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Opportunities for Utilizing Vortex Generators on Vertical Axis Ocean Current Turbines: A Review

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Abstract. Researchers have studied vertical axis turbines (VATs) for their low power efficiency, focusing on the turbine blades, selecting suitable airfoils, modifying the original airfoil shape, and adding other devices to the blades. The proposed method is to add a passive vortex generator device, which generates vortex flow to delay the separation flow at the surface, thereby increasing efficiency. Initially, VGs were used on aircraft wings to improve stability and performance efficiency; later, they were developed for other transport industries, such as cars, trucks, high-speed trains, and ships. In the renewable energy sector, VGs are used to improve turbine performance and efficiency. The research aims to obtain comprehensive information on the effect of using VG on vertical-axis ocean current turbines. To achieve this goal, we collected articles related to VG, reviewed the published articles on VG research on wind turbines and marine current turbines, then analysed the research results and determined the results based on the research methodology. At present, research has been developed to obtain the shape, dimension, and configuration of VG suitable for a vertical-axis ocean current turbine. The research is carried out in stages, which currently prioritize the shape and VG dimensions used in VAT with NACA 0021 blades, followed by the development of VG configuration research on VAT blades.

1 Introduction

The Indonesian government targets carbon net zero emissions (NZE) to be obtained by 2060. One potential source of renewable energy in Indonesia is hydrokinetic energy which comes from ocean tidal currents. The potential for marine renewable energy in Indonesia has prompted researchers to create marine energy conversion devices that are appropriate for Indonesian marine environments. The marine energy conversion device is a low-cost, basic device that can be submerged on the seabed, suspended from a bridge or jetty pillar, and mounted floating. There are various types of marine current turbines, such as vertical and horizontal axis turbines, each of which has advantages and disadvantages. Researchers have researched horizontal axis turbines (HATs) to convert wind and hydrokinetic energy so that more and more HATs are created, while vertical axis turbines (VATs) have weaknesses, especially in very low turbine performance efficiency, poor self-starting, cavitation, and vibration [1,2].

In the early 2000s, researchers made efforts to create vertical-axis current turbines to enhance overall turbine performance in wind and ocean current turbines, emphasising turbine rotors. The primary component of an ocean current turbine is the rotor, which transforms the hydrokinetic energy of flowing ocean currents into mechanical energy that revolves on an axis and is then transformed into electrical energy. Among the various aspects of turbine rotor development and research are alterations to the angle of attack (AoA), adjustments to the pitch and blade angles, modifications to the foil's form based on standard foil, and the addition of a rotor blade component.

A lot of research has been done to improve the self-starting capability of vertical axis ocean current turbines (VAOTs). Some of the modifications are done by changing the geometry of the turbine blade, such as variable pitch control [3,4], inclined blade [5], changes of the angle blade [6], addition of wells rotor [7], addition of winglets [8–10], and helical blade [11]. While others employ an augmentation device to change the fluid flow behavior around the VAOT, such as flow disturbance [12,13]; flow deflector [14]; tubercle [15,16]; and vortex generator (VG) which will be analyzed in the present study.

VG was first used in the study of aerodynamics, particularly as it related to aeroplane wings. During the Second World War, VG was installed on military aircraft wings in the early 1940s to maximize airflow, boost lift force, and enhance aerodynamic performance while the aircraft was in flight. Compared to aircraft without VG, it flies at a low speed and enhances landing and take-off conditions, reducing the need for a lengthy runway.

Adding a VG device to the turbine blades is one of the more intensely developed and innovative methods used to increase the efficiency of VAT performance. This is novel; earlier studies on the use of VG had been conducted on a HAT, while there was still a shortage of studies on horizontal axis wind turbines (HAWTs), but vertical axis wind turbines VAWTs, horizontal axis ocean current turbines (HAOTs) and VAOTs. VG is a mechanical component in the shape of a tiny fin that is applied to the surface of an object or foil-shaped profile. It creates a vortex flow that delays the separation of the flow and, thus, delays stall (loss of lift). Since passive VG does not need the power to move or activate it.

