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Influence of the vertical wind and wind direction on the power output of a small vertical-axis wind turbine installed on the rooftop of a building

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HIGHLIGHTS

- The vertical wind has an impact on the power output of a SVAWT in an urban area.
- 90% of the power is generated when the vertical angle is less than 45°.
- Efficiency is over 40% only when the horizontal wind speed is more than 8 m/s.
- Ratio of the power generated by the unknown direction is between 31.1% and 8.4%.
- Turbulence intensity converges at about 30% when the wind speed is more than 8 m/s.

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ABSTRACT

The goal of this study is to investigate the performance of a small vertical-axis wind turbine at an environment with the turbulence intensity more than 30%, particularly on the influence of the vertical wind, the vertical angle, the wind with the unknown direction, the horizontal wind speed, and the turbulence intensity on the power output, which are seldom reported before. The results show that more than 90% of the power is generated when the vertical angle is less than or equal to 45°. The vertical wind speed has the obvious influence on the power when the horizontal wind speed is between 5 m/s and 8 m/s. The percentage of the power generated by the wind with the unknown direction decreases from 31.1% to 8.4% as the horizontal wind speed increases from 4 m/s to 9 m/s. The efficiency is over 40% only when the horizontal wind speed is over 8 m/s. The higher turbulence intensity increases the power at the lower wind speed, but decreases the power at the higher wind speed. Furthermore, the results can be used as a reference for the improvement of aerodynamic characteristics, efficiency, CFD simulation and the location selection of a vertical-axis wind turbine.

1. Introduction

It is well known that small wind turbines which are classified into horizontal-axis wind turbines (HAWT) and vertical-axis wind turbines (VAWT) are differentiated from larger wind turbines by the amount of generated power [1–3]. The small wind turbines are mainly used in residential areas for a distributed power generation or in remote communities as a power source. Therefore, the interactions between the winds and the buildings and topologies in a residential area are very important when considering the locations of the wind turbines for the distributed power generation. Frandsen [4] illustrated that the wind flow field in a metropolitan area is much more complicated than that of a flat ground area, which has an effect on the performance of a wind turbine. Turbulence will be induced when the wind interacts with the surface of both the buildings and the ground. Turbulence is the continuously changing movement superimposed on the average of the wind movement. Consequently, turbulence will affect turbine loads, fatigue, and noise [5], resulting in a significant reduction in the power output. Arifujjaman et al. [6] discussed how generators that are scattered on residential buildings, apartments, and office buildings in order to a create a distributed power generation scheme need to be connected with the electrical grid. To ensure the best use of the wind turbine, most small wind turbines are placed on the rooftop of buildings in a metropolitan area in order to reduce interference from turbulence induced by the interaction of the wind with the ground and the buildings.

Jimenez et al. [7] and Wu et al. [8] indicated that not only does the interaction of the wind with the buildings cause turbulence, but also the operation of the wind turbine. Hence, the induced turbulence may affect the efficiency of the power output. In addition, Bowen et al. [9] used a wind tunnel to study the characteristics of wind turbulence and

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Nomenclature

3D	three-dimension
Bin	data binning in an interval
CFD	computational fluid dynamics
HAWT	horizontal-axis wind turbine
Nan	unknown wind direction
P_{AVG}	average power output
P_{TI}	power output at TI greater or less than average TI
PIV	particle image velocimetry
R	ratio
RMS	root-mean-square
S_H	horizontal wind speed
SVAWT	small vertical-axis wind turbine
TI	turbulence intensity
VAWT	vertical-axis wind turbine
u'	RMS of the standard deviation of wind speed in 3D [m/s]
U	average wind speed in 3D [m/s]
u'_x	the standard deviation of the wind speed along the x-axis (horizontal)
u'_y	the standard deviation of the wind speed along the y-axis (horizontal)
u'_z	the standard deviation of the wind speed along the z-axis (vertical)
Ux	the wind speed along the x-axis
Uy	the wind speed along the y-axis
Uz	the wind speed along the z-axis

found that the fluid flow is affected by the topography. Consequently, it is almost impossible to completely eliminate turbulence.

Hansen et al. [10] explained the influence of turbulence intensity (TI) on fluid structures and indicated that this influence may cause a reduction in the power output of the wind turbine. Hara et al. [11] highlighted that pulsating wind gusts have an effect on vertical-axis wind turbines. This type of wind is a sudden strong gust lasting for approximately one second, commonly seen in the measurement data. In these situations, the wind speed is high, but the power output is relatively low.

