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Article *in* Experimental Thermal and Fluid Science (EXP THERM FLUID SCI) · April 2011

DOI: 10.1016/j.expthermflusci.2010.12.005

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Experimental Thermal and Fluid Science 35 (2011) 565–569

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Blockage corrections in wind tunnel tests of small horizontal-axis wind turbines

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ARTICLE INFO

Article history:
Received 22 April 2010
Received in revised form 30 November 2010
Accepted 13 December 2010
Available online 17 December 2010

Keywords:
Horizontal-axis wind turbine (HAWT)
Wind tunnel
Blockage effect

ABSTRACT

This study quantitatively investigates the effects of tunnel blockage on the turbine power coefficient in wind tunnel tests of small horizontal-axis wind turbines (HAWTs). The blockage factor (BF), $\left(\frac{U_T}{U_F}\right)^3$, was determined by measuring the tunnel velocities with and without rotors using a pitot–static tube under various test conditions. Results show that the BF depends strongly on the rotor tip speed ratio (TSR), the blade pitch angle (β), and the tunnel blockage ratio (BR). The larger the TSR and BR are, the smaller the BF is. The BF approaches a constant value when the TSR exceeds a certain value. No blockage correction is necessary for small TSR under all of the investigated conditions, and for the investigated blade pitch angle of 25°. This study also shows that the blockage correction is less than 5% for a BR of 10%, which confirms that no blockage correction for a BR less than 10% in literatures is acceptable.

1. Introduction

Many aerodynamic designs, such as aircrafts, automobiles, high-rise buildings, and wind turbines, are based on the combined results of experimental, theoretical, and computational methods. A wind tunnel is the most important tool in experimental aerodynamics. Wind tunnels make model studies possible and can provide a large amount of reliable data to support design decisions. Wind tunnels also save time and money in the design process. However, the flow conditions in a wind tunnel are not the same as those in an unbounded air-stream; mainly because the wind tunnels test section is finite in size. Consequently, wind tunnel tests must consider some effects, including horizontal buoyancy, solid blockage, wake blockage, and so on [1]. In an ideal case, the solid blockage (the ratio between the model frontal area and the test-sectional area) for a solid model, such as an aircraft model, is 5% or less. Higher blockages require corrections. This research focuses on experimental blockage studies in wind tunnel tests of rotating rotors.

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, blade strength, and so on. Rotor aerodynamics plays a particularly important role in wind energy extraction. Many researchers have conducted rotor performance experiments in wind tunnels. As noted above, when a wind turbine operates in a closed wind tunnel, the tunnel walls constrict the airflow. This constraint forces air to flow through the turbine faster than it would normally, meaning the turbine produces more power than when operating in an unbounded environment. This tunnel blockage effect is generally a function of the rotor blockage ratio (BR), and the power produced by rotors [2]. The power produced is dependent on the tip speed ratio (TSR) and the rotor pitch angle (β). The BR is the ratio between the rotor disk area and tunnel test-sectional area, the TSR is defined as the ratio between the blade tip speed and the free stream velocity, and the β is the angle between the blade chord line and the rotor rotating plane.

In wind turbine experimental studies, it seems that no blockage correction is required for a rotor blockage ratio of around 10%. Schreck et al. [3] conducted their 10.1 m diameter of rotor performance studies in the NASA Ames 80 ft × 120 ft wind tunnel with a rotor blockage ratio of 9.3%, and they made no blockage correction. Hirai et al. [4] conducted wind tunnel experiments to understand the basic aerodynamics of a HAWT. The rotor blockage ratio in their study is around 10% in a wind tunnel with cross section area of 30 m^2. Also, they made no blockage correction.

Watkins and Walter [2] performed a wind tunnel study of a wind generator and associated electronics for its performance characteristics in the RMIT industrial wind tunnel. The tested wind turbine had an external diameter of 1.1 m, and the closed-jet type wind tunnel had a 2 m high, 3 m wide, and 9 m long test section. The rotor blockage ratio was 16%, and correction methods have been applied to the data presented in their report to account for this effect. Bahaj et al. [5] measured the power and thrust of an 800 mm diameter model of a marine current turbine in a cavitation

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doi:10.1016/j.expthermflusci.2010.12.005

tunnel and a towing tank. The cavitation tunnel was 5 m long, 2.4 m wide and 1.2 m tall. They used a rotor blockage ratio of around 17.5%, and applied blockage corrections to their data. The appendix of their paper presents the equations for blockage corrections. The correction of the non-dimensional power coefficient is $C_{PF} = C_{PT}\left(\frac{U_T}{U_F}\right)^3$, where C_{PF} is the power coefficient in freestream condition, C_{PT} is the power coefficient in the wind tunnel condition, U_T is the wind speed in wind tunnel conditions (tunnel wind speed with the rotor), and U_F is the wind speed in freestream conditions (tunnel wind speed without the rotor).The C_P is the ratio of the mechanical power at the shaft to the power constituted by a wind velocity across the rotor swept area.

The current study applies the equation of blockage correction presented in Ref. [5] to determine the blockage factor (BF), $\left(\frac{U_T}{U_F}\right)^3$, for small horizontal-axis wind turbines. The effects of tunnel blockage on the turbine power coefficients in wind tunnel tests are quantitatively and parametrically investigated.

2. Experimental setup and methods

Figs. 1 and 2 show the schematic and photograph of the primary experimental setup utilized in this study. A 9 m long, open-circuit wind tunnel was developed for the studies of rotor aerodynamics of small horizontal-axis wind turbines. 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 maximum air speed reaching 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 15 cm, which was connected to a measurement apparatus including torque, rotor rotating speed, and axial force sensors, and a brake system. The blade pitch angle can be adjusted using the apparatus shown in Fig. 2c. The whole measurement apparatus was placed on a support located in the middle of the tunnel test section. A pitot–static tube, mounted on a two-axis translating system, measured wind velocities. The total and static pressures were read by a digital pressure meter. The local pressure and temperature were measured during each test to reduce the calculation errors. The velocities were calculated using Bernoulli's equation. Each velocity (U_T and U_F) was averaged from 16 velocities measured at 16 equally spaced positions, as shown in Fig. 2a, in the tunnel cross section 1 m upstream of the rotor. The uncertainty in the velocity measurement is less than 1%, which results in 4% uncertainty in the blockage factor.

The blade cross-sectional profile was NACA 4415 and the blades were non-twisted. This study used blade lengths of 30 cm, 24 cm and 14.5 cm, which resulted in tunnel blockage ratios of 28.3%, 20.2% and 10.2%, respectively. The 30 cm blade had root and tip chord lengths of 2.5 cm and 1.2 cm, respectively. The 24 cm blade had root and tip chord lengths of 2.5 cm and 1.8 cm, respectively. The 14.5 cm blade had root and tip chord lengths of 2.5 cm and 2.1 cm, respectively.

3. Results and discussion

This study discusses the tunnel blockage effects on the turbine power coefficients in terms of the blockage factor (BF). As stated above, the tunnel blockage effect is a function of rotor blockage ratio (BR), tip speed ratio (TSR), rotor pitch angle (β) and so on. The measurements were conducted under different freestream wind speeds (U_∞), blade numbers, TSR, rotor rotating speeds (rpm), β, and BR. The brake system adjusted the rotor rotating speeds and thus TSR. Figs. 3a and 3b present the relationships between BF and TSR, and the relationships between BF and rpm, respectively, under the test conditions of BR = 28.3%, six blades, $\beta = 7.5°$, and four different U_∞. The TSR is proportional to the blade radius, blade rotating speed, and the freestream velocity. Thus, under a constant blade length and freestream velocity, the larger the rpm is, the larger the TSR is, and vice versa. Consequently, the BF vs. TSR and BF vs. rpm have similar distributions, as Figs. 3a and 3b indicate. These figures indicate that BF approaches 1 as TSR (rpm) approaches 0. The BF gets smaller as TSR (rpm) becomes larger. The decay rate of BF becomes smaller when TSR is around 6.5 (1500 rpm), and the BF finally approaches a constant value of 0.75. A small TSR (rpm) means that the air particles collide less with the turbine blades as they pass through the blades. As a result, the blade effect on air particles is small and the tunnel blockage effect is small as well. When the TSR (rpm) gets larger, the air particles collide more with the turbine blades and lose more of their kinetic energy. In this case, the blade effect on air particles increases, and the tunnel blockage effect is also large. However, as the blades reach a certain rpm, they will blur and act like a solid wall to air particles. In this case, the tunnel blockage effect becomes independent of TSR (rpm), and the BF approaches a constant value.

Fig. 4 presents the relationships between BF and TSR under four different U_∞ for BR = 28.3%, $\beta = 7.5°$, but 12 blades. This setup produces similar results as those in Fig. 2a. The BF approaches 1 as TSR

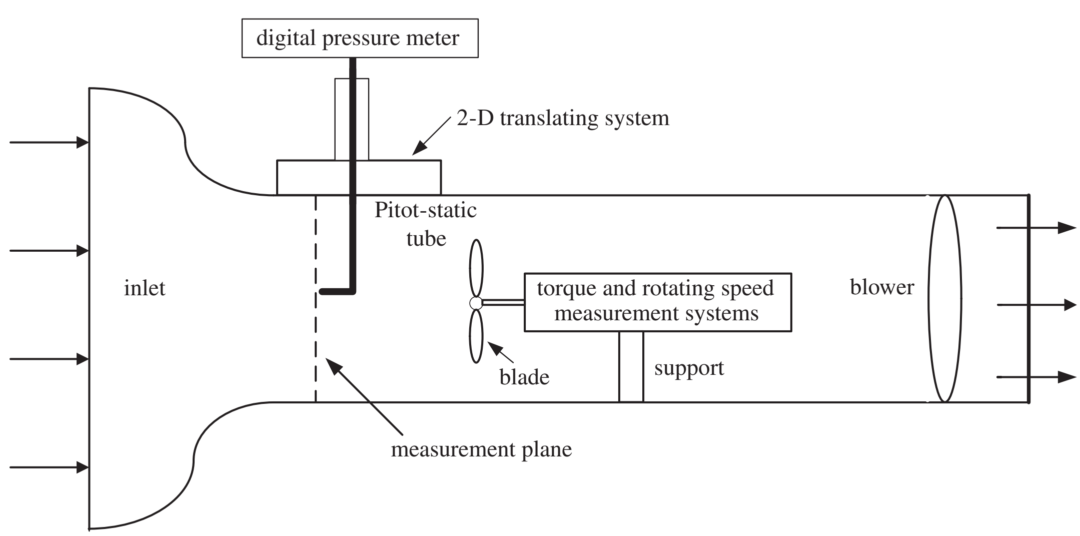
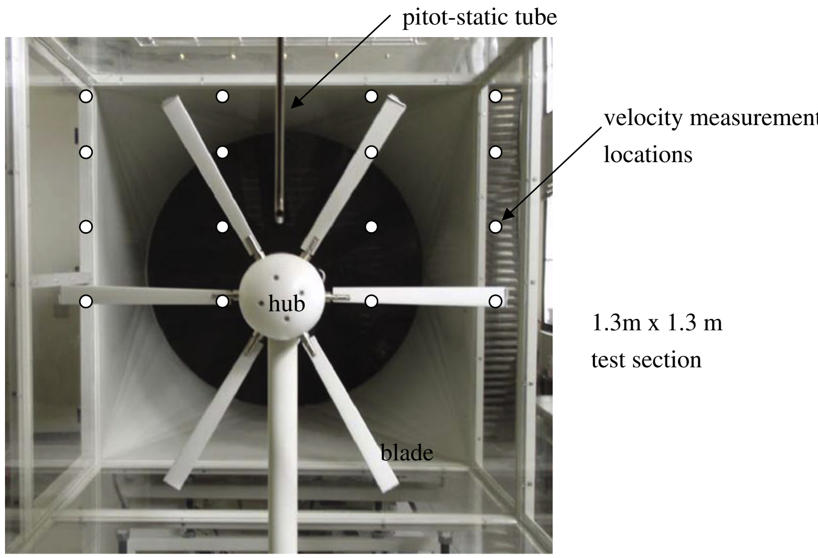
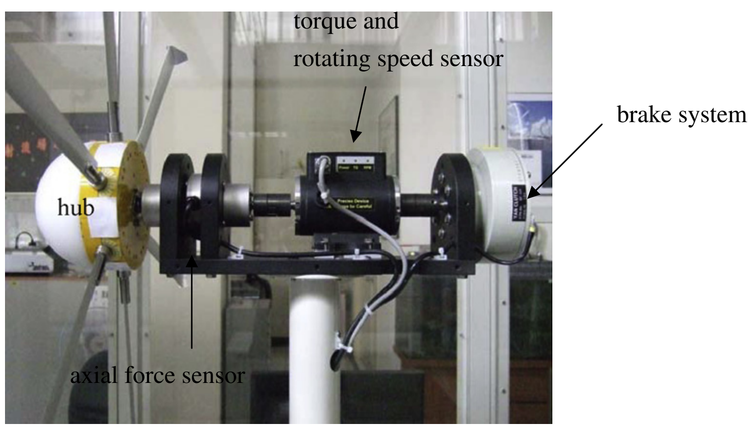


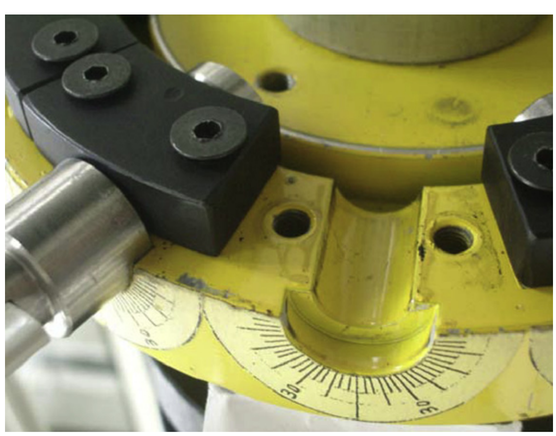
Fig. 1. A schematic of the wind tunnel system.



(a) The cross-sectional view of the test section



(b) The measurement systems



(c) The pitch angle control apparatus

Fig. 2. The Photographs of the primary experimental setup.

approaches 0. The BF gets smaller as TSR becomes larger. The decay rate of BF becomes small when TSR is around 6, and the BF finally approaches a constant value of 0.75. Due to the increased number of blades, the 12-blade turbine acts like a solid wall earlier than the 6-blade turbine. The tunnel blockage effect and the decay rate of BF are larger for the 12-blade turbine than the 6-blade one at the same TSR. For example, the BF is 0.9 at TSR = 3 and the decay rate of BF becomes small at TSR = 6.5 for the 6-blade turbine. The BF is 0.86 at TSR = 3 and the decay rate of BF becomes small at TSR = 5.5 for the 12-blade turbine. As the blades act like a solid wall, both turbines have the same BF of 0.75. Figs. 2 and 3a and 3b show that the distributions of BF–TSR are qualitatively and quantitatively

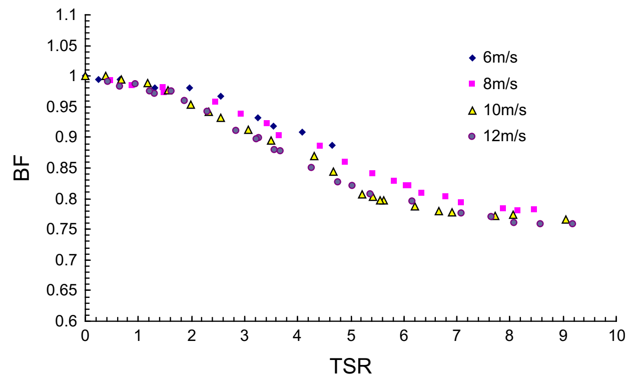


Fig. 3a. Relationships between BF and TSR under four different wind speeds for six blades, $\beta = 7.5°$ and BR = 28.3%.

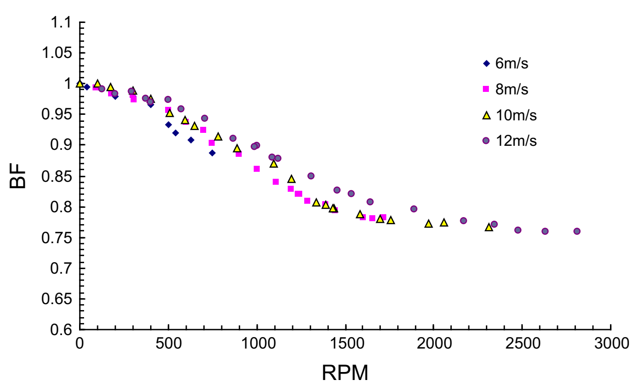


Fig. 3b. Relationships between BF and RPM under four different wind speeds for six blades, $\beta = 7.5°$ and BR = 28.3%.