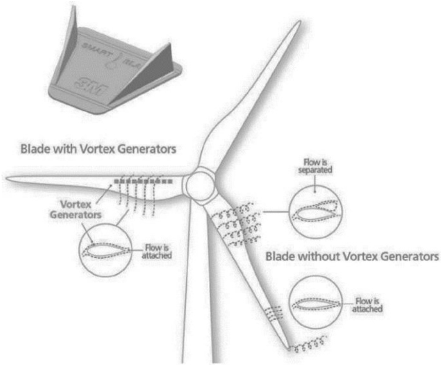


Fig. 1. VG application to flow control on horizontal axis wind turbine blades [17]

VG is very simple and cost-effective without additional external energy. This causes the application of VG on HAWT to be very good (Fig. 1). The VG consists of a pair of triangular or rectangular fins that point toward the free-flow inlet and protrude from the surface of the airfoil. The VG induces upwash and downwash wake regions via flow vortices generated by momentum mixing between the near-wall flow and the outer flow, then significantly enhanced by efficient momentum transfer to the surface so that the boundary layer flow is successfully re-energized by the VG to overcome higher adverse pressure gradients and also effectively suppress separated flow [18]. The resulting lifting force can delay stalling and reduce drag.

When compared with non-VG designs, some studies show that VG reduces drag and increases lift by 6%, however, the findings of these studies cannot be generalized. The effect of VG depends on the reactivity of the airfoil to surface roughness, and also because sea water has a density 1000 times greater than air, the ocean current turbine used in this research will be used to develop to replace the VAWT in previous research.

In addition to the many benefits VAOTs offers, there are a number of drawbacks that VG must address. This work offers an analysis of earlier VG research that was conducted on wind turbines with both vertical and horizontal axes. What if VG was particularly applied to the NACA 0021 airfoil on the VAOTs. This would allow research to address the issues surrounding the application of VG technology on VAOTs.

2 Vertical axis turbine principles

Several types of open-flow devices can be used to absorb ocean current energy; some are in the form of windmills with modifications to the shape of the blades to adapt to differences in fluid properties. However, technically new designs, derived from wind-powered rotors, are likely to achieve sufficient effectiveness and performance to be implemented in future scenarios that utilize large amounts of ocean current energy. In general, for open flow water turbine, some sources call them flow turbines.

The main types of water flow turbines are based on the turbine rotation axis such as HAOT and VAOT (passive variable pitch or fixed pitch). This turbine can be combined with a floating system, a system submerged on the seabed, and an intermediate system. The ocean current turbine with a monopile structure installed on the seabed is a first-generation ocean current electricity generation system which has the advantage of being installed in relatively shallow waters (around 20 to 40 meters deep).

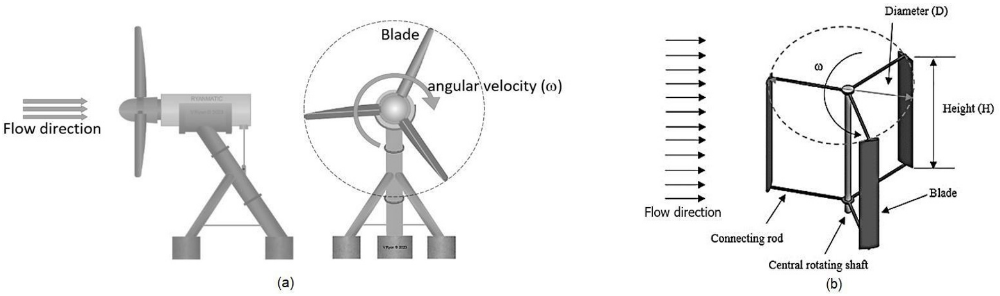


Fig. 2. the comparison between (a) horizontal axis ocean current turbines (HAOT), (b) vertical axis ocean current turbine (VAOT) [19]

HAOT and VAOT use the kinetic energy of ocean currents to drive an electric generator but have several differences. The main difference between HAOT and VAOT lies in when the turbine receives flow, where in HAOT the flow direction is parallel to the turbine shaft axis (Fig. 2.(a)), and in VAOT the flow direction is perpendicular to the turbine shaft axis (Fig. 2.(b)) In the introduction, it was explained that VAOT has very basic weaknesses compared to HAOT, although it also has several advantages. Some disadvantages of VAOT include low-performance efficiency, poor self-starting, low tip speed ratio (TSR), vibration and cavitation, but also VAOT has advantages including, being able to accept flow from all directions, easy maintenance, low cost and simple construction.

