Flow Simulations of Modified Diffuser Augmented Wind Turbine

Saravana Kannan Thangavelu¹*, Timothy Goh Leong Wan¹, and C Piraiarasi²
¹Faculty of Engineering, Computing and Science, Swinburne University of Technology, 93300 Kuching, Sarawak, Malaysia
²Department of Architecture, Thiagarajar College of Engineering, Madurai 625 015, Tamilnadu, India

* Corresponding Author: sthangavelu@swinburne.edu.my

Abstract
In order for wind technology to compete with conventional sources of energy, in terms of energy production costs, researchers are working on different ways to increase the energy density in wind. Development of wind power augmentation system is one of the most promising concepts in this field. The main objective of this research is to propose a new diffuser design for Diffuser Augmented Wind Turbine (DAWT) by introducing air vents and vortex generators. This study also investigates the effect of wind velocity and air pressure on the proposed modified diffuser to develop a suitable diffuser for DAWT. The purpose of this modified diffuser is to create a low-pressure region in the centre of the diffuser to increase the inlet mass flow rate. Three modified designs were developed and were simulated using CFD techniques. Results showed an outstanding increment in wind speed, which is 8.56 m/s (2.14 times increment), over the 4 m/s initial wind speed in a modified diffuser (Model 3 Air vents with splitter). This modified diffuser is based on the parameters: rotor diameter (D) = 500 mm, diffuser length (L) = 1000 mm, diffuser open-angle (θ) = 12º, flange size = 221.73 mm and inner splitter with 14º open-angle (α).

Keywords: DAWT, Diffuser with splitter, Air vents, Wind Velocity, CFD

1. Introduction
Wind energy is the second largest source of energy and it is the fastest-growing renewable energy resource around the world. The main problem of using wind energy is the uncertainty of wind pattern. Low wind speeds result in less energy per unit volume of air passing through a turbine. This leads to higher electricity production cost from wind energy than from fossil fuels. In order for wind technology to compete with conventional sources of energy in terms of energy production costs, researchers are working on different ways to increase the energy density in wind [1]. One of the most promising concepts in this field is the growth of wind power augmentation systems. By the use of diffuser in the wind turbine, wind power augmentation system is also called a Diffuser Augmented Wind Turbine (DAWT). In DAWT, the diffuser or flanged diffuser generates separation regions behind it, where low-pressure regions appear to draw more wind through the rotors compared to a ‘bare wind turbine’. DAWTs can provide an opportunity to extract power from unstable low wind speeds [2].
The concept of ‘diffuser’ is to increase the power output of a wind turbine by accelerating the wind velocity that approaches the wind turbine. To increase the wind velocity, low pressure would appear at the back of the wind turbine to act as a vacuum to suck the wind and accelerate it towards the blades. The region of the area surrounding or near the vortex would have typically lower pressure where the suction force will be formed by the vortex. Therefore, it will act as an accelerator to accelerate the wind velocity approaching the wind turbine. The vortex is used to generate a low-pressure region in the wake of the turbine. Vortex should appear at the wake of the diffuser but as little as possible inside the diffuser wall. If the vortices formed inside the diffuser, the pressure inside the diffuser might be lower than the pressure at the back of the wind turbine [3].

The performance increases of DAWT is proportional to the mass flow through the duct and that larger performances are possible by lowering back pressure levels at the exit. Many numbers of experimental and numerical studies reported in DAWT since 1950 presented the effect of diffuser length and open-angle of diffuser on the performance of the DAWT. In addition, some studies presented the effect of brim (flange) heights on the DAWT performance [4]. From the previous studies, it was concluded that DAWT exhibits the best advantages compared to other augmentation solutions in the production of power at high performance exceeding the Betz limit. The configurations of the shroud of DAWT included the simple diffuser, diffuser with an inlet shroud, converged - diverged diffuser, curved diffuser, flanged diffuser, and multilayer diffuser [3-9]. The optimum design for shroud will generally increase power obtained from any turbine used, but in order to reach optimum power from this turbine, a combination with a modified design for the turbine blade is necessary.

Kannan et al. [3] developed five different DAWT models using CFD and found that the flange and inner splitter are the effective features to increase the inlet air velocity of the diffuser. This research is the extension of this previous study having the objective to propose a new diffuser design for DAWT by introducing air vents and vortex generators. This study also investigates the effect of wind velocity and air pressure on the proposed modified diffuser to develop a suitable diffuser for DAWT. The purpose of this modified diffuser is to create a low-pressure region in the center of the diffuser to increase the inlet mass flow rate.

