Jurnal Kejuruteraan 36(3) 2024: 1079–1090
https://doi.org/10.17576/jkukm-2024-36(3)-20

Experimental Investigation into the Effects of Flat Plate Guiding Walls on the Performance of Vertical Axis Wind Turbine

Roaa Ansaf[a], Mohamed Mohamed Elsakka[b], Khaled Almohammadi[c], Ahmed Fazlizan[d], Mohammad Rasidi Rasani[a] & Zambri Harun[a*]

[a] *Mechanical and Manufacturing Engineering Department Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia 43600 Bangi, Malaysia*

[b] *Mechanical Power Engineering Department Faculty of Engineering, University of Port Said, Port Said, Egypt*

[c] *Mechanical Engineering Department Faculty of Engineering, University of Taibah, Madinah, Saudi Arabia*

[d] *Solar Energy Research Institute (SERI) Universiti Kebangsaan Malaysia, 43600 Bangi, Malaysia*

**Corresponding author: zambri@ukm.edu.my*

Received 15 May 2023, Received in revised form 2 November 2023
Accepted 2 December 2023, Available online 30 May 2024

ABSTRACT

Vertical axis wind turbines (VAWTs) are expected to have good market potential soon. However, it suffers from relatively lower performance in contrast with the market-leading horizontal axis wind turbine (HAWT). To overcome the disadvantages of VAWTs and improve their performance, this study aims to experimentally investigate the effect of flat plate guiding walls on the performance of VAWTS. The experimental study was carried out in an open-jet wind tunnel with an airflow speed range between 8 - 12 m/s and a different tip speed ratio (TSR). The rotor is of NACA0021 with three blades, 50 mm length, 300 mm diameter and 300 mm height. The guiding wall row is composed of six flat plates. The results show that a straight-bladed vertical axis wind turbine surrounded by guiding walls could be self-starting at the wind velocity of 4 m/s which is lower than the wind speed required for the turbine without guiding plates is about 5 m/s. The rotational speed increases for all test conditions with the increase in wind velocity. The power coefficient (Cp) increases with TSR (λ) until reaching its peak at experimental results for all tests. The power coefficient of the turbine reaches its highest value Cp = 0.25 at λ = 1.79 at 12 m/s with the guiding walls. The optimal Cp using the fixed guiding walls shows about 23% improvement at 8 m/s in contrast with the optimal Cp of the reference turbine without the guiding walls.

Keywords: Wind energy; VAWT; Guiding walls; Darrieus wind turbine; TSR.

INTRODUCTION

Wind energy is becoming more common as an alternative energy source to meet the world's growing energy demands and necessities due to depleting fossil fuels. The use of wind energy can be relied upon to reduce fossil fuels. Wind turbines are devices that convert wind energy into mechanical and later convert it to electrical by generators (Manyonge et al. 2012). It is an important non-conventional energy source for a variety of uses. Wind turbines are economically and environmentally friendly (Masseran et al. 2012).

Engineers have successfully developed vertical axis designs that can also effectively use aerodynamic lift. The design proposed by French engineer Darrieus in 1925 was considered a promising concept for modern wind turbines. The use of vertical axis wind turbines is common in electrical energy production because their power coefficient is high. Different types of vertical wind turbines, such as the Savonius, Darrieus, crossflow and helical wind turbines are used and studied in the literature (Abdalkarem et al.

2023; Cho et al. 2017; Hashem & Zhu 2021; Seralathan et al. 2019; Zhao et al. 2020). These turbines are classified primarily based on aerodynamic forces. The Darrieus VAWT is a lift-based turbine whose aerodynamic force is vertical to the inlet flow. The Darrieus wind turbines have been proposed and adopted by researchers and manufacturers alike (Ramlee et al. 2020; Tjiu et al. 2015) to achieve higher efficiency for the VAWT. The Darrieus turbine has the highest efficiency among the other VAWTs, but does not have a self-start capability and low starting torque (Bhutta et al. 2012) but it can provide reasonably good efficiency at high rotational speed (Shankar 1979).

Several attempts have been made by researchers to improve the VAWT efficiency by adding external parts augmentation device such as guide vanes, deflectors, stators, or wind lenses in several studies (Chong et al. 2014; Dessoky et al. 2019, 2021; El-Askary et al. 2020) modifying on the configuration of vertical axis wind turbine as reported by Andrews et al. (2019) and Turbine et al. (2021) or on blades as reviewed by El-Askary et al. (2020), Ismail & Vijayaraghavan (2015) and Khai et al. (2022). Parneix et al. (2016) and Zanforlin & Nishino (2016) studied the benefits aerodynamic interaction between the VAWTs. Zhang et al. (2019) studied the aerodynamic effect of adding a winglet to VAWT blades, while Mohamed (2016) introduced an innovative design of the lift VAWTs, where every blade in the turbine is constructed by two airfoils. Hashem & Mohamed (2018) carried out on 24 novel airfoil shapes, both symmetric and non-symmetric, which were used as sectional profiles. Mitchell et al. (2021) predicted the aerodynamic characteristics of a new vented airfoil based on the well-established NACA0012 profile.

The design and manufacturing new blades are often expensive and long-term endeavor. Installation of guiding walls (GW), deflectors, stators, or wind lenses and others are the simple and practical methods that have been found beneficial in several studies (Dessoky et al. 2021; Kim & Gharib 2013). The efficiency of VAWT can be significantly improved by using flat plate GWs, which are assembled and economical devices. The purpose of introducing GWs was to control the flow of both upstream and downstream for the rotor (Grönman et al. 2018).

The use of GW system around a Darrieus turbine can provide two benefits as reported: the first one is the enhancement of the self-starting ability, and the second one is the improvement of the overall performance. The design of the guiding walls has greatly influenced the overall performance of the turbine. Korprasertsak & Leephakpreeda (2016) studied the effect of wind booster on efficiency of the Savonius 2-bladed turbine and it is increased up to 55% coefficient of power by selecting optimal design variables: the number, shape, and leading angle of the guide vane.