There are fundamental physical principles that all VATs share, as seen in Figure 3., the force and velocity vectors of the VAT blade are visible. The tangential velocity U and the inlet velocity V_∞ combine to give the resultant velocity W when the blade rotates counter-clockwise. The resulting speed, as shown in Figure 2 lift and drag forces, as well as normal and tangential forces, are components of the resultant speed and AoA, so that is what determines the force acting on the angle blade angle. can be written as:

$$\vec{W} = \vec{U} + \vec{V}_{\infty} \quad (1)$$

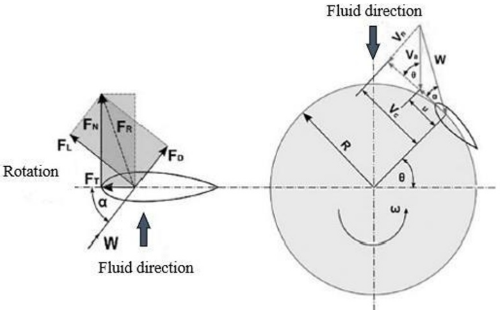


Fig. 3. Force and velocity vectors of a VAT [20]

Figure 4. shows the change in a single blade's speed vector over a single rotation. Even with constant rotating speed and wind speed, the resultant velocity and AoA vary in both direction and amplitude with azimuth angle. The upstream half-cycle ($0^\circ < \theta < 180^\circ$) of the bar is positive, whereas the downstream half-cycle ($180^\circ < \theta < 360^\circ$) is negative. Cross-flow devices, or VAWTs, have aerodynamics that are more complicated than axial-flow HAWTs in the following ways.

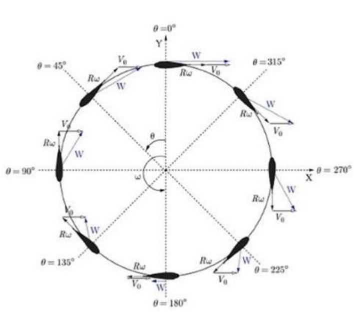


Fig. 4. Velocity vectors at different azimuth angles [21]

The double-multiple stream-tube (DMST) model is based on the MS (multi-stream) concept, which divides the actuator disk into two pieces, upstream and downstream. Figure 5 depicts the DMST model diagram. This model assumes a constant speed at the actuator disc and a central pressure equal to the asymptotic pressure. The upstream disk is governed by Bernoulli's equation. This model has various drawbacks, including assuming constant flow and failing to characterize flow behavior throughout the full region. However, the advantages of this model for evaluating the performance of vertical-axis wind turbines include its simplicity and short computation time.

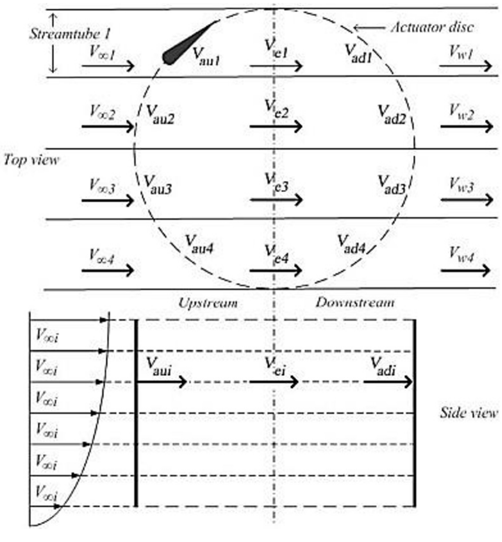


Fig. 5. DMST diagram [22]

According to Figure 5., the fluid flow velocity is not disturbed by $V_{\infty i}$ which decreases in the axial direction. Additionally, V_{aui} reduces upstream speed. When the flow reaches the center of the disk, it has the equilibrium velocity V_{ei} and downstream it becomes V_{adi}. The mentioned speed equations are shown below.

$$V_{aui} = auV_{\infty i} \tag{2}$$

$$V_{ei} = (au-1)V_{\infty i} \tag{3}$$

$$V_{adi} = (2au-1)V_{\infty i} \tag{4}$$

The Tip Speed Ratio (TSR) is an incredibly significant aspect of turbine design. TSR refers to the ratio of wind speed to the speed of the turbine blade tips. The blade tip speed could be computed as ω (omega) times R (radius), where ω is the rotor's rotational speed in radians/second and R is the rotor radius in meters. Therefore, we can also write,

$$TSR\ (\lambda) = \frac{R.\omega}{V_{in}} \tag{5}$$

Power coefficient (Cp), a dimensionless parameter, is defined as the ratio between the maximum output power and the kinetic energy flux passing through the front of the turbine, where ρ (kg/m^3) is the air density, $V\infty$ (m/s) is the wind speed, and A (m^2) represents the swept area.

