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Development of small wind turbines for moving vehicles: Effects of flanged diffusers on rotor performance

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ABSTRACT

The main object of this research is to develop a shrouded, small, horizontal-axis wind turbine for moving vehicles. Specifically, this study investigates the effects of flanged diffusers on rotor performance of small (30 cm rotor diameter) wind turbines with different rotor solidities (20–60%) and wind speeds (10–20 m/s). The experiments are conducted in a wind tunnel with and without a flanged diffuser. Results show that the flanged diffuser may significantly increase the power output, torque output, and rotor rotational speed of the wind turbine, largely depending on rotor solidity and wind speed. The higher the solidity and wind speed are, the smaller the effect of the flanged diffuser is. The 30%- and 40%-solidity rotors generate the largest power and torque outputs, respectively, while the 60%-solidity rotor has the lowest rotor rotational speed among the test rotors. These results provide some useful information when considering rotor-generator matching problems and the selection of rotor solidity for moving vehicles. This study also shows that a small wind turbine has the characteristics of low torque and high rotor rotational speed, and high rotor solidity for maximum power output compared to a conventional large wind turbine.

1. Introduction

The development and application of renewable, clean energy have become a very important issue in recent years due to the serious effects of global warming and rapid depletion of fossil fuel. Wind energy technologies have become one of the fastest growing energy sources in the world. Many factors play a role in the design of a horizontal-axis wind turbine (HAWT), including rotor aerodynamics, generator characteristics, rotor-generator matching, electrical output control and so on. Rotor aerodynamics plays a particularly important role in wind energy extraction.

Rotor aerodynamics of wind turbines have been the subject of much research. Duquette and Visser [1] examined the effect of rotor solidity and blade number on aerodynamic performance, revealing that the range of tip speed ratio for maximum C_P (power coefficient) varies strongly with solidity and weakly with blade number. Higher than traditional solidities and blade numbers result in higher C_P. Increasing the solidity from the conventional 5–7% to 15–25% yields higher $C_{P,max}$. Lanzafame and Messina [2] studied the performance of a double-pitch wind turbine with non-twisted blades. Results show that a non-twisted blade rotor has 15% less power output than a twisted one. The wind turbine they designed can effectively increase rotor power output compared with the traditional non-twisted blade rotor.

Diffuser augmented wind turbines (DAWT) were a hot topic at the 1979 Wind Energy Innovative Systems Conference [3]. 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. Wind power generation is proportional to the cube of the wind speed. A large increase in power output can be achieved with a slight increase in the velocity of the approaching wind to a wind turbine. Van Bussel's study [3] shows that the power augmentation is proportional to the mass flow generated at the nozzle of the DAWT. Such mass flow augmentation can be achieved through two basic principles: increase in the diffuser exit ratio and/or by decreasing the negative back pressure at the exit. Comparison with a large amount of experimental data found in literatures shows that power augmentation factors above three have never been achieved. Matsushima et al. [4] studied the effect the diffuser's shape had on wind speed. Results show that the wind speed in diffuser is greatly influenced by the length and expansion angle of the diffuser, and maximum wind speed increases 1.7 times with appropriate diffuser shape. Abe et al. [5] investigated the flow fields of a small wind turbine with a flanged diffuser, showing that the power coefficient of the shrouded wind turbine is about four times that of a bare wind turbine. Ohya et al. [6] examined the optimal form of the flanged diffuser, and demonstrated that power augmentation by a factor of about four to five, compared to a bare wind turbine.

Wang et al. [7] investigated a convergent–divergent scoop effect on the power output of a small wind turbine. Results show

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that the scoop boosts the airflow speed and increases the power output of 2.2 times with the same swept area. Bet and Grassmann's [8,9] results show that the power of a wind turbine is increased by a factor of two, through a wing structure placed at some distance around the turbine. Framlpvoc and Vrsalovic [10] designed a ring wing and placed it around a wind turbine, with its lower-pressure side pointed towards the center. The lift force on every part of the wing is directed radically centripetally. This forces a greater air mass flow to pass through the turbine and increases power efficiency up to 3.5 times. The investigations into the effect of diffusers on the performance of hydrokinetic turbines also received attention [11,12]. Similar to the results in DAWTs, these studies show that the use of diffusers is able to augment the power output.

These previous studies focused on relatively large rotor diameters and low speeds, revealing that all the different-type diffusers are able to augment the power output. None of these researches discussed the diffuser effects on torque output and rotor rotational speed, which may be important to a small-size wind turbine. One of the conclusions from the 1979 Wind Energy Innovative Systems Conference was that power augmentations are possible by diffusers, but economic application of DAWT's seemed not feasible because of the high costs of the configuration [3]. A technology status review by Khan el al. [13] also doubt whether duct augmentation is worth attempting in hydrokinetic turbines. In addition, the field tests conducted by Matsushima et al. [4] showed when the wind direction changes frequently, the diffuser may not make effective use of wind energy. Although several small DAWTs have recently entered the market [14,15], they are not designed for moving vehicles.

