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Experimental and simulation investigation into the effects of a flat plate deflector on vertical axis wind turbine

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ABSTRACT

Power augmentation features have been proven as one of the wind turbine performance enhancement methods particularly for vertical axis wind turbines (VAWTs). Researches showed that with the aid of a deflector, shroud or a single plate, the power output of a VAWT can be increased remarkably. In this paper, lab tests and simulations were performed to investigate the aerodynamic effects and the flow field around a flat plate deflector as a power augmentation device which is placed at the lower upstream of a micro H-rotor VAWT. From the study, the deflector is able to induce a high velocity wind at the near-wake region which was about 25% higher compared to the oncoming wind velocity. The deflected wind flows improve the performance significantly as well as reduce the self-start velocity of the turbine. Nonetheless, it is highly dependent on the positioning of the flat plate deflector. Both experiment and simulation showed a notable observation on the position effect of the flat plate deflector. From the lab test, with the deflector at the optimal position, the maximum coefficient of power (C_P) achieved was 7.4% increment compared to the bare turbine. Also, from the simulation, the optimal position showed an improvement of averaged C_P up to 33% compared to the bare turbine. The flat plate deflector is simple, low cost, and can be easily retrofitted to existing stand-alone VAWT systems to improve the efficiency making them suitable for on-site power generation in urban and isolated places.

1. Introduction

Recently, vertical axis wind turbines (VAWTs) have gained attention for wind energy harvesting due to their unique omni-direction characteristic, compactness, and the ability to operate in harsh turbulence conditions. Various innovative ideas have been proposed and adopted by researchers to achieve higher efficiency for the VAWT including the modification of the VAWT configuration and the blade section.

A new patented Darrieus VAWT design was introduced by Batista et al. [1] in which the end of the blades can be bent into any angle inside, outside or parallel to the main blade body. When the blade's end is bent inward, it allows the wind turbine to extract wind energy from both the vertical and horizontal directions. Moreover, the augmented blade profile height improves the self-starting behavior of the turbine. The articulating H-rotor is another idea that allows the blades to oscillate freely and tilt around the rotor shaft by an articulating joint [2]. This design allows a low self-start, and the blades are swift to adapt to the wind flow. Hara et al. [3] suggested a double blade VAWT which can be transformed into a butterfly-shaped wind turbine that improves the self-starting behavior at low *TSR*, especially when the ratio of the inner blade to the outer blade is increased. Modification on the rotor blade is another approach to improve the performance of the VAWT. As reported in [4], winglets and endplates were added to the rotor blades to produce extra lift forces while lowering the drag forces and eliminate the blade tip losses, resulting in significant efficiency improvement where the airfoil behaved like a 2-D blade. Beri and Yao [5] claimed that a modified airfoil divided into two sections with a trailing edge was able to improve the self-start of a VAWT. Adding semi-circular dimple cavity [6,7] and Gurney flap [7] on the blade profile improved the turbine efficiency by about 25% due to the generated flow recirculation that increased the lift force at a positive angle of attack and hence the tangential force was increased.

Power augmentation device is another popular method that can improve the performance of the VAWT output significantly. Some researches have shown that with the power augmentation feature, the wind turbine can exceed the Betz limit [8,9]. However, the addition of

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Nomenclature

CFD	computational fluid dynamics
C_P	coefficient of power
C_T	coefficient of torque
D	rotor diameter (m)
H	rotor height (m)
R	rotor radius (m)
$U\infty$	oncoming wind speed (m/s)
VAWT	vertical axis wind turbine
X	horizontal distance (m)
Y	vertical distance (m)
α	angle of attack (°)
β	pitch angle (°)
ω	rotational speed (rpm)
λ	tip speed ratio, TSR
θ	azimuthal angle (°)

components will incur extra cost. Among the power augmentation features reported in [8], a flat plate deflector is the simplest power augmentation device. Mohamed et al. [8,10] employed an obstacle shielding plate in front of a Savonius rotor returning blade which reduced the counter moment of the turbine, hence improving the total moment of the turbine. The measured power output coefficient was increased by about 38.9% compared to the conventional Savonius rotor. For the conventional Savonius rotor, the negative static torque coefficient that prevents it to self-start was fully eliminated by the optimal obstacle plate, and it further increased the static torque coefficient significantly, hence the self-start capability was always obtained as the major advantage of the obstacle shielding plate. A similar finding was reported by Golecha et al. [8,11], where the position of the deflector plate was investigated. The research revealed that an optimal position of a deflector plate at upstream would maximize the Savonius rotor power output, where the coefficient of power was increased by about 50% in the experiment. The deflector plate acted as an obstacle for the flow towards the returning blade that generated negative torque. However, the positioning of the deflector was crucial; for an inappropriate orientation, the plate did not cover the returning blade, but the accelerated flow created higher reverse flow. Atlan and Atilgan [12,13] conducted experiments and simulations of a curtain plate on the performance of a Savonius rotor. The curtain plate comprises two flat plates with the same function as the aforementioned research. With the curtain plate, the rotor performed better.