$$C_p = \frac{P}{\frac{1}{2}\rho A V_\infty^3} \tag{6}$$

Power (P) is calculated by multiplying the turbine's torque by the angular speed. The following equations are used to compute solidity, which is a significant aspect in rotor design and analyzing turbine efficiency;

$$P = \tau\ \omega \tag{7}$$

The variable n represents the number of blades, c represents the length of the blade series, and R is the rotor radius

$$\sigma = \frac{nc}{R} \tag{8}$$

3 Vortex generator working principle

Figure 6. illustrates the air flow on the airfoil surface with and without VG, where the fast-moving fluid delays the flow separation and expands into thinner waves, and the VG generates a drag force, so that the installation success depends on a larger reduction. pulling force. Airflow separation causes significant resistance and can be reduced by installing a VG. The energy consumed by the VG causes the drag force to be distributed to the boundary layer, thereby delaying the separation of the air flow and its eventual stalling, which has advantages [23].

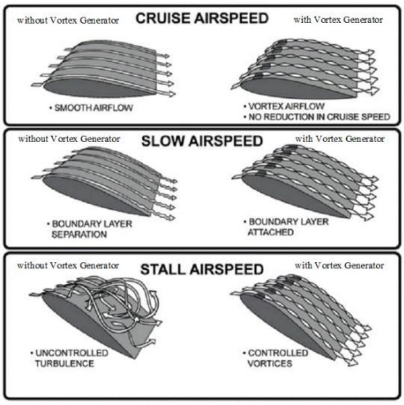


Fig. 6. Flow separation behind the vortex generator [24].

The VGs are positioned on a longitudinal line between two and fifteen percent of the chord length. VG controls fluid flow over the upper surface of the airfoil surface by generating vortices that energize the boundary layer. This results in improved performance and control at low fluid speeds up to critical angles of attack. VG creates small vortices in the fluid flow above the airfoil. These vortices provide energy to the boundary layer which usuallypools on the surface of the airfoil, so that the energy of the boundary layer is able to withstand flow separation compared to the stagnant boundary layer. without VG. The airflow attached to the airfoil surface provides better surface control and increases lift at lower speeds

These factors influence airfoil performance and can help reduce drag loss while maximizing overall lift-to-drag (L/D) improvement. Geometric VG variables include height, shape, orientation, one- or two-line layout, etc. [25].

3.1 Vortex generators profile

VGs can be manufactured in a variety of forms, including rectangular, triangular, round, airfoil, and trapezoidal, as seen in Figure 7. Because of the various longitudinal vortex strengths, different shapes create variable separation suppression effects. Prior research has mostly concentrated on rectangular, triangular, and trapezoidal VGs. Godard et al. [26] utilized PIV to measure the flow field impacted by VGs of various shapes and configurations and discovered that counter-rotating triangular VGs functioned the best and created the least resistance. Li et al. (2015) [27] researched the influence of three forms on the performance of the DU97-W-300 and discovered that while all three shapes contributed equally to lift force, the difference in drag force was substantial. Among the VGs, the triangular-shaped VG had the highest lift-to-drag ratio. According to Fouatih et al. (2016) [28], the triangular VG outperforms the rectangular type in terms of enhancing lift force and minimizing drag force, with a 21% gain in coefficient lift. However, not all researchers agree on this impact, necessitating further extensive investigation.

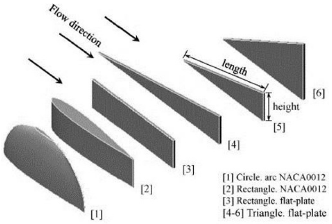


Fig. 7. Profile of VGs [29]

3.2 Vortex generator position

Figure 8. shows an airfoil device with VG facing each other, where the airfoil has a chord length, *C*; span length, *S*; position VG, *x/C*; and VG geometry includes, height, *h/C*; Length, l/hour; angle, β; centre distance between VG pairs, *p/h*; tip distance between VG, *f/h*; rear distance between VG, *r/h*.