A moving vehicle can easily induce high-speed wind, and usually induces more stable wind than natural wind. When applying a wind turbine in vehicles, the rotor diameter must be small for installation and drag considerations. Also, the wind turbine can be installed in right positions to avoid or minimize additional aerodynamic drag [16,17]. Thus, the DAWT is very suitable for moving vehicle applications either from economic or wind-source consideration.

The rotor performance of a small DAWT may be different from a conventional large DAWT. The three-blade rotor has been adopted extensively for large commercial horizontal-axis wind turbines. However, rotors with more than three blades have been used in small (rotor diameter of a few meters) commercial horizontal-axis wind turbine [14,15]. The results by Duquette and Visser [1] indicated that higher than traditional solidities and blade numbers result in higher C_P for small rotor diameters. Increasing the solidity from the conventional 5–7% to 15–25% yields higher $C_{P,max}$. The current study investigates the aerodynamic characteristics of small, horizontal-axis wind turbine for moving vehicles. Thus, more than three-blade rotors (high-solidity rotors) will be adopted in the study.

A series of studies are currently conducted to develop a shrouded, small, horizontal-axis wind turbine for moving vehicles, including the studies of turbine rotor performance, rotor-generator matching and electric power-output control. The generated electricity can be used to charge batteries to increase the endurance of electric vehicles, to supply electric power to vehicles to save energy. It can also provide DC power to charge portable electronics, to water electrolyzers for hydrogen production. This study applies a flanged diffuser on a small (30 cm rotor diameter) wind turbine, and focuses on the flanged diffuser's effects on turbine power output, torque output, rotor rotational speed, and compares the rotor performance with different blade numbers and wind speeds.

2. Experimental setup and methods

Figs. 1 and 2 present a schematic of the wind tunnel system and photographs of the primary experimental setup utilized in this study, respectively. A 9 m long, open-circuit wind tunnel was developed for the present study. The test section of the wind tunnel is 1.3 m high, 1.3 m wide and 3 m long. A 60 hp blower was used to drive the airflow, with the maximum air speed 25 m/s in the test section. The flow turbulence intensity was less than 1%, and the flow uniformity was greater than 99%.

Turbine blades were attached to a cone hub with a base diameter of 6 cm, which was connected to a measurement apparatus, including a torque sensor, a rotational-speed sensor, and a magnetic particle brake by Chain-Tail Co., LTD, Taiwan [18]. The torque sensor measures the torque range from 0 to 1 N-m with the uncertainty of 0.1%, the rotational-speed sensor measures the rotor speed up to 6000 rpm (revolution per minute) with the uncertainty of 1%. The magnetic particle brake utilizes electromagnetic powder to transmit torque, which simulates loadings on the rotor. When the voltage is applied to the brake, the torque is generated, which can be adjusted by the applied voltage. The measurement apparatus was placed on a support located in the middle of the tunnel test section. A pitot-static tube, placed 1 m upstream of the rotor, measured the total and static pressures of moving air by a digital pressure sensor. Local pressure, temperature and humidity were also measured to account for density variation during each run. The free-stream air velocities were calculated using Bernoulli's equation. Repeatability tests indicate that the uncertainty due to the measurement system on rotor performances is less than 6%.

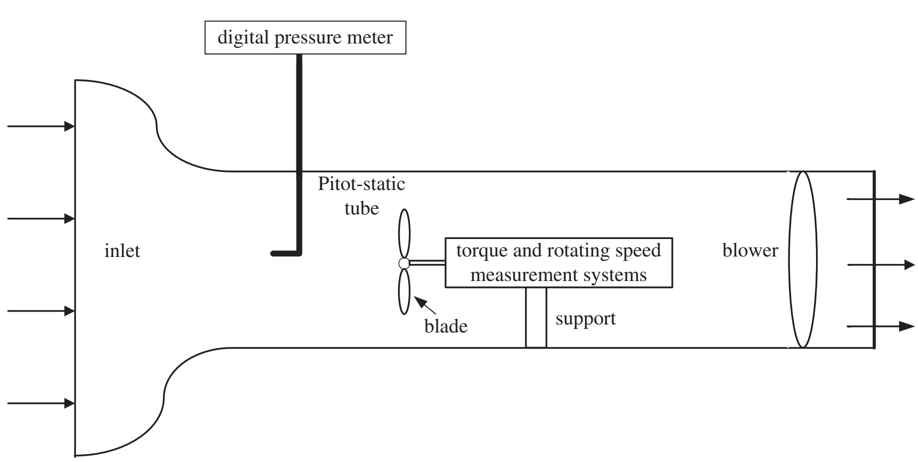

Fig. 1. A schematic of the wind tunnel system.