Guiding walls flat plate increase the wind turbine efficiency by directing the wind in the right direction. Takao and other researchers worked on improving the performance parameters with the addition of guiding walls flat plates around the turbine. As a result, they observed an increase in power coefficient was approximately 1.5 times higher than that of the original turbine without any guide vanes (Takao et al. 2009). Chong et al. (2013) evaluated 5-bladed H-rotor with and without guiding walls and the findings indicated a higher torque output and an increased performance improvement of 58%. Nobile et al. (2014) utilized an omni-directional stator around a Darrieus wind turbine. The results of numerical studied showed that the performance of wind turbines improved by 30–35 % when omnidirectional stator was used. Grönman et al. (2018) demonstrated a vaned Savonius turbine and conducted wind tunnel experiments to verify numerical simulations. The results showed that the numerical simulation predicted a slightly higher torque output at low rotation speeds and a slightly lower torque output at higher rotational speeds, as compared to the experimental values. The difference in results at low rotational speeds can be attributed to the dynamic stall. Aboelezz et al. (2022) had investigated the effect of the guide vane on the aerodynamics performance of NACA 0018 airfoil experimentally and numerically with and without the GW. According to the experimental investigation, the peak power of the turbine increased by about 26 %. The highest improvement was observed in 12–14 m/s wind speed range, and performance was reduced by wind speeds below 10 m/s.

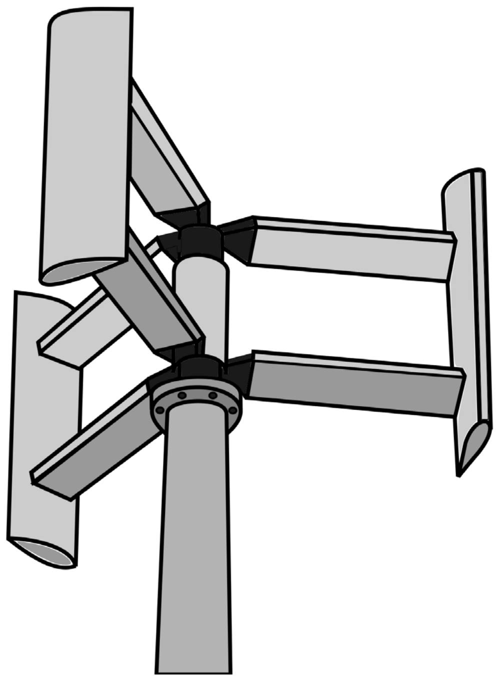


FIGURE 1. Darrieus (straight bladed) VAWT

PURPOSE OF THE PRESENT STUDY

Previous studies have indicated that the use of directed GWs can enhance the performance of a straight-bladed vertical axis turbine. The purpose of this paper is to investigate experimentally the effect of flat plate guiding walls (FPGWs) on the performance of VAWT. The novelty of this paper is based on the implementation of recently optimized FPGWs (Ansaf et al. 2023 that incorporate the optimal guiding wall angle and optimal distance between the GWs and blades of Darrieus. The paper provides an assessment of the performance enhancement of VAWT with the optimized FPGWs and ability of self-starting through experimental wind tunnel tests.

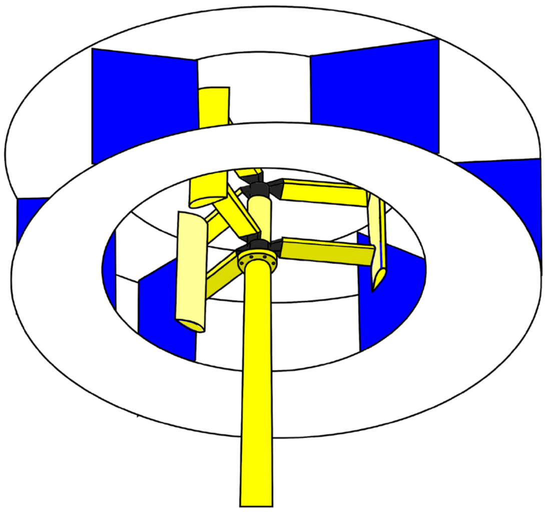


FIGURE 2. Darrieus VAWT with flat guiding walls.

METHODOLOGY

SELECTION OF GEOMETRIC PARAMETERS OF VAWT AND GWS

This section outlines the consideration and parameters needed to build Darrieus wind turbine and FPGWs, along with the identification of commonly used blade profiles or geometries for small scale VAWTs based on a literature review. The design process, which takes aerodynamic into consideration, can be summarized as follows:

The symmetric NACA0021 is a relatively large thickness profile and is the most widely used VAWT profile family. The study conducted by Raciti Castelli et al. (2011) investigated the performance of various airfoil profiles on VAWTs, with a focus on symmetrical airfoils. The findings indicated that the NACA0021 blade profile had better starting performance due to its thickness, and it demonstrated relatively good turbine performance as shown by Castelli et al. (2011) and Nguyen & Thi-Hong-Hieu Le (2015). A straight blade has high *Cp* value, and this configuration can have any number of blades, from one to five (Bhutta et al. 2012). According to Ali et al. (2019) this configuration is better than helicoidal types at low wind speed, and the power coefficient of the Darrieus turbine straight model is higher than other models.

Regarding the description of the geometric parameters of Darrieus and flat plate guiding walls, computational fluid dynamics (CFD) simulations have been performed by evaluating a model that surrounded Darrieus using different geometrical parameters including the internal- distance (X_1,Y_1) which represent an the internal radius (R_{in}), and the external distance (X_2,Y_2) represents the external radius (R_{out}) as shown in Figure 3; the angle of the six guiding walls has been investigated and analyzed by CFD simulations, Ansaf introduces more details of the functions and parameters. The design of the turbine and guiding walls has been completed for the purpose of this study. A Darrieus wind turbine, equipped with flat plate guiding walls, was utilized in the experiments, and the specifications are listed in Table 2. However, the size of the wind tunnel was insufficient to use the same geometrical dimensions as the model used in numerical simulations, so a scaled-down model was utilized instead.