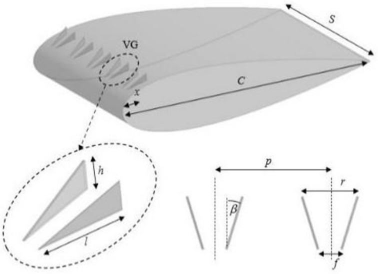


Fig. 8. Position of a VGs single row [30]

VG's position may be represented as x/c, where c is the chord's length and x is the chord's direction. After testing two settings in a wind tunnel, x/c = 0.2 and 0.3, researchers conducted a study of the position of VG, found discovered that x/c = 0.2 improved stall AoA and raised coefficient lift from 1.55 to 1.97 [28], on the DU97-W-300, x/c = 0.2 shows the ideal lift force as well as the top and bottom drag forces, analyzed to determine the effect of location on the performance of the DU91-W2-250 airfoil and make sure x/c = 0.2 is the ideal position [29]. The National Technical University of Athens (NTUA) states that the most efficient VG reversal at x/c = 0.2 in.

3.3 Vortex generator configurations

VG orientations can be either counter-rotating or co-rotating to result from low-momentum fluid upward and high-momentum fluid downward between two adjacent VGs, co-rotating orientations create co-rotating longitudinal vortices (Fig. 9. (a)). Closely separated vortices lose their efficiency and persistence due to conflicting spinning orientations. Being able to keep the vortices close to the surface is the main benefit of co-rotating VGs. Figure 9. (b) illustrates how the upward and downward momentum transports are separated by the counter-rotating VGs. While the low-momentum part is provided uphill to the free stream between two VGs, the high-momentum part is sent downhill to the wall surrounding each VG's symmetry plane [30]. Because it transfers momentum in a non-conflicting way, the counter-rotating kind is theoretically more effective. Researchers have validated this idea through investigations on airfoil surfaces, where counter-rotating VGs exhibit double the efficiency of co-rotating VGs.

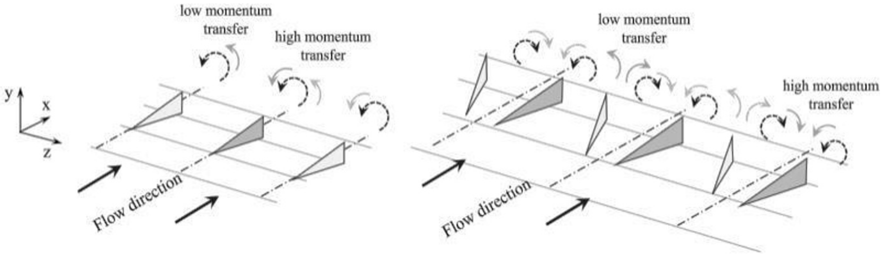
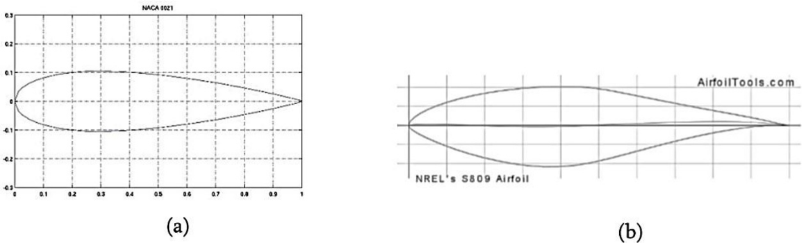


Fig. 9. (a) Co-rotating and (b) counter-rotating configuration of VGs, [24]

According to NTUA [31], co-rotating VGs causes the bubble separation height and length to increase, thereby disrupting airfoil performance. To maintain boundary layer flow at the separation boundary, [24] positioned the device on the impact surface. They then conducted experiments using a heated film sensor, a skin friction measuring device, and a stereoscopic Particle Image Velocimetry (PIV). Although co-rotation vortices exhibit more stable momentum transfer, counter-rotation triangular VGs are more successful in reducing drag [33,34].

4 Influence VGs on airfoil shape

Airfoils are divided into two types, namely symmetrical (Fig. 10**.** (a)) and asymmetrical airfoils (Fig. 10. (b)). In vertical turbine applications, the addition of VG impacts turbine performance. Researchers have carried out many investigations to determine the influence between airfoil types, symmetrical airfoils, NACA 0015, NACA 0018, NACA 0021; asymmetrical airfoils, NACA 63(3)618, DU97-W300, DU17-DBD25, DU93-W210, National Renewable Energy Laboratory (NREL) S1210, S809, etc. shown in Table 1.



