Experimental investigation of a diffuser-integrated vertical axis wind turbine

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Abstract. The increase in energy demand and environmental pollution issues has led to the growth of utilizing renewable energy. Wind energy has become one of the main alternatives for power generation. In order to enhance the performance of the horizontal axis wind turbine (HAWT), the application of a diffuser is one of the innovative methods. At present, research on deploying the diffuser on the vertical axis wind turbine (VAWT) remains scarce. This paper presents the experimental study on the aerodynamic characteristics of a small H-rotor VAWT integrated with a diffuser. The diffuser comprises a pair of flat plates with an inclined angle of 30° at the outlet, with the VAWT located between the diffuser. A comparison between the turbine performance with and without the diffuser has been conducted. From the experiment, it shows that with the presence of the diffuser, the performance of the VAWT has increased significantly. The power obtained for the bare turbine and with the diffuser is 0.38 W and 0.48 W respectively which is increased by about 26.3% and occurring at 300 rpm. Moreover, with the diffuser, the incoming velocity is also increased. This is due to the presence of the diffuser which enables the flow expansion and creates a low-pressure region at the downwind; inducing a higher incoming wind flow to the VAWT and enhancing its performance. In addition, the rotational speed and a better self-start ability can be achieved with the presence of the diffuser.

Keywords: Vertical axis wind turbine; diffuser; experiment; coefficient of power, tip speed ratio

1. Introduction

Global warming, unusual climate change and other negative effects from the usage of fossil fuel have led to the rise of interest in renewable energy. Solar, hydro, wind, geothermal, wave and many other forms of energy are clean, inexhaustible and able to replenish themselves naturally; making them the best alternative to replace fossil fuels. The exploitation of wind energy for power generation is a
promising technology and has become increasingly popular since the last decade. In order to extract wind power, a wind turbine is the machine that converts the kinetic energy available in wind flow to electric energy connected to the grid line. The wind turbine can be categorized into two types according to its rotational axis which are the horizontal axis wind turbines (HAWTs) and the vertical axis wind turbines (VAWTs). The iconic HAWTs are widely used at onshore and offshore wind farms due to the higher efficiency that can be achieved in the laminar flow condition. However, the main shortcoming is that the turbines need to yaw to confront to the wind direction. On the other hand, the VAWTs have piqued researchers’ attention due to the unique omnidirectional characteristic. Nevertheless, most of the VAWTs suffer from low self-start ability and are low in performance levels.

A diffuser is an additional device integrated with the turbine to enhance the performance of the turbine by giving an augmented effect on the wind flow towards the turbine [1]. The application of a diffuser is not new and has been used for HAWT since the last decade [2-6]. According to Ohya et al. [2], a shrouded HAWT with a flanged diffuser was developed. The broad-ring flange is located at the exit periphery of the turbine where it converges and accelerates the oncoming wind by generating a low-pressure region behind the flanged diffuser. Due to the vortex formation, it draws a higher wind flow rate to the turbine. At the same time, the flange diffuser functions as the yawing mechanism. The study of the diffuser performance on a HAWT was also conducted by Cresswell et al.[4], who made an interesting finding that with the incorporation of the diffuser, the HAWT can maintain its performance during yaw. Furthermore, the diffuser performance is strongly affected by the ratio of length to diameter. The simulations investigated a diffuser on a horizontal axis hydro turbine is reported in [7], and it reveals that the performance of the turbine is not only directly linked to the shape, but the rotor and diffuser also affect the power coefficient. A similar finding was reported in [6]. Khamlaj and Rumpfkeil [8] employ the multi-objective genetic algorithm for the optimization of the diffuser shape design where a piece-wise quadratic polynomial was used to define the diffuser shape. Rather than a single HAWT, Lipian et al.[9] deploy a twin-rotor wind turbine system incorporated with the diffuser and by doing this, a more evenly distributed load for the turbine was achieved. Another multi-rotor system of the diffuser was investigated by Goltenbott et al.[10]. In their studies, comparisons between single, two, and three HAWTs with diffusers arranged on the same plane were conducted. Their findings revealed that the power generated increased by up to 5% and 9% for two and three rotors respectively, where the flow velocity near the gap between the diffuser was increased.

For VAWT, the typical design for the diffuser includes a concentrating nozzle at upwind of the turbine, where Watanabe et al. [11] conducted experiments of a curved wind lens on VAWT obtained a augmentation factor of 2.1. Whereas Hashem and Mohamed [3] conducted CFD simulation of the diffuser design on a Darrieus rotor, where the cycloidal-surface diffuser performed better compared to the flat-panel and curved-surface diffuser. Santoli et al. [12] designed a power augmented device for VAWT which combine a concentrator and a diffuser together, where at wind speed of 8 m/s, the output power produced increased up to 125%. An innovative application of the diffuser and VAWT at the exhaust air was reported in [13]. As abovementioned, the application of a diffuser on HAWTs is popular; however, in contrast to this, research done regarding diffusers without a concentrating nozzle at upwind on VAWTs is scarce. The objectives of the present paper include:

1. to design and fabricate a downwind diffuser without an upwind concentrating nozzle.
2. to conduct experiments to investigate the aerodynamics performance of a VAWT.
3. to compare the VAWT performance with the presence of the downwind diffuser.