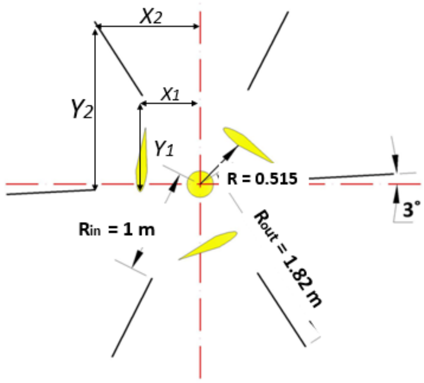


FIGURE 3. Optimal geometry of guiding walls by CFD

DETAILS OF THE MODELS FABRICATED (ROTOR MODEL AND GUIDING WALLS)

In structural design, all materials must be considered for use. The design of the turbine requires a cost-effective material that can provide the properties required for each application. The simple H-rotor have three NACA0021 blades. Blade chord and height are 50 mm and 300 mm respectively, and the blade chord is symmetric. The solidity of the turbine (N c/r) is 0.5, where c is the blade chord, N is the number of blades, and r is the rotor radius. The wind turbine used in this study were constructed with 3D printer. The decision was made to use fused deposition modeling (FDM) technology using materials known as polyethylene terephthalate glycol (PETG) with low infill for blades and struts with high infill. A PETG-based structure is generally stronger than that based on a polylactic acid (PLA) material and a has higher temperature resistance. Each blade is secured by three horizontal support arms. To connect the blades to the arms with sufficient precision and strength, the weight of NACA0021 blade = 65 g, weight of top and bottom holder = 210 g. For VAWT, Darrieus design has been chosen for this study. As shown in Figure 4, the blade is designed using Solidworks before the file is converted into stereolithography (STL) format for reading and printing by the 3D printer as listed in table 1. The material chosen for the shaft is stainless steel because of its high strength properties and is very compatible with the requirements of the wind turbines. The turbine was coupled with a shaft and placed into a fixed ball bearing on the test bench. Bearing is a mechanical device that supports the moving parts of the machine, guides the moving part, or restricts its movement, while preventing the movement in the direction of the applied load. The ceramic bearing has been used in this study, its main purpose is to minimize friction and reduce energy losses while controlling wear. In addition, the purpose of the machine is to support load while allowing relative movement between the two elements of the machine.

Many studies have demonstrated the usefulness of guiding walls. A VAWT that is combined with GWs is usually operated at the optimal parameter. So, then the GWs had to be designed according to the obtained parameters. So, Solidworks was used to draw the rotor geometry for ease of assembly as shown in Figure 5.

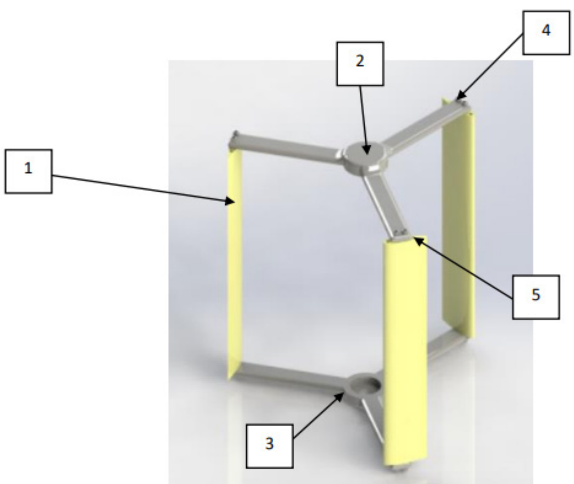


FIGURE 4. NACA 0021 Blades

TABLE 1. The wind turbine is to be constructed of the following pieces

No	Item	Quantity
1	NACA0021 Blade	3
2	Top Holder (D300 mm) + Bearing Housing	1
3	Bottom Holder (D300 mm) + Bearing Housing	1
4	M4 Bolt 20 mm	12
5	M4 Threaded Insert	12

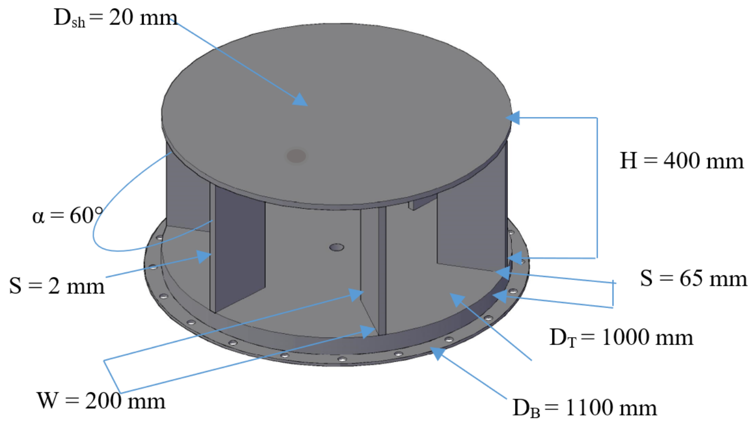


FIGURE 5. Flat plate guiding wall (FPGW) dimensions

TABLE 2. Turbine Specifications

Parameter	Value
H- rotor	VAWT
Diameter	300 mm
Turbine Height (H)	300 mm
Blade profile	NACA0021
Chord length	50 mm
Shaft diameter	15 mm
Blade number	3 blades
FPGWs	
Material	Steel
Height (H)	400 mm
Diameter	1000 mm
Width (W)	200 mm
Angle of FPGWs	3°
Thickness	2 mm

WIND TUNNEL EXPERIMENTS

Figures 6 and 7 show the experimental apparatus. The experiments were carried out in an open-circuit wind tunnel at the Beach and Water Resources Engineering Laboratory of the Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia (UKM). With regards to the wind tunnel, Harun et al. (2016a, 2016b), described detailed functions and parameters. The wind tunnel consists of two-dimensional contraction nozzle with an area of 2.4:1, followed by test section with cross-sectional area of 1.2 m × 0.5 m (width × height) and a total test length of 3m. Before the test section there is a settling chamber to ensure constant flow conditions. The maximum speed of the wind tunnel is 16 m/s, and the intensity of flow turbulence is less than 0.5%. The wind speed can be adjusted by controlling the fan frequency.