(a) (b)

Fig. 10. airfoil shapes (a) symmetrical airfoil, NACA 0021, (b) asymmetrical airfoils NREL's S809 [35]

In this focusing research, the focus is the VAOT (H-Darrieus type) with symmetrical blades NACA 0021 which has several advantages such as, having a maximum thickness of 21% of the chord length, good stability, suitable for high rotation, and working at low Reynolds numbers increasing lift force and reducing drag force [36]. The Vg shapes used on turbine blades include triangle, rectangle, trapezoid. VG Position on the blade surface 5%-25% of the chord length and counter-rotating configuration.

Table 1. Summary of research on the influence of vortex generators on turbine blade types

Investigator, year	**Airfoil**	**VGs Shape**	**VGs position of chord length**	**Lift increment**	**Stall angle increment**
Yan, et al. 2019 [37]	Naca 0018 **(VAWT)**	Triangle, Rectangular	15%, 20%, 22%, 25%	37.5%	25° – 30°
De Tavernier et al., 2021 [16]	DU17-DBD25 **(VAWT)**	Triangle	20% - 40%	30% - 40%	12° – 22°
Satrio D, et al., 2023 (Manuscript) [30]	Naca 0021 **(VAOT)**	Triangle	1%, 2.5%	8%	20°-30°
Manolesos M, et al., 2023 [38]	NACA63(3) 618, DU97-W300 **(HAOT)**	Triangle, Rectangular	30%	34% 17.6%	10°-25°
Kundu P, et al., 2019 [39]	S1210 **(HAOT)**	Triangle	12% - 21.4%	11.44%	10° – 12°
Alber J, et al., 2022 [40]	NACA63(3) 618, DU97-W300 **(HAWT)**	Triangle	30% - 50% 5% - 10%	increase	-
Parra H, et al., 2023 [41]	S822 **(HAWT)**	used shapes present in animals	-	-	Reduction vibration
Zhu C, et al., 2019 [42]	DU97-W300 **(HAWT)**	Triangle	10% - 40%	40%	-
Wang H, et al., 2017 [43]	NREL S809 **(HAWT)**	Rectangular	10% - 40%	49.8%	18°
Chillon S, et al., 2020 [44]	DU97-W300 **(HAWT)**	Triangle	19.5%	62%	12° – 18.18°
Li X, et al., 2019 [45]	DU93-W210 **(HAWT)**	Triangle	21%	48.77%	16° - 18°
Chng L, et al., 2022 [46]	SIT250 **(HAWT)**	Triangle	30%	30%	-

Moon H-Gi, et al., 2021 [47]	DU-X5 DU-X0 DU-X05 DU-X **(HAWT)**	Trapezium	10%-30% S, 20%	2.8%	-
Tiwari N, et al., 2023 [48]	DU96-W180 **(HAWT)**	Triangle	20%	13% -17%	-
Chen H, 2021 [49]	Bell A821201 **(HAWT)**	Triangle	20%	62.23%	18° - 20°
C. Zhu et al., 2019 [50]	NREL S809 **(HAWT)**	Rectangular	15%, 40%, 15% and 40%	40%	17.2º – 18.6º
Jiang et al., 2022 [51]	NREL S809 **(HAWT)**	Triangle	20%	4.4%	-
C. Zhu et al., 2021 [52]	NREL S809 NREL Phase V **(HAWT)**	Rectangular	20%	57%	15º
Suarez et al., 2016 [53]	NREL S809 **(HAWT)**	Rod Vortex Generator (RVG)	35%, 40%, 45%, 55%	11%	12.2º
Zhao et al., 2016 [54]	U91-W2-250 **(HAWT)**	Triangle	32.2%	7.9%	20º

The summary of Table 1. shows that the VG position is between 5% and 30% of the chord length, which is widely used in research for triangular and rectangular VG shapes. Adding VGs creates increased lift, reduced drag, delayed stall, and reduced vibration. HAWT and HAOT mostly use turbines with asymmetrical blades, however VAWT and VAOT tend to use symmetrical blades.