2. Methodology

2.1. Experiment setup

Experiments have been conducted to investigate the effects of the presence of a downwind diffuser on a commercial unit five-bladed micro H-rotor VAWT. As shown in Figure 1, for the sake of measuring the VAWT performance, a torque transducer was used to measure the rotational speed, torque and power output by the rotor shaft that connects to the VAWT. A hysteresis brake connected to the torque transducer was used to employ different loads onto the VAWT shaft. The brake holding force
was regulated by the power supply, whilst the data from the torque transducer was recorded by the computer using RS 232 communication. Figure 2 illustrates the experimental setup of the VAWT located between the diffuser plates. As shown in the figure, the diffuser was constructed with a 10 mm thickness acrylic sheet. For each side, the plate was divided into two sections at an angle of 30°, the neck (shorter length plate) and the diffuser (longer length plate). Some supporting ribs were added on to the diffuser to strengthen the structure of the downwind diffuser. The diffuser was located at the downwind of the turbine in order to eliminate the converging flow effect that could be caused by an upwind concentrator. The neck section design is to ensure that the wind flow is straight before passing through the diffuser. A hot-wire anemometer was placed in front of the turbine to measure the oncoming wind velocity, whilst the wind source was generated by the blower arrays. The VAWT was placed at a distance of 3m from the wind source. Further detail of the experiment setup is reported in [14].

2.2. Testing procedure
The experiment was first conducted on the VAWT without the diffuser at the average oncoming wind speed of 7.2 m/s. The turbine was allowed to run freely without applying any load to observe the maximum rotational speed and self-start capability. Subsequently, different magnitudes of braking force were applied on the shaft by increasing the power supply to the hysteresis brake. At the same time, data measured by the torque transducer was recorded. This load was increased until the VAWT was unable to rotate further. For comparison purposes of this experiment, the same testing procedure was repeated for the VAWT with the downwind diffuser.

3. Results and Discussions
From the experiment, it showed that the application of a downwind diffuser increases the performance of the VAWT immensely. The performance criteria including the power generated and the maximum rotational speed of the VAWT were recorded.
3.1. Rotational speed
Figure 3 shows the self-start behaviour of the VAWT and with the presence of downwind diffuser for the duration of 180s after a steady rotational speed is recorded. It is perceptible that with the diffuser, the rotational speed obtained by the VAWT is much higher (about 350 rpm) whereas the bare turbine only achieved about 300 rpm; and this is an increase of approximately 16.67%. It is also noticeable that a steeper gradient of the curve is observed for the case with the employment of the diffuser, indicating that the angular acceleration of the turbine is higher.

![Figure 3. Rotational speed for the bare turbine and with diffuser.](image)

3.2. Power generated
As denoted in Figure 4, the plot of power against rotational speed is shown. It is observed that the power generated with the diffuser is higher than without the diffuser for all rotational speeds. With the diffuser, the maximum power generated was approximately 0.48 W at 300 rpm, whilst the power generated without the use of the diffuser was about 0.38 W, approximately 26.32% higher.

![Figure 4. Power versus rotational speed for the bare turbine and with diffuser.](image)

The increment in the performance is because the flow passing through the diffuser gets accelerated due to a greater pressure difference. The presence of the diffuser expands the wind flow, creates vortexes and a low-pressure region behind the diffuser, inducing a greater volume flow rate of the wind that impinges the VAWT. A similar finding is reported in [3].
4. Conclusion and future work

As a conclusion, a downwind diffuser was fabricated and integrated with a five-bladed H-rotor vertical axis wind turbine to investigate the aerodynamic performance. The design of the diffuser in the research is in such a way to eliminate the concentration effect of the wind at the upwind section of the turbine. Comparisons between the performance of the VAWT with and without the diffuser were conducted by lab experiment. During the testing, the rotational speed and the power generated by the turbine were observed by applying different loads. From the investigation, it showed that the presence of the diffuser improves the performance of the VAWT significantly, where in the free-running condition, the turbine with a diffuser achieved 350 rpm; 16.67% higher than the bare turbine of 300 rpm. Besides that, the maximum power generated for the turbine with the diffuser was approximately 26.31% higher than the case without a diffuser in place. The augmented effects of the diffuser are due to a higher wind velocity flowing toward the turbine before interacting with the VAWT. The wind expands at the downwind region after passing through the diffuser and generates a low-pressure region, resulting in a higher wind flow rate being induced.

For future studies, the optimization of the diffuser is a good research area to investigate the effect of various design parameters such as the diffuser opening, distance between rotor and diffuser, and the diffuser shape. In addition, for the sake of understanding the flow field around the diffuser, the authors are currently conducting the CFD simulation.

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