VAWT is mounted vertically in open wind tunnel and has a central shaft supported by two bearings at both ends to minimize vibration at high rotational speeds. In general, sets of measurements were conducted, one with the Darrieus turbine with 3 blades H rotor only and the other case included both the guiding walls and the rotor, the rotational speed is measured using a digital laser tachometer

(DT 2230). This procedure is repeated for different wind tunnel speeds and the output power is obtained as function of the tip speed ratio which was obtained when the wind condition and turbine rotational speed were in steady state. Each experiment was repeated three times. When presenting the turbine performance data, the parameters are used to evaluate the performance of the VAWT. Wind velocity is measured using a 9535-A VelociCalc digital anemometer air velocity meter.

The swept area is the section of air that surrounds the turbine while its moves, the shape of the swept area depends on the rotor configuration, so the HAWT swept surface is circular, and the vertical axis straight-bladed wind turbine is rectangular, and the swept area is calculated in Eq 1. The state of the turbines in the wind tunnel is shown in Figure 7 (a) and (b) for H-rotor and in combination with FPGWs respectively. The equation for swept is

$$A = D \times H \tag{1}$$

where, A = Swept area, D = Diameter of rotor, H = Height of rotor. The power of the vertical axis wind turbine can be found in the following formula.

$$P_W = 0.5\ A\, V^3 \tag{2}$$

where, P_w = Output power [W], = Velocity of the wind [m/s], ρ = Air density [kg/m^3], A = Swept area [m^2].

the turbine generator is connected to resistor, and the resistor varies to change the turbines rotating speed. The voltage on the resistor is measured. The power P is calculated from the current of the I circuit. The power coefficient depends mainly on tip speed ratio, which is the ratio between the tangential speeds to the actual wind speed as defined in Eq 3.

$$\lambda = \frac{\omega R}{U} \tag{3}$$

$$P = \mathrm{V\ I} \tag{4}$$

$$Cp = \frac{P}{0.5\,\rho\, A\, V^3\, \eta_m} \tag{5}$$

where Eq 4 shows generator power P, V, and I which are the generator power, applied voltage, and current. In Eq. 5, Cp is the power coefficient, P is output electrical power (Watt), A is the swept area (m^2), V is the wind velocity (m/s), and is the efficiency of the generator.

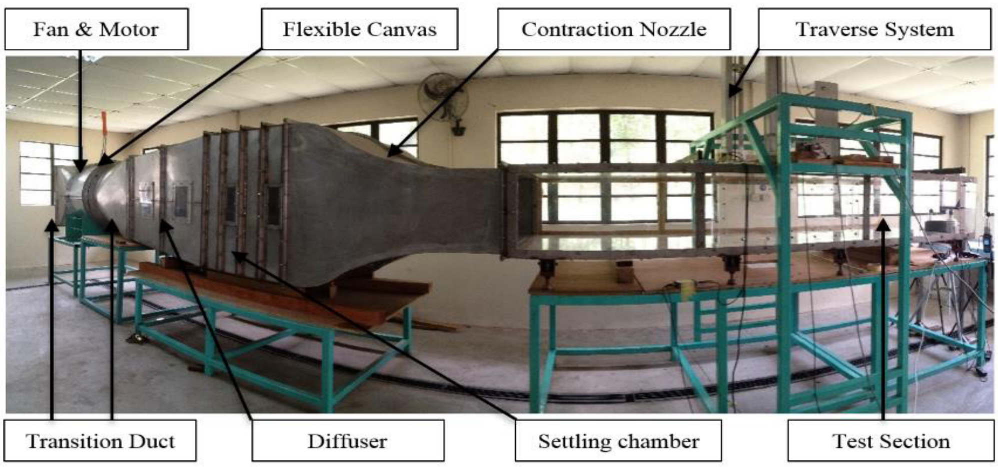
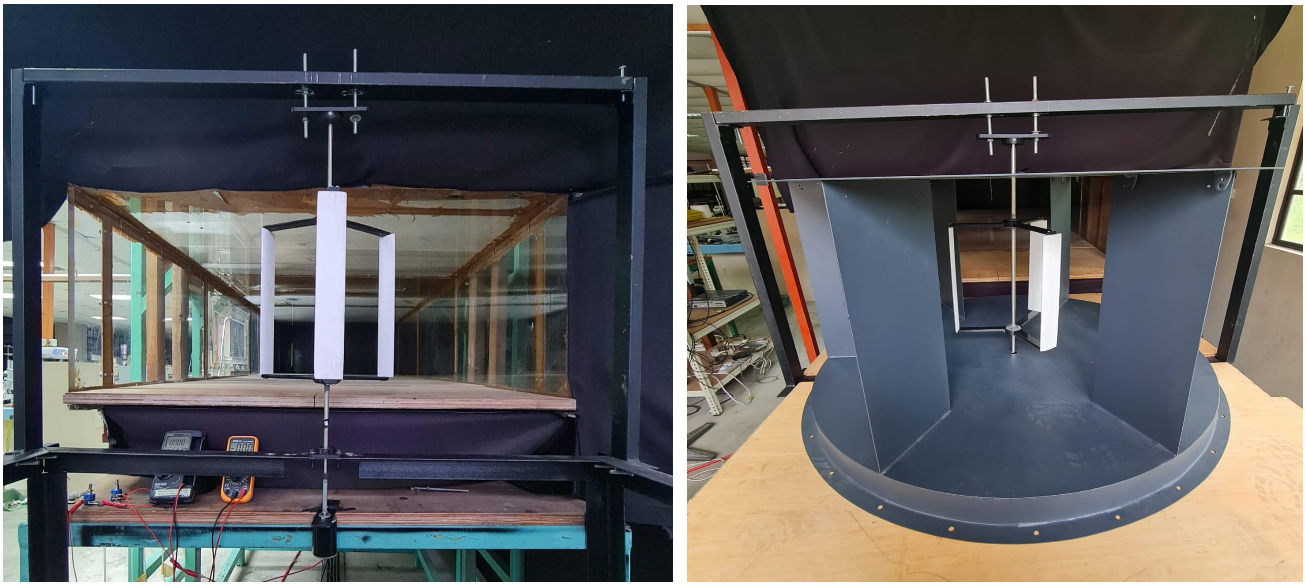