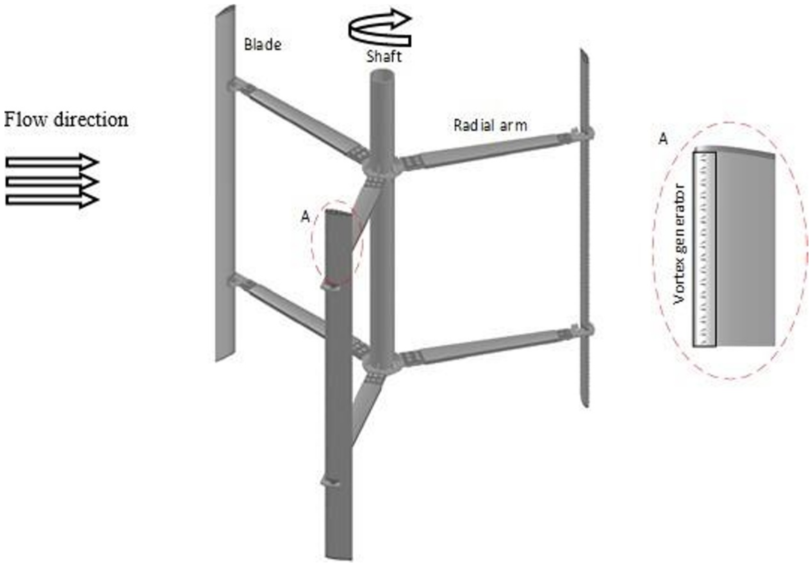
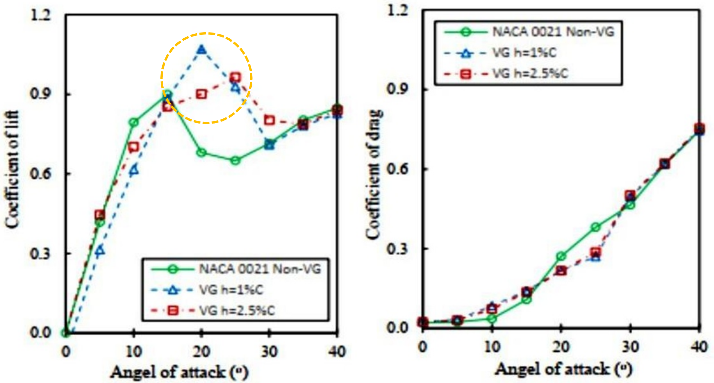


Fig. 11. Vertical axis current ocean turbine, H-darrieus type with vortex generators

Figure 11. shows a VAOT H-Darrieus type with VGs, where the VGs are positioned on the blade surface in the couples of VG configurations along the blade span. The dimensions, position, configuration, and type of airfoil determine the success of adding a vortex generator in producing vortex flow with stall delay, increasing lift, and reducing drag. According to Paraschivoiu (2002) [55], the Darrieus turbine, which powers the VAOT, is a lift-driven device. Improving lift performance is expected to boost the turbine's efficiency and ability to self-start on its own.

5 Discussion

The results of research conducted between Yan (2019) [37] and Satrio (2023) [30] using symmetrical airfoils of the Naca series type showed that there was a stall delay whose value was almost the same in the range of 20°-30° and a different increase in lift force due to differences in VGs positions during the research. This proves that the use of VGs in VAT can improve turbine performance.



(a) (b)

Fig. 12. Numerical variations of (a) coefficient of lift, (b) coefficient of drag and coefficient of lift and drag in the α range of 0°-40° [30]

Figure 12. shows the lift and drag forces performance was re-evaluated with the addition of VG, when compared with the results without VG, the performance results of the NACA 0021 blade equipped with VG showed an improvement. The lift coefficient increases up to 20% for the VG configuration with a height of 1% ofthe chord length, C (1%C) at an angle of attack of 20°. For a VG height of 2.5%C, the lift coefficient increases to8%. The stall angle is also slowed from an angle of attack of 20° to 25° for a VG with a height of 1%C and from 20° to 30° for a VG with a height of 2.5%C.

Figure 13. shows, the NACA 0018 airfoil, the optimal VG position is at a chord length of 20% along the suction side of the airfoil with a rectangular shape and a mounting angle of 16°. The stall angle is delayed to 16° from 14° with MVG installation. The maximum lift force increases by 37.5% from 0.96 to 1.32, while the drag force decreases from 0.178 to 0.137 at post-stall conditions α=18°.