For the HAWT, the small wind turbine performance and safety standard have been developed [1–3]. Research with tunnel experiments for power performance and TI, and computational fluid dynamics (CFD) methods for aerodynamic force on the blades of the HAWT has abundantly investigated [12–15]. Li et al. [12] found that the TI has no significant effect on the performance of the HAWT in wind tunnel experiments at the turbulence intensities of 1.4%, 8.0% and 13.5% and at the free stream wind velocity of 7.0 m/s. Li et al. [13] also reported that the power coefficient is highly related to the pitch angle and the yaw angle. Sheinman et al. [14] reported that turbulence may change an estimation of power coefficient by more than 10% via using a dynamic model. Sicot et al. [15] reported that turbulence has bare influence on power and thrust coefficients at the turbulence intensities of 4.4%, 9.0%, and 12%, while the wind velocity is more than 8.0 m/s via wind tunnel experiments.

Comparing with the HAWT, the advantages of the VAWT are (1) the VAWT has less material stress on the tower [16]; (2) the VAWT can obtain wind energy from any wind direction without yawing [16–19]; (3) the VAWT can has higher efficiency in a built environment [18,20,21]; (4) the VAWT can be operated in an environment with high TI [17,18,21–25]. The disadvantages of the VAWT are that the VAWT has unstable aerodynamic characteristics during the rotation caused by the fluctuation of velocity of the blade and the blade angle of attack [19,20]. For HAWT, airflow is uniform into the rotor surface and the torque retains constant. However, for VAWT, the aerodynamic behavior is much more complicated. Airflow into the rotor surface will be disturbed in the downstream region and then the fluctuation torque will be induced [26,27]. Furthermore, the small wind turbine performance and safety standard for VAWT have not been developed due to the small amount of experimental data and consistent results [26]. Consequently, substantial wind tunnel experiments and CFD simulations focused on VAWT are performed [28–39]. Ferreira et al. [28] reported the influence of the turbulence from the vertical structures induced by the blade. Danao et al. [29] reported the influence of stable and unstable airflow with a speed of 7 m/s on the performance of the VAWT via CFD simulation. Howell et al. [24] developed a 3D CFD model to investigate the influence of solidity, roughness, and the tip vortices. Although CFD simulation can analyze the fluid dynamic characteristics, it is still difficult to completely investigate the physical phenomena of the VAWT during rotation. Therefore, Ferreira et al. [30] introduced particle image velocimetry (PIV) method to analyze the flow field around a single blade of the VAWT. Rezaeiha et al. [31] reported that power coefficient of a VAWT is increased by 6.6% by using a pitch angle of -2° at a tip speed ratio of 4 from CFD simulation. It indicates that dynamic pitching for a VAWT might be a promising approach for the better power output. Balduzzi et al. [32] reported that the attended capacity factor of H-Darrieus VAWT on the rooftop of a building in the urban environment is increased up to 70% when the height of the building is reasonably higher than the average of the surrounding constructions and other factors are fulfilled. In addition, the skew angles between 15° and 35° seem to increase the energy harvesting on the rooftop of a building up to 12%. Li et al. [33] and Maeda et al. [34] reported that the velocity deficit becomes greater from upstream to downstream regions in the main stream direction inside the VAWT. Li et al. [35] reported that the wind energy obtained by the VAWT is mainly depended on the upstream side. Li et al. [36] further investigated the influence of TI on power performance and found that power is slightly affected by the increasing TI at low tip speed ratios and power increases as TI increases at higher tip speed ratios. Bravo et al. [37] also investigated the influence of wind speed on power output via wind tunnel experiments and found that the optimum power coefficient is higher and the optimum tip speed ration is lower at the higher wind speed. Chen et al. [38] reported that the mean power coefficient can be increase by 9.97% with the optimal design at the wind speed of 8 m/s. Danao et al. [39] reported the unsteady free stream causes a drop in energy generation of the VAWT. In addition, Yang et al. [40] reported that the CFD-based evaluation model for the possible sites of the wind turbines in the urban area by considering the local topography, boundary conditions, wind speeds, wind directions and TI is developed and then compared with field measurements to validate the model.

From the above-mentioned research results, it can be seen that aerodynamic characteristics of the VAWT is well studied via the wind tunnel experiments and CFD simulations. However, the field experiments for a small vertical-axis wind turbine (SVAWT) at an environment with the average TI more than 30% is not reported yet. Furthermore, though a VAWT can obtain wind energy from any wind directions, the vertical wind and various horizontal wind directions may affect the power output of the SVAWT in certain conditions.

Therefore, the goal of this study is to investigate the influence of the vertical and horizontal winds, the wind direction and TI on the power output of the SVAWT that is located on the rooftop of a building in Danshui, Taiwan, where the average TI is more than 30%.

The novelty of the present study which is seldom reported before is briefly described below.

(1) The influence of the vertical wind on the power output of the VAWT is investigated. It can be understood whether the prevailing wind