FIGURE 6. General View of the Wind Tunnel at Universiti Kebangsaan Malaysia (UKM)



(a) (b)

FIGURE 7.(a) open Darrieus VAWT (without GWs) (b) Darrieus VAWT (with GWs)

EXPERIMENTAL RESULTS AND DISCUSSION

The power output of a wind turbine is measured in wind tunnel experiments to evaluate the performance, and three different wind speeds turbine data are plotted without and with FPGWs were considered in this study.

The results of the experiment are plotted in Figures 8 to 13. The power coefficient *Cp* is used to evaluate the efficiency of VAWT at different values of the tip speed ratio λ. The *Cp* is defined in Eq 5. Figures. 8, 9, and 10 are shown from the uniform flow distribution of the *Cp* at the wind speed in the range of 8 m/s to 12 m/s. Figures 8, 9, and 10 show that the *Cp* increases as wind speed increases in all tests. The highest *Cp* values are found to be 0.23 for the open rotor VAWT without GWs as shown in Figure 11, and 0.25 VAWT with GWs at the incoming wind speed of 12 m/s.

This confirms that the wind velocity drops abruptly behind the open Darrieus turbine. While in the case of the VAWT with guiding walls, the wind velocity decreases on the vicinity of the guiding walls, then it goes higher again after passing through guiding walls and before entering the turbine rotor. According to this logic, guiding walls can improve the incoming wind speed before it approaches the turbine rotor due to the Venturi effect (wind flows from broad to a narrower area) before it hits the turbine blade. Additionally, the *Cp*-max of the guiding wall rotor is observed to be greater than that of the open turbine in all wind speeds tested at 12 m/s, and that the power curves increase with the increase in the free-stream wind velocity throughout the entire λ range under study without or with GWs.

The guiding walls show a better power coefficient at any point of wind speed as shown in Figure 12 due to the guiding walls which act as a wind concentrator and wind shield that direct the wind to the turbine blade. Based on Figures 8, 9 and 10, it is observed that the implementation of FPGWs not only increases the maximum power coefficient, but also increases the range of operating TSR. The relatively larger TSR improve the aerodynamics of the wind turbine by reducing the maximum angle of attack, while also maintaining the angle between the flow and rotating blades at all position.

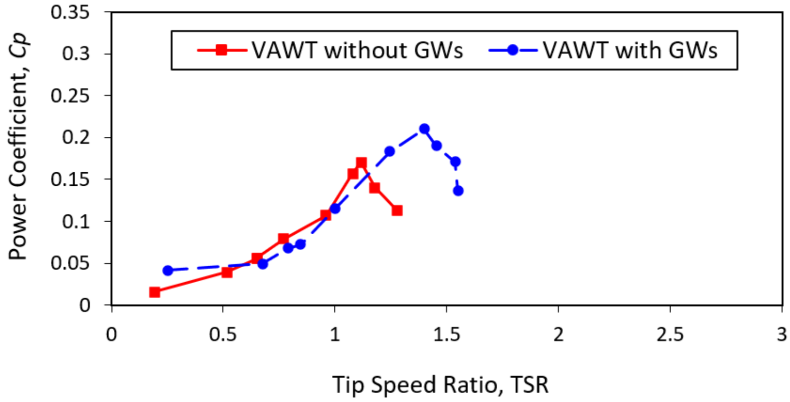


FIGURE 8. Performance curves of Darrieus wind turbine without and with guiding walls at 8 m/s

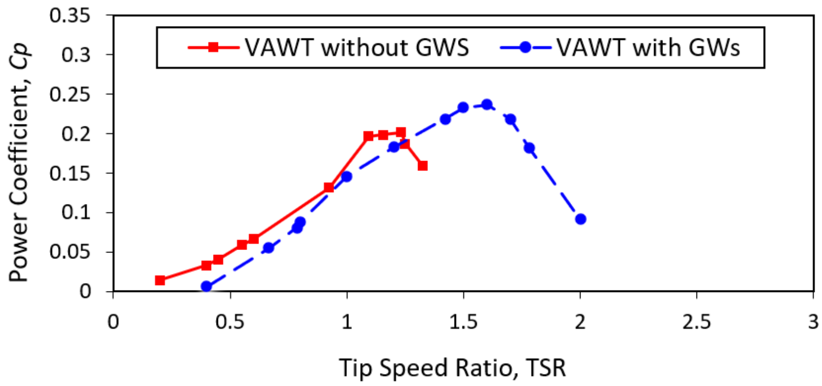


FIGURE 9. Performance curves of Darrieus wind turbine without and with guiding walls at 10 m/s