2. Methodology

Three different modified DAWT models were developed as shown in Figure 1 using SolidWorks and start from sketch the section cut on the front plane then revolve. All models are fixed to the inlet diameter \((D) = 500\) mm; diffuser length \((L) = 1000\) mm; thickness \((t) = 10\) mm; open-angle \((\theta) = 12^\circ\) and flange length \((h) = 221.73\) mm and the length diameter ratio \((L/D)\) is 2. All models have a converging duct with the length \(l = 102.23\) mm. However, model 3 has an extra small splitter inside it with the dimensions, splitter \(L_2 = 300\) mm, splitter diameter \(D_2 = 150\) mm and splitter angle \(\alpha = 14^\circ\). All models have a converging duct with a radius of 106 mm and length of 102.23 mm.

![Figure 1. Front plane sketch of modified DAWT Models (a) Model 1 & 2 (b) Model 3](image)
Most of the design are referred to and cited to the previous research by Kannan et al. [3]. From the previous research, it was found that the flange is the most efficient feature to improve the diffuser performance. Therefore, the flange feature is taken into the new design with other features to test the performance. As shown in Figure 2, Model 1 and Model 3 have eight air vents surrounding the outlet of the diffuser but Model 3 has a splitter inside it. The dimension for the air vents is 250 mm in length along the diffuser wall, 50 mm height and 202 mm in hypotenuse. Model 2 has eight pairs of vortex generators inside the outlet. The vortex generators are 5 mm in thickness, 350 mm in height and 100 mm in length with the open-angle of 35°. The air vents idea come from tornado and fire tornado generator; vortex generators are taken from the same application on a racing car; flange and splitter come from previous research [3].

The geometry model is saved and uploaded as IGS file in ANSYS Fluent. As shown in Figure 3, a tunnel is created by using Envelope in DesignModeler with 10000 mm height, 10000 mm width and 20000 mm long. Then the model is subtracted from the tunnel by using subtract Boolean in DesignModeler. The fluid flow inside the tunnel is set as air and the model is made by aluminium. The mesh is set as hexahedron mesh, initial wind speed is as 4 m/s, initialization is hybrid, the solution method is SIMPLE and 500 interactions are set for calculation. The air velocity and pressure data of X-axis collected and plotted into graphs. Realizable k-epsilon model is used for the simulation with Single Reference Frames (SRF) model [1, 9]. Density and viscosity based flow solver is used. Grid density validation was done as similar to our previous study [9].

### Figure 2. (a) Model 1 Air vents (b) Model 2 Vortex generator (c) Model 3 splitter with air vents

### Figure 3. Tunnel dimension

#### 3. Results and Discussions

The inlet air velocity and static gauge pressure at the diffuser inlet (X= 0 m) are taken for all models and reported in Table 1. For Model 1, the inlet air velocity increases up to 8.3079 m/s, which is 207.70%
increment (over 4 m/s initial wind velocity). Model 2 increases the inlet air velocity up to 6.1260 m/s, which is 153.15% increment, and Model 3 increases the inlet air velocity up to 8.5594 m/s, which is 213.985% increment. Model 3 is the best model to improve the inlet air velocity and 52.7% more than the previous model, 6.45 m/s as reported in Kannan et al. [3]. The suction power of the diffuser also can be determined by analysing the static gauge pressure at the inlet centre. The static gauge pressure from lowest to highest was as follows: Model 2 (-6.5172 Pa), Model 1 (-26.3601 Pa), and Model 3, -29.7099 Pa. A negative pressure region formed at the back of the diffuser help to draw more air out of the diffuser and cause the diffuser inlet mass flow rate increase [8-9].

| Model | Inlet Air Velocity (m/s) | Static Gauge Pressure (Pa) |
|-------|--------------------------|---------------------------|
| 1     | 8.3079                   | -26.3601                  |
| 2     | 6.1260                   | -6.5172                   |
| 3     | 8.5594                   | -29.7099                  |

Figure 4 shows the change of air velocity in the centre of the diffuser. The diffuser located at X= -0.102 m to 0.898 m and the rotor located at X= 0 m. The graph shows that the air velocity increases from initial air velocity, 4 m/s to highest peak when near the rotor position then decreasing. Model 2 has the lowest peak and decreases rapidly after the inlet. While Model 1 & 3 have a similar characteristic at the beginning due to similar geometry. However, Model 3 shows a slightly high peak with the splitter inside it. The splitter helps to increase the air velocity at the end of the diffuser or after X= 0.5m. The results showed that the splitter successfully was drawn more air out of the diffuser and increases the inlet air velocity.

