, has a mesh of 1,775,328 nodes with 1,695,154 elements.

The simulation was conducted under free-stream and transient conditions. Based on the required TSR, the rotor was set to rotate at a constant velocity. The inlet velocity was set to 8 m/s. A pressure outlet boundary condition was applied at the turbine outlet. The walls on the top and bottom were set to zero shear stress to prevent the generation of boundary layer velocities.



(a) (b)

Fig. 6: The turbine model meshing (a) rotating domain; (b) domain farfield

The simulation was solved using incompressible three-dimensional continuous and momentum equations. The governing equation is available in[39]. The semi-implicit pressure-linked equations (SIMPLE) method was used to solve the incompressible unstable Reynolds-averaged Navier-Stokes (URANS). The turbulent model was simulated using Realizable k-ε. The pressure, turbulent kinetic energy, and specific dissipation rate were solved using a second-order interpolation scheme.

2.4 Model Validation

The simulation is validated in the current study using the previous research by Song[36]. The two models' coefficient of performance (Cp) was compared at various TSRs. The Cp of the turbine was determined from the average moment coefficient (Cm) multiplied by the correlated TSR. The comparison of the two models can be shown in Fig. 7. The 8.7% average discrepancy was found when we compared the previous study by Song et al.[36] and the current research. It can be concluded that the current model is in good agreement with the literature[36].

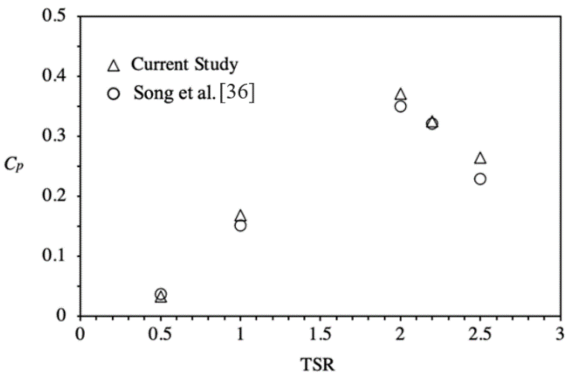


Fig. 7: Cp value comparison for the validation.

3. Result and discussion

3.1 Moment coefficient

The Cm has a different value at each position angle of the rotor because of the turbine rotation, so the blade angle of attack is constantly changed. The radar diagram in Fig. 8 depicts Cm on each rotor position at a TSR of 1.0 for the turbine without VG addition and the rectangular straight VG addition for one complete rotation (360°).

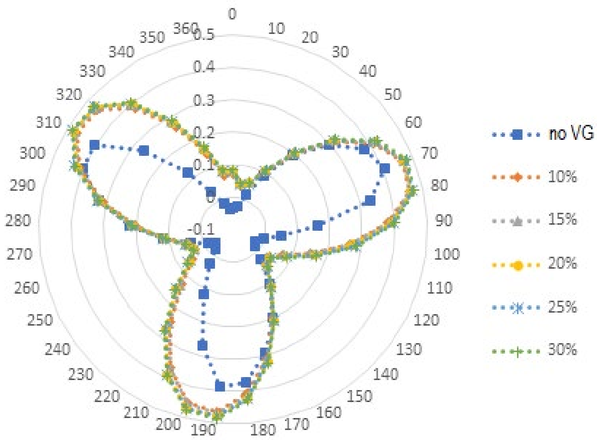


Fig. 8: Turbine Coefficient of Moment at TSR of 1.0.

Figure 8 shows that the Cm of the turbine repeats every 120° because three rotor blades are used in this study. The modeling results differ between the turbines without VG and turbines with VG. The Cm distribution of the turbine without VG looks smaller than the turbine with VG for most of the rotation position. The VG addition on all positions on the turbine blades can increase the turbine's coefficient of moment. The same results are also obtained for the different TSRs.

3.2 Power coefficient

The average Cm multiplied by the corresponding TSR determines the turbine power coefficient (Cp). The Cp of each VG position variation in the TSR range of 0.5, 1, 1.5, 2, and 2.5 is provided in Table 1 below.

Table 1. Cm and Cp average of the turbines with VG

TSR	**10% Variation**		**15% Variation**		**20% Variation**		**25% Variation**		**30% Variation**	
	Average Cm	**Cp**	**Cm Average**	**Cp**	**Cm Average**	**Cp**	**Cm Average**	**Cp**	**Cm Average**	**Cp**
0.5	0.125	0.063	0.127	0.064	0.127	0.064	0.128	0.064	0.129	0.065
1.0	0.240	0.240	0.245	0.245	0.249	0.249	0.252	0.252	0.254	0.254
1.5	0.252	0.378	0.298	0.447	0.299	0.449	0.301	0.451	0.302	0.452
2.0	0.175	0.349	0.190	0.380	0.190	0.381	0.192	0.383	0.193	0.385
2.5	0.084	0.210	0.085	0.213	0.087	0.218	0.094	0.235	0.090	0.226

The simulation results show that the VG positions affect the turbine performance. The most effective position for the VG is at x/c = 30% from the leading edge. However, there is only a minimal difference with the 25% position, which can be considered to have a similar result. This finding aligns with a previous study by Yan et al.[35) , which also suggested that x/c = 25% is the optimal position for VG. The highest Cp of 0.452 is obtained by a 30% position at a TSR of 1.5. Figure 9 shows an increase of about 30% from the turbine without VG addition.