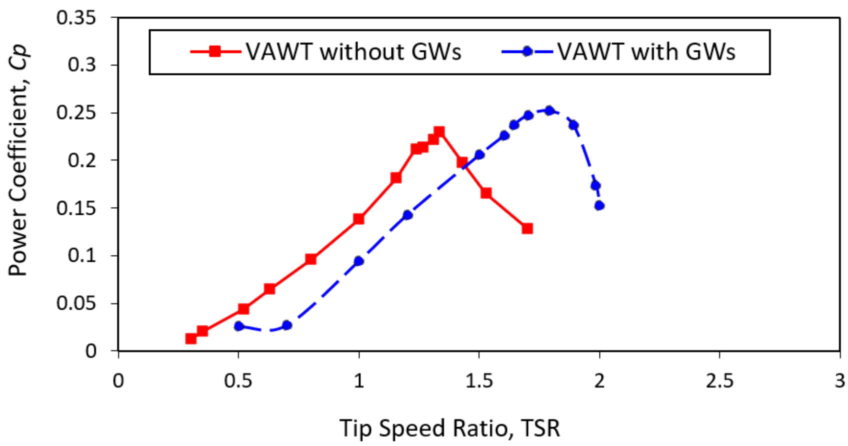


FIGURE 10. Performance curves of Darrieus wind turbine without and with guiding walls at 12 m/s

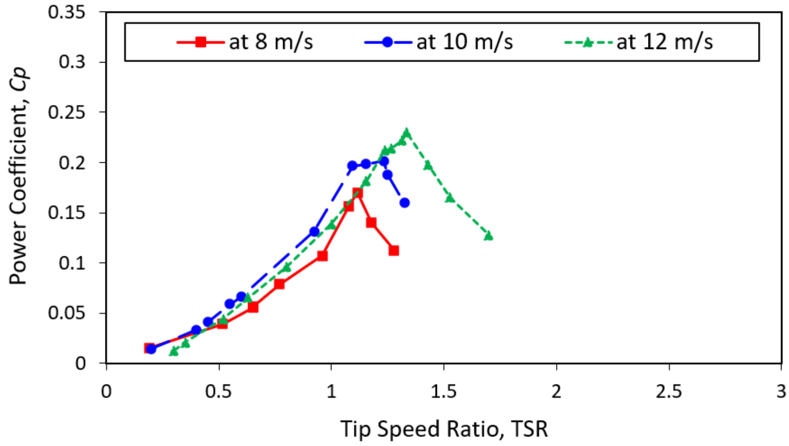


FIGURE 11. Comparison of power coefficient of open Darrieus at 8, 10, 12 m/s

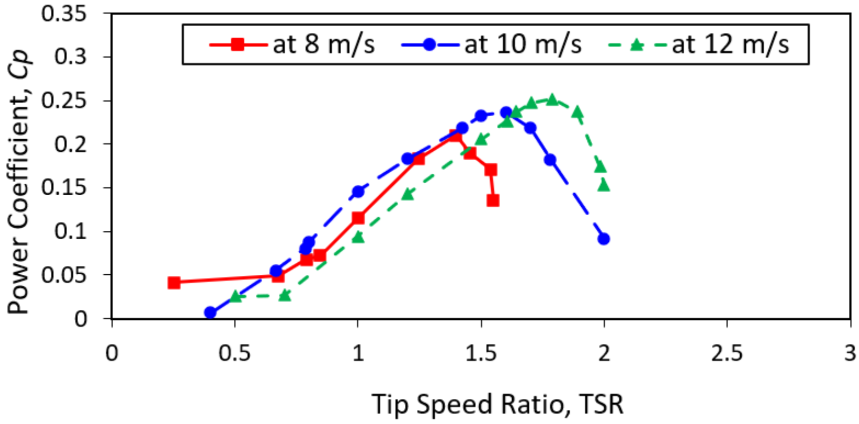


FIGURE 12. Performance curves of Darrieus wind turbine with guiding walls at 8, 10, 12 m/s

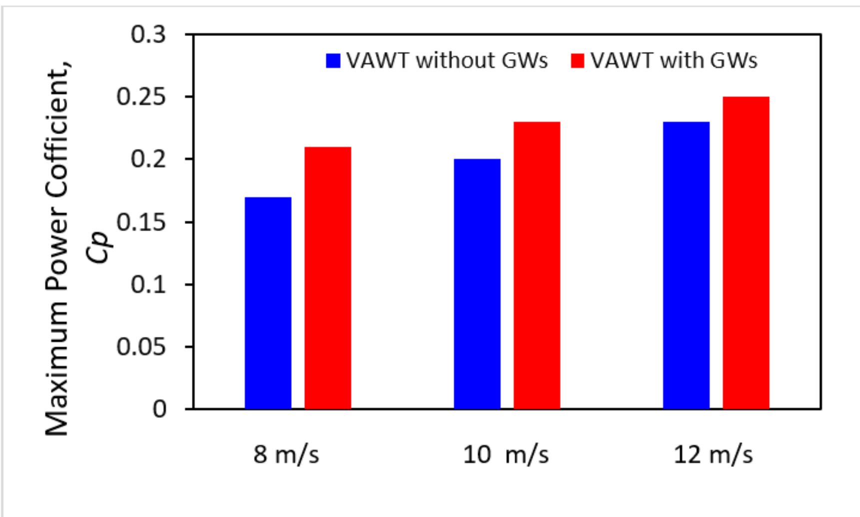


FIGURE 13. Optimal *Cp*

Figure 13 shows the highest power coefficient of a turbine with a value of Cp = 0.25 at λ = 1.79. This means that the apical feasible efficiency of the turbine was reached under these operational settings. The optimal Cp of fixed guiding walls show approximately 23% performance improvement at 8 m/s with respect to the reference wind turbine. The Cp of the H-turbine increases slightly after adding the GWs and the corresponding TSR which means that Darrieus with guiding walls are more suitable for operation at low rotational speed, a phenomenon that has been observed not just in this investigation, but also in previous studies (Dessoky et al. 2021; Wicaksono et al. 2018).