The VG effect is sensitive to geometry, profile, height and configuration, distance, and angle of incidence [56]. There are two types of VG arrangements, namely co-rotating and counter-rotating VGs, where two vortices roll in the same direction and are released from two adjacent co-rotating VGs. For wind turbines, the counter-rotating VG array is therefore recommended [57]. Various studies have examined the impact of height on various airfoils. The findings indicate that VGs with h = 0.2–0.5 δ (where h is the VG height and δ is the airfoil thickness) are better [58] since larger VGs typically result in increased drag but only marginally improve flow control [59].

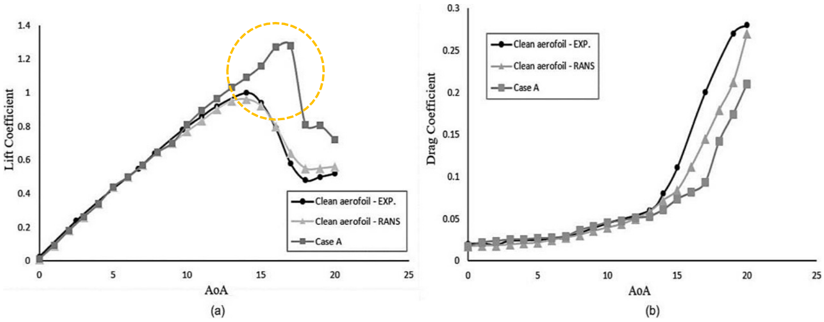


Fig. 13. Airfoil performance at different angles of attack: (a) lift coefficient and (b) drag coefficient [37]

The airflow passes through the VG at an incident angle, and a vortex is released from the leading edge of the VG. The vortex flow mixes the high-energy air flow above the boundary layer with the low-energy air flow within the boundary layer; This mixing amplifies the fluid's momentum and energy near the walls, allowing the fluid to move further along the blade surface, delaying airflow separation, and increasing lift.

Studies have shown that VG successfully delays airflow separation and significantly increases airfoil lift, as well as turbine performance and Cp values for HAWT. Another major cause of the improved performance of HAWT turbines, besides efficient vorticity suppression, is the reduced sensitivity of the airfoil to roughness. Studies regarding the impact of VGs on VAWT are still inadequate because it is not known how VGs affect dynamic stopping. VG technology is a promising and successful technique in optimizing VAWT performance in the future, so it needs to be explored thoroughly and comprehensively.

6 Conclusions

A common phenomenon in turbines is airflow separation, where VGs are airflow control device that are useful for improving turbine performance. VGs are generally used in the aviation sector, but VG is not widely used in turbines. As discussed in this paper, several researchers have estimated the possibility of using VG to improve VAWT performance.

Optimal design of geometric parameters including profile, height, position, VG array configuration and row layout can significantly improve the performance of an airfoil or wind turbine. Many researchers have investigated the VG principle in controlling separate flow in airfoils, based on symmetric, asymmetric and modified airfoils. VG can significantly increase the turbine power output based on experiments and CFD analysis methods.

The increase in performance is more visible in turbine experiments with the addition of VG to the blades. Conclusions and potential research directions that require further research attention can be summarized as follows.

1. The profile and layout effects still require further development investigation.
2. VG design optimization on VAOT is still lacking. In contrast to airfoils, rotating VAT blades exhibit strong 3D aerodynamic characteristics. These effects on VG performance should be investigated for optimal design.
3. The CFD approach combined with parametric VG modelling is a potential method to improve the understanding of VG principles in large-scale full-blade wind turbines. Further efforts should be made on parametric modelling.
4. Dynamic stall is an aerodynamic feature of VAWT that occurs at low TSR. As a result, more study is needed to determine the usefulness of VGs in VAWT.
5. Ocean current turbines can encounter the same challenges in numerical analysis by employing the same type of rotor (horizontal axis turbine or vertical axis turbine). These problems include static disturbances, dynamic disturbances, 3D flow fields, and so on.

Thus, research on VGs influences the performance of ocean current turbines is also meaningful. The topic of this research is VAOT, and close to that topic is VAWT; Therefore, research is focused on VAWT even though the fluid properties are not the same, whereas wind energy has high speed and low density, but ocean current energy has low speed but high density, so this will affect the lift and drag coefficients.

Currently, there are still few research papers on the use of VGs, therefore, future research will examine the impact of VAOTs in more detail to ensure their superiority with the addition of VGs to improve performance. The use of VGs has a great opportunity to correct the shortcomings that characterize VAOTs.

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