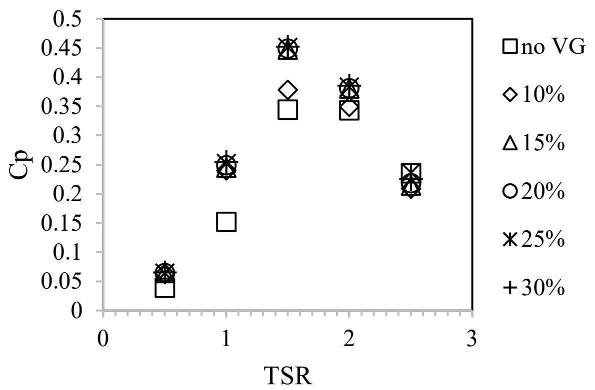


Fig. 9: Cp vs TSR

These data confirm that adding VG would increase the resulting Cp. This is because the VG creates a vortex or vortices. The fluid velocity near the surface will be faster in turbulent flow than under laminar flow. If the fluid velocity is higher, the kinetic energy of the fluid will also be higher, allowing the fluid to resist the adverse pressure that causes flow separation. By canceling the flow separation, the turbine blade can delay the stall condition, increasing the lift force that will improve the Cm of the turbine.

3.3 Flow characteristics

Figure 10 shows the kinetic energy flow visualization near the turbine blades. The visualization is taken at 0° rotation angle and TSR of 1.0. The visualization was taken at a rotation angle of 0° and a TSR (tip speed ratio) of 1.0. Turbulence refers to the irregular motion of particles in a fluid flow, making it challenging to predict. High turbulence intensity leads to increased turbulent velocity. The visualization confirms that the VG turbine generated superior turbulent kinetic energy, indicated by a reddish color, especially on the airfoil surface with VG attachment. When comparing variations at x/c of 10%, 15%, 20%, and 25%, the turbulent contour is largest at 30% variation. This aligns with the obtained power coefficient value, where the highest increase occurs at the x/c = 30% position variation.

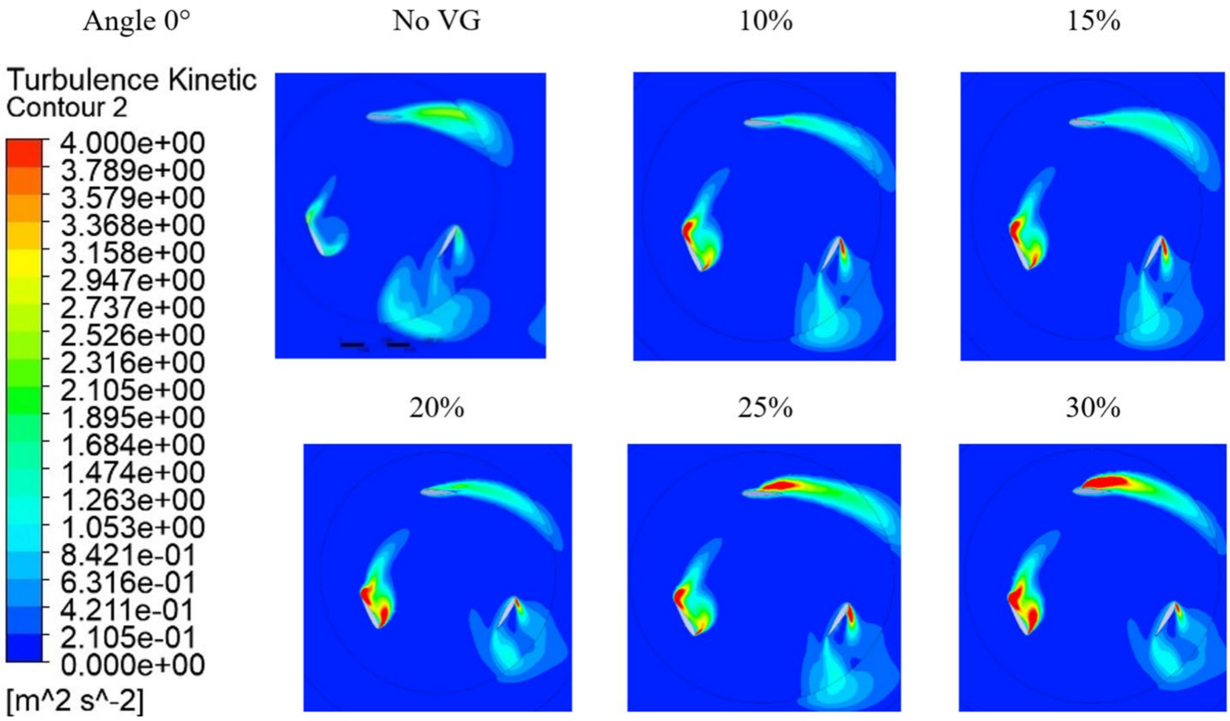


Fig. 10: Kinetic energy visualization at 0° rotation angle for each chord length variation.