Figure 5 shows the change of air static gauge pressure in the centre of the diffuser. The diffuser located at X= -0.102 m to 0.898 m and the rotor located at X= 0 m. All models have the lowest pressure at the inlet of the diffuser. Model 2 has the overall higher pressure compared with Model 1 & 3. Model 1 & 3 has a similar trend line but Model 3 has a slightly lower pressure than Model 1. The splitter at the end of the Model 3 also causes the pressure at the end decrease for the second time. A pressure lower than atmospheric pressure increases the suction power of the diffuser and draws more air.

All models can generate a low-pressure region behind the diffuser outlet due to the flange and larger outlet area. Model 3 has the lowest backpressure according to the analysis on the pressure contour as
shown in Figure 6, which is around -11.587 Pa to -2.422 Pa. While Model 1 has a slightly higher backpressure than Model 3, from -6.523 Pa to -2.629 Pa. The backpressure of Model 2 is the highest and varies, approximately about -0.767 Pa. The lowest pressure region occurred at the rotor position where X = 0 m.

![Graph of Distance versus Static Pressure](image)

**Figure 5.** Static pressure across X-axis

![Static pressure contour across X-axis](image)

**Figure 6.** Static pressure contour across X-axis (a) Model 1 (b) Model 2 (c) Model 3
Figure 7. Velocity streamlines and end airflow (a) Model 1 (b) Model 2 (c) Model 3

Model 1 (Air vent features) and Model 3 (Splitter with air vents features) succeed to create a tornado at the end of the diffuser. Model 3 generates a more obvious tornado and the air velocity in the centre is faster. This is due to the splitter, which separated the outer airflow with inner airflow. Model 1, which does not have a splitter, had caused the airflow on both sides imbalanced. Model 2 (Vortex generator features) has a lower air velocity but fairly distributed. The vortices generated at the back of Model 1 and Model 3 are much larger and concentrated. Meanwhile, Model 2 has many small vortices at the back due to the vortex generators.

Figure 7 shows the streamlines on the Z-plane. Figure 7 explains the airflow pattern at the end of diffuser, in addition, how the modified features improve the performance of the diffuser. The airflow of the Model 1 starts to spin slightly after the end while Model 3 has a more obvious spinning of the airflow near a tornado. The airflow in the centre of Model 3 is more stable due to the splitter. The airflow of Model 2 bends towards one side. The higher air velocity flow occurs mostly in the centre of the diffusers.

Figure 8. Detailed views of Model 3 splitter with air vents

4. Conclusion
This research examined the different designs of Diffuser Augmented Wind Turbine by using SolidWorks for CAD and ANSYS Fluent for CFD. Three modified diffuser designs (3 models) were developed and all models succeed to improve the diffuser’s performance. Among them, Model 3 (Splitter with air vents features as in Figure 8) has the highest improvement on inlet air velocity, 8.5594 m/s with 213.99% increment. This study also proved that the features, flange and inner splitter come from previous research are feasible and effective to improve the diffuser’s performance. The new idea, air vents and vortex generators also show their strength. The performance of the air vents is more significant. Air vents can provide horizontal airflows and cause the airflow at the end to behave like a tornado. The suction power of the tornado increases the mass flow rate and air velocity at the inlet.
References
[1] Thangavelu S K Goh C Y Sia C V 2019 *IOP Conf. Series: Mater. Sci. Eng.* **501** 012041
[2] Ohya Y Karasudani T Sakurai A Abe K I Inoue M 2008 *Wind Engineering and Industrial Aerodynamics* **96**(5) 524-539.
[3] Kannan T S Mutasher S A Lau Y H K 2013 *Journal of Engineering Science and Technology* **8**(4) 372-384.
[4] Al-Quraishi B A J Asmuin N Z B Mohd S B Abd al-wahid W A Mohammed A N Didane D H 2019 *The International Journal of Integrated Engineering* **11**(1) 178-206.
[5] Roshan S Z Alimirzazadeh S Rad M 2015 *J. Wind. Eng. Ind. Aerodyn.* **145** 270-279.
[6] Sorribes-Palmer F Sanz-Andres A Ayuso L Sant R Franchini S 2017 *Renew. Energ.* **105** 386-399.
[7] El-Zahaby A M Kabeel A E Elsayed S S Obiaa M F 2017 *Alexandria Engineering Journal* **56** 171-179.
[8] Jadallah A A Farag S R Hamdi J D 2018 *Journal of Engineering Science and Technology* **13**(7) 1891-1904.
[9] Hooi L B Thangavelu S K 2018 *IOP Conf. Series: Mater. Sci. Eng.* **297** 012057