Most of the research on the flat plate deflector employs a drag-type VAWT. In Kim and Gharib [14] research, an upstream deflector was introduced to improve the efficiency of two counter-rotating straight bladed VAWTs. A proper positioning of the VAWT behind the deflector was able to increase the tailoring free stream. As the power output is proportional to the cube of the oncoming wind velocity, thus the VAWT power output increased significantly. However, the power output was reduced in the situation when the turbine was placed inside the streamline or too close to the deflector due to small flow inside the wake region. A similar investigation of the upstream deflector on a pair of counter-rotating H-rotor VAWTs was performed by Jin et al. [15] by experiment and simulation. The study revealed that the upstream deflector is able to enhance the power output significantly; however, it is highly dependent on the size and the position. As the deflector width was increased, the near wake region became larger which reduced the power output of the VAWT, also, the further the distance of the deflector from the VAWTs, the augmentation effects became less. Other than using a flat deflector, Takao et al. [16,17] employed the guide vane row which comprises of three arc plates that are positioned at the upstream of a three-bladed H-rotor VAWT. The design can be yawed by the tail vanes to orientate the direction to align to the wind flow. The guide vane row deflects the wind flow to increase the positive torque where the maximum C_P was increased by 1.5 times with the design. Also, Santoli et al. [18] investigated a convergent duct on a H-rotor VAWT. From his research, by using the concept of the Venturi effect, the wind velocity was increased with the reduction of the cross-sectional area of the convergent duct, hence the power generated was increased by about 125% and 30% at wind velocity 8 m/s and 15 m/s respectively. Another curve-shaped upstream deflector design was investigated by Stout et al. on a three-bladed H-rotor [19]. This deflector redirects the wind flow from the returning turbine blade, hence reducing the negative torque generated on the VAWT.

For most of the augmentation devices, they are based on the principle of obtaining higher mass flow rate for the wind stream by converging the flow before it interacts with the turbine, thus, creating a higher positive torque on the VAWT. In comparison between the drag type and lift type VAWT, the drag type VAWT mainly reduces the negative torque created on the returning blade by diverting the flow towards the advancing blade. While for most of the lift type VAWT, the function of the augmentation device is to change the wind path to a better angle of attack on the airfoil blade to create higher lift forces for the rotation [8].

From the literature review, scarce research has been conducted on the effects of a flat plate deflector as a power augmentation device on lift-type VAWTs. Also, most of the research have been conducted with the deflector being placed side by side with the VAWT using 2D simulation. The 3D flow effects are still unclear. The key objective of this work is to investigate the effect of the flat plate deflector on a VAWT by varying the position at the lower upwind via experiment and 3D simulation. The present paper is organized as follows: in Section 2, the basic formulation of a VAWT, the lab tests setup and methodology are explained. The CFD simulation modeling and numerical settings are reported in Section 3. Section 4 presents the results of the experiment and simulation, with discussions on the findings. Finally concluding remarks on the study are reported in Section 5.

2. Lab test

2.1. VAWT performance parameters

The flow characteristics for a straight bladed VAWT is complicated compared to the HAWT, where the lift and drag forces created on each HAWT blade are the same. For the VAWT, because the resultant wind velocity impinges on the blade at a different angle of attack, the lift and drag forces generated on each blade at various azimuthal angles periodically changes [20]. Fig. 1 illustrates the forces and velocities on a VAWT, F_L and F_D representing the lift force and the drag force created by the rotor blades.

For the wind turbine, the tip speed ratio (*TSR)*, λ is defined as the ratio between the blade's tip speed and the on-coming wind speed [6,21–23].

$$TSR,\lambda = \frac{R\cdot\omega}{U\infty}, \tag{1}$$

where ω denotes the rotational speed of the VAWT, R is the rotor radius and $U\infty$ is the oncoming wind speed. The relation between the angle of attack, α, the pitch angle, β, the azimuthal angle, θ and the TSR, λ is expressed as [20,24]:

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\lambda + \cos\theta}\right) - \beta, \tag{2}$$

In order to evaluate the wind turbine efficiency, there are two important parameters which are the coefficient of torque, C_T and the