Figure 11 shows the kinetic energy flow for the maximum Cm values when the blades rotate at 70°. When the blades are equipped with the VGs, they induce a swirl flow at the airfoil boundary layer, as depicted in Fig. 11 for nearly all VGs configurations. This swirl flow increases the kinetic energy of the existing laminar flow near the airfoil surface, promoting the development of turbulent flow. This delay in flow separation across changes in angle of attack also delays stall occurrence, allowing the airfoil to generate more lift force while reducing drag force[28]. Additionally, Figure 11 demonstrates that as the x/c position increases, turbulence kinetic energy also increases, especially in the area near the airfoil and around the VGs. This finding aligns with previous research, indicating that wind turbine performance can be enhanced by preventing stalls[28-31]. The VGs can manipulate the flow, and their effectiveness is influenced by their geometric parameters. Our findings suggest that the optimal x/c position is 30%. These results imply that this wind turbine design is most suitable for low wind speed turbines and is well-suited for deployment in urban areas.

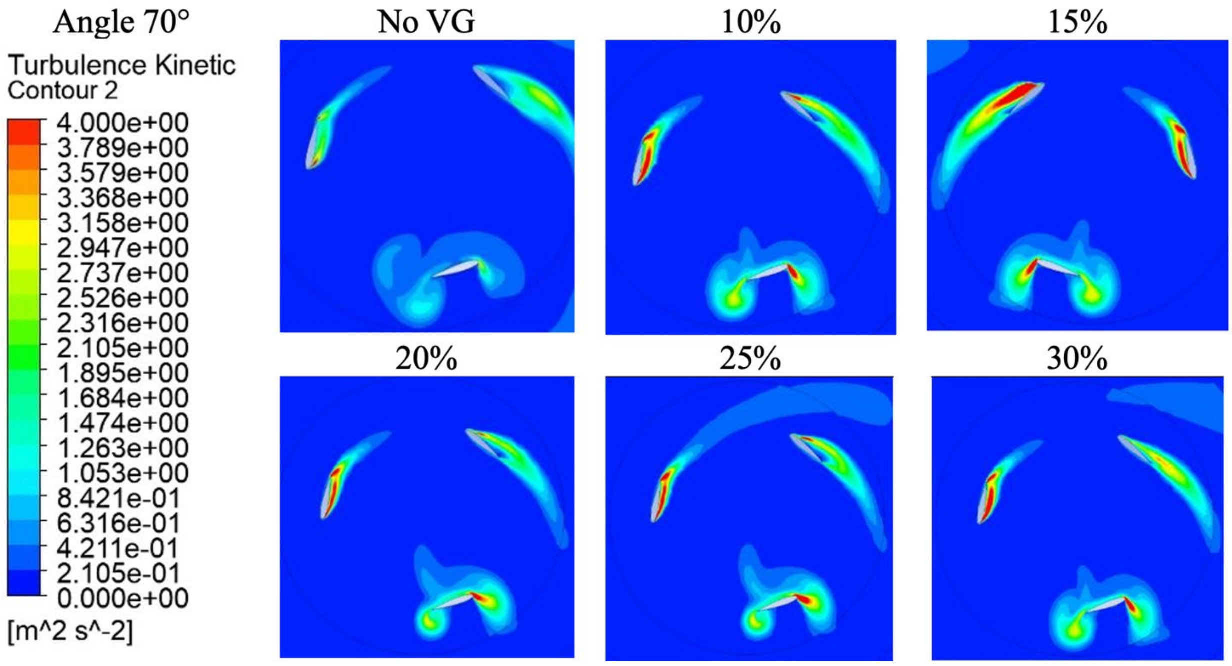


Fig. 11: Kinetic energy visualization at 70° rotation angle for each chord length variation.

4. Conclusion

In this study, a three-dimensional simulation was conducted to assess the impact of straight rectangular vortex generators (VGs) on the performance of Darrieus H-rotor wind turbine blades. The study also evaluated a rotor turbine without VGs to compare the improvements achieved by adding VGs. The VGs were attached at five different chordwise (x/c) positions to determine the most effective attachment position.

The simulation results indicate that incorporating straight rectangular VGs enhances the Cm and Cp of the wind turbine. The wind turbine with VGs achieved a peak Cp of about 30% higher than that without VGs. This maximum Cp was observed at a TSR of 1.5 with the VGs attached at x/c = 30%. Flow visualization revealed that the VGs generated vortices that increased the turbulent kinetic energy of the flow, thereby delaying the stall of the blades.

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