CONCLUSION

In this study, the experimental study of straight-bladed vertical axis wind turbine with directed guiding wall is designed and manufactured for wind tunnel experiments. It has been found that the running and starting properties of the wind turbine with guiding walls were superior to those without guiding walls. The optimized FPGWs were introduced to regulate both upstream and downstream flows for the rotor. The results show that, using GWs, the average air velocity around the VAWT increases due to the venturi effect, when the wind moves from a large area to a smaller area before hitting the wind turbine blade. Furthermore, the power augmentation is achieved through the use of guiding walls due to the blade interacts with the vortices generated by the edges of the guiding walls which decreases the flow disturbance on the blade and thus increasing the total lift force. This results in an improvement in the power produced from the wind turbine. It is concluded that the implementation of FPGWs not only increases the maximum power coefficient but also increases the range of operating TSR and ability of self-starting.

ACKNOWLEDGEMENT

The works are financially supported by a scholarship from the Government of Iraq and Universiti Kebangsaan Malaysia (UKM) grant GUP-2020-015.

DECLARATION OF COMPETING INTEREST

None

ACKNOWLEDGEMENT

The Ph.D. work of Ms. Roaa Ansaf is financially supported by a scholarship from the Government of Iraq and Universiti Kebangsaan Malaysia (UKM) grant GUP-2020-015.

REFERENCES

Abbas, A.A., Ghopa, W.A.W., Mat, S., Choi, K.S., Abdullah, M.F. & Harun, Z. 2018. Surface roughness effects on turbulent boundary layer structure of NACA 0026 Airfoil. *International Journal of Engineering & Technology* 7(3.17): 254–259.

Abdalkarem, A.A.M., Ansaf, R., Muzammil, W.K., Ibrahim, A., Harun, Z. & Fazlizan, A. 2023. Preliminary assessment of the NACA0021 trailing edge wedge for wind turbine application. *HELIYON*: e21193.

Aboelezz, A., Ghali, H., Elbayomi, G. & Madboli, M. 2022. A novel VAWT passive flow control numerical and experimental investigations: Guided Vane Airfoil Wind Turbine. *Ocean Engineering* 257(May).

Ali, N.M., Aljabair, S. & Abdul Hassan, A.K. 2019. An experimental and numerical investigation on Darrieus vertical axis wind turbine types at low wind speed. *International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS* 19(06): 97–110.

Andrews, A.A.E., Karthick, P., Jeraled, A.A., Anuroop, K. & Chidanand, G. 2019. Experimental and Numerical Study on Modified Vertical Axis Wind Turbine. *IOP Conference Series: Materials Science and Engineering*, p. 12007.

Ansaf, R., Abdelhameed, H.S., Hashem, I. & Harun, Z. 2023. Efficiency-based design optimization of the H-type Darrieus wind turbine with fixed guiding-walls. *Energy Reports* 9: 3576–3592.

Bhutta, M.M.A., Hayat, N., Farooq, A.U., Ali, Z., Jamil, S.R. & Hussain, Z. 2012. Vertical axis wind turbine–A review of various configurations and design techniques. *Renewable and Sustainable Energy Reviews* 16(4): 1926–1939.

Castelli, M.R., Englaro, A. & Benini, E. 2011. The Darrieus wind turbine: Proposal for a new performance prediction model based on CFD. *Energy* 36(8): 4919–4934.

Cho, S.-Y., Choi, S.-K., Kim, J.-G. & Cho, C.-H. 2017. Numerical study to investigate the design parameters of a wind tower to improve the performance of a vertical-axis wind turbine. *Advances in Mechanical Engineering* 9(12): 1687814017744474.

Chong, W.T., Fazlizan, A., Poh, S.C., Pan, K.C., Hew, W.P. & Hsiao, F.B. 2013. The design, simulation and testing of an urban vertical axis wind turbine with the omni-direction-guide-vane. *Applied Energy* 112: 601–609.

Chong, W.T., Hew, W.P., Yip, S.Y., Fazlizan, A., Poh, S.C., Tan, C.J. & Ong, H.C. 2014. The experimental study on the wind turbine's guide-vanes and diffuser of an exhaust air energy recovery system integrated with the cooling tower. *Energy Conversion and Management* 87: 145–155.

Dessoky, A., Bangga, G., Lutz, T. & Krämer, E. 2019. Aerodynamic and aeroacoustic performance assessment of H-rotor darrieus VAWT equipped with wind-lens technology. *Energy* 175: 76–97.

Dessoky, A., Lutz, T. & Krämer, E. 2021. Aerodynamic and aeroacoustic performance investigations on modified H-rotor Darrieus wind turbine. *Wind Engineering* 46(1): 69-88.

El-Askary, W.A., Saad, A.S., AbdelSalam, A.M. & Sakr, I.M. 2020. Experimental and theoretical studies for improving the performance of a modified shape Savonius wind turbine. *Journal of Energy Resources Technology* 142(12), p. 121303 .

Grönman, A., Backman, J., Hansen-Haug, M., Laaksonen, M., Alkki, M. & Aura, P. 2018. Experimental and numerical analysis of vaned wind turbine performance and flow phenomena. *Energy* 159: 827–841.

Harun, Z., Abbas, A.A., Dheyaa, R.M. & Ghazali, M.I. 2016a. Ordered roughness effects on NACA 0026 airfoil. *IOP Conference Series: Materials Science and Engineering*, p. 12005.

Harun, Z., Ghopa, W.A.W., Abdullah, S., Ghazali, M.I., Abbas, A.A., Rasani, M.R., Zulkifli, R., Mahmood, W.M.F.W., Mansor, M.R.A. & Abidin, Z.Z. 2016b. The development of a multi-purpose wind tunnel. *Jurnal Teknologi* 78(6–10).

