Journal of Wind Engineering & Industrial Aerodynamics 179 (2018) 229–239

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Blockage corrections for wind tunnel tests conducted on a Darrieus wind turbine

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ARTICLE INFO

Keywords:
Blockage effect
Blockage correction
Darrieus wind turbine
Vertical axis wind turbine
Wind tunnel test

ABSTRACT

In this study, the influence of the blockage ratio in three wind tunnel tests conducted on a small vertical-axis Darrieus wind turbine was quantitatively investigated. The vertical-axis Darrieus wind turbine was installed in three wind tunnels with different test-section sizes corresponding to blockage ratios of 3.5, 13.4, and 24.7%. The rotor torques, drag force, and upstream wind speeds were measured for the different blockage ratios. It is recommended from the tests that the reference wind speed of the wind turbine should be measured upstream at a distance of 3.5 times or more than the turbine diameter. The power coefficient of the wind turbine was severely distorted based on the blockage ratio. The power coefficients at blockage ratios of 13.4 and 24.7% were respectively 1.3 and 2 times higher than that at a blockage ratio of 3.5%. The optimal tip speed ratio also significantly shifted to a higher range. Based on the method proposed by Maskell (1963), a new correction coefficient is proposed for the Darrieus turbine from the measured drag coefficients obtained at three different blockage ratios. The validity of the proposed correction coefficient was confirmed by comparing it with the corrected power coefficients obtained using other correction methods.

1. Introduction

To increase the economic efficiency of wind power generation, wind turbines with a very large diameter are installed in mountainous or coastal areas where wind resources are abundant. With each passing year, the numbers of large wind-power generators and large-scale wind farms are increasing. In recent years, a significant growth is observed in small wind-turbine systems, which can supply independent power to streetlights, telecommunication equipment, and disaster monitoring equipment; moreover, they serve as distributed power sources (Pitteloud and Gsanger, 2016). Recent research results reveal that a vertical-axis wind farm might produce higher power densities compared to a horizontal-axis wind farm by arranging counter-rotating vertical-axis wind turbines (Dabiri, 2011).

When a new wind turbine is developed, the output performance must be evaluated prior to releasing it on the market. In addition, the output performances of the individual wind turbines must be known for micro siting of a wind farm. The following is a method of evaluating the output performance of a wind turbine. First, a wind turbine is installed in the field, the output power of which is directly measured. Second, a wind tunnel test is conducted to measure the output performance of the wind turbine. Compared to the field test method, the wind tunnel test has an advantage in that the output performance can be measured in a short period of time and at a low cost. In addition, the wind tunnel tests can be precisely controlled, allowing experiments to be conducted at various desired wind velocities and low turbulence intensities to obtain consistent and high-quality data. Thus, the wind tunnel tests are often used to evaluate the output performance of a small vertical axis wind turbine (VAWT).

However, the boundary walls in closed jet test section wind tunnels generally prevent free expansion of the separated flow behind the wind turbine, resulting in a distorted wind flow around the model, which is different to that observed in an actual wind environment (Chen et al., 2011). The flow and pressure around the model and along the wind tunnel will be affected by solid and wake blockage effects. Thus, as the output power of the wind turbine is proportional to the third power of the wind speed, the wind acceleration due to the blockage effect significantly affects the output performance of the wind turbine. Ideally, to avoid these effects a small test model size would be selected but there cases where this is not possible, like Reynolds scaling, better signal-noise in

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https://doi.org/10.1016/j.jweia.2018.06.002
Received 2 September 2017; Received in revised form 7 June 2018; Accepted 7 June 2018

force and torque measurement, use of available model, ignorance of acceptable scale for an unsteady blockage, etc. Hence, it is necessary to correct the blockage effect to accurately evaluate the output power of a wind turbine measured in a wind tunnel test.

Since the 1930s, wind tunnel tests have been conducted on a VAWT; however, most authors lacked confidence in the experimental results because the effect of the blockage was neglected (Blackwell et al., 1977). Several studies have applied the blockage correction method to the results of the wind tunnel test. Blackwell et al. (1977) used the correction formula proposed by Pope and Harper (1966) to correct the effects of the blockage on the wind speed and pressure to analyze the output performance of a Savonius wind turbine. In the study, although the uncertainty in the Pope and Harper's correction factor was estimated to be 50%, the method was applied because there was no other method to correct the blockage effect for the Savonius wind turbine at the time. Alexander et al. (1978) suggested a slight modification of Maskell's method (1963) to the Savonius turbine. They measured the drag force of a Savonius turbine, and then presented modified the correction factor. Ross and Altman (2011) investigated wake characteristics and performance produced by the same Savonius vertical-axis wind turbine at different physical scales and in two different wind tunnels.

Bahaj et al. (2007) measured the output power and thrust based on the rotor speed, flow velocity, and hub pitch angle for a marine current turbine in a cavitation tunnel and a towing tank. The correction methods for general propellers, such as the methods proposed by Glauert (1947) and Pope and Harper (1966), are unsuitable for negative thrust generators. Hence, Bahaj et al. (2007) modified the method proposed by Glauert (1947) to correct the blockage effect on the marine current turbine.

By conducting a wind tunnel test using a small horizontal-axis wind turbine, Chen et al. (2011) confirmed that the blockage effect was more affected by the tip speed ratio (TSR), blade pitch angle, and blockage ratio, and less affected by the wind speed. In addition, the correction coefficient obtained from the experiment was applied to the correction formula proposed by Bahaj et al. (2007). The results show that the correction is unnecessary when the pitch angle is 25° or more and when the blockage ratio is less than 10%. Cho et al. (2012) placed three different wind turbines in one wind tunnel, and corrected the power coefficient using the method proposed by Bahaj et al. (2007). However, they did not verify that the electrical and mechanical characteristics of the three wind turbines used were the same. It is therefore unclear whether their test results were affected by the blockage ratio or other factors.

Cavagnaro and Polagye (2014) measured the torque of a tidal generator based on the blockage ratio and flow velocity in water channels of different sizes. They corrected the results obtained by the methods proposed by Pope and Harper (1966), Bahaj et al. (2007), and Werle (2010). The corrected results show that the output powers were reduced in all the methods; the method proposed by Werle (2010) resulted in the most reduction in the output power among them. However, as Cavagnaro and Polagye explained, the methods applied were ineffective in correcting the turbine output likely because the correction methods don't account for the full physics in blockage effect problems. Although various studies have been conducted to solve the problem of the blockage effect in the wind tunnel test conducted on a wind turbine, studies on correcting the blockage effect for a Darrieus turbine are lacking.

The purpose of this study is to propose a method to effectively correct the blockage effect observed in three wind tunnel tests conducted on a small Darrieus turbine. Hence, a single vertical-axis Darrieus turbine was installed on three wind tunnels with different test sectional sizes. The torque and angular velocity were measured and then power, power coefficient and tip speed ratio were calculated. We applied the various existing correction methods and the proposed correction method to the measured output power to compensate for the blockage effect, and presented the results.

2. Blockage effects and correction methods

2.1. Blockage effects

Unlike a wind turbine exposed to free air without a boundary away from the ground, the wind flows in a closed test section of a wind tunnel are different because the four walls serve as boundaries. The distance from the test specimen to the stream boundary of the test section of the wind tunnel is usually shorter than that in an actual operating condition in natural environments (Barlow et al., 1999), resulting in a blockage effect.

The blockage effect can be divided into solid blockage and wake blockage (Fig. 1). A solid blockage occurs because of the decrease in the area for wind passing due to the test specimen inside the wind tunnel (Fig. 1(a)); moreover, it depends on the blockage ratio defined by the ratio of the projected specimen area to the cross-sectional area of the wind tunnel. As shown in Fig. 2, the wind speed increases and the pressure decreases to satisfy the Bernoulli equation, wherein the mass flowing through the area reduced by the test specimen must be constant. The wind speed temporarily increases near the test specimen, and after passing through the specimen, the solid blockage effect decreases, and the wind speed is restored to a free air flow condition. For the same blockage ratio, the effect of the solid blockage is known to be greater in a closed test section than in an open test section.

For a wind turbine, the near wake extends several diameters downstream; however, the size of the turbine wake is limited because of the test section wall. This wake blockage is more complicated because the size of the wake is itself a function of the drag or energy extracted from the flow and the wake to tunnel area ratio. The magnitude of the correction for the wake blockage increases with an increase in the wake size, which corresponds to an increase in the drag (Barlow et al., 1999). The wake blockage in an open test section is considered negligible because the air flow is freely diffused. However, in a closed test section, the wake blockage leads to an increase in the wind speed and should be considered.

If the solid and wake blockages can be superimposed, the variations in the wind speed occur along the wind tunnel, as shown in Fig. 2 (Hacket and Wilsden, 1975). These blockage effects influence the results of the wind tunnel tests, and thus, the blockage ratio is generally limited to 5% to avoid these effects (Cockrell, 1980; Barlow et al., 1999; ASCE, 2012). For the Savonius turbine, the blockage ratio should be kept to under

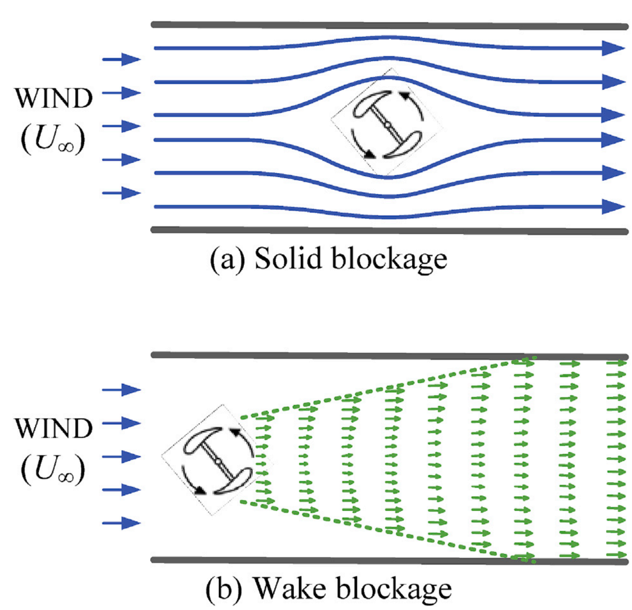

Fig. 1. Effect of a vertical-axis wind turbine on streamlines.