Hashem, I. & Mohamed, M.H. 2018. Aerodynamic performance enhancements of H-rotor Darrieus wind turbine. *Energy* 142: 531–545.

Hashem, I. & Zhu, B. 2021. Metamodeling-based parametric optimization of a bio-inspired Savonius-type hydrokinetic turbine. *Renewable Energy*.

Ismail, M.F. & Vijayaraghavan, K. 2015. The effects of aerofoil profile modification on a vertical axis wind turbine performance. *Energy* 80: 20–31.

Khai, T.C., Mohammad, A.F., Fazlizan, A., Zaki, S.A. & Redzuan, F.L.M. 2022. Numerical Investigation of the Power Performance of the Vertical-Axis Wind Turbine with Endplates. *CFD Letters* 14(6): 90–101.

Kim, D. & Gharib, M. 2013. Efficiency improvement of straight-bladed vertical-axis wind turbines with an upstream deflector. *Journal of Wind Engineering and Industrial Aerodynamics* 115: 48–52.

Korprasertsak, N. & Leephakpreeda, T. 2016. Analysis and optimal design of wind boosters for Vertical Axis Wind Turbines at low wind speed. *Journal of Wind Engineering and Industrial Aerodynamics* 159: 9–18.

Manyonge, A.W., Ochieng, R.M., Onyango, F.N. & Shichikha, J.M. 2012. Mathematical modelling of wind turbine in a wind energy conversion system: Power coefficient analysis. *Applied Mathematical Sciences* 6(89–92): 4527–4536.

Masseran, N., Razali, A.M., Ibrahim, K., Zin, W.Z.W. & Zaharim, A. 2012. On spatial analysis of wind energy potential in Malaysia. *WSEAS Transactions on Mathematics* 11(6): 467–477.

Mitchell, S., Ogbonna, I. & Volkov, K. 2021. Improvement of self-starting capabilities of vertical axis wind turbines with new design of turbine blades. *Mitchell, Samuel Ogbonna, Iheanyichukwu Volkov, Konstantin* 13(7): 1–24.

Mohamed, M.H. 2016. Reduction of the generated aero-acoustics noise of a vertical axis wind turbine using CFD (Computational Fluid Dynamics) techniques. *Energy* 96: 531–544.

Nguyen, C.-C. & Thi-Hong-Hieu Le, P.-T. 2015. A numerical study of thickness effect of the symmetric NACA 4-digit airfoils on self starting capability of a 1kW H-type vertical axis wind turbine. *International Journal of Mechanical Engineering and Applications* 3(3–1): 7.

Nobile, R., Vahdati, M., Barlow, J.F. & Mewburn-Crook, A. 2014. Unsteady flow simulation of a vertical axis augmented wind turbine: A two-dimensional study. *Journal of Wind Engineering and Industrial Aerodynamics* 125: 168–179.

Parneix, N., Fuchs, R., Immas, A., Silvert, F. & Deglaire, P. 2016. Efficiency improvement of vertical-axis wind turbines with counter-rotating lay-out. *Proceedings of the EWEA*: 1–8.

Raciti Castelli, M., Englaro, A. & Benini, E. 2011. The Darrieus wind turbine: Proposal for a new performance prediction model based on CFD. *Energy* 36(8): 4919–4934.

Ramlee, M.F., Fazlizan, A. & Mat, S. 2020. Performance Evaluation of H-Type Darrieus Vertical Axis Wind Turbine with Different Turbine Solidity. *Journal of Computational and Theoretical Nanoscience* 17(2–3): 833–839.

Seralathan, S., Thomai, M.P., Jayakumar, R.L., Reddy, B.V.L. & Venkatesan, H. 2019. Experimental and numerical assessment of cross flow vertical axis wind turbine. *ASME 2019 Gas Turbine India Conference, GTINDIA 2019* 2(December).

Shankar, P.N. 1979. Development of vertical axis wind turbines. *Proceedings of the Indian Academy of Sciences Section C: Engineering Sciences* 2(1): 49–66.

Takao, M., Kuma, H., Maeda, T., Kamada, Y., Oki, M. & Minoda, A. 2009. A straight-bladed vertical axis wind turbine with a directed guide vane row - Effect of guide vane geometry on the performance. *Journal of thermal Science* 18(1): 54–57.

Tjiu, W., Marnoto, T., Mat, S., Ruslan, M.H. & Sopian, K. 2015. Darrieus vertical axis wind turbine for power generation II: Challenges in HAWT and the opportunity of multi-megawatt Darrieus VAWT development. *Renewable Energy* 75: 560–571.

Turbine, D., Suffer, K.H. & Jabar, Z.S. 2021. Numerical Investigation of the Aerodynamics Performance of Hybrid Icewind- Numerical Investigation of the Aerodynamics Performance of Hybrid Icewind-Darrius Turbine(January).

Wicaksono, Y.A., Tjahjana, D.D.D.P. & Hadi, S. 2018. Influence of omni-directional guide vane on the performance of cross-flow rotor for urban wind energy. *AIP Conference Proceedings* 1931(February).

Zanforlin, S. & Nishino, T. 2016. Fluid dynamic mechanisms of enhanced power generation by closely spaced vertical axis wind turbines. *Renewable Energy* 99: 1213–1226.

Zhang, T. Tian, Elsakka, M., Huang, W., Wang, Z. Guo, Ingham, D.B., Ma, L. & Pourkashanian, M. 2019. Winglet design for vertical axis wind turbines based on a design of experiment and CFD approach. *Energy Conversion and Management* 195: 712–726.

Zhao, Y., Meng, T., Jing, C., Hu, J. & Qian, S. 2020. Experimental and numerical investigation on thermal performance of PV-driven aluminium honeycomb solar air collector. *Solar Energy* 204(June 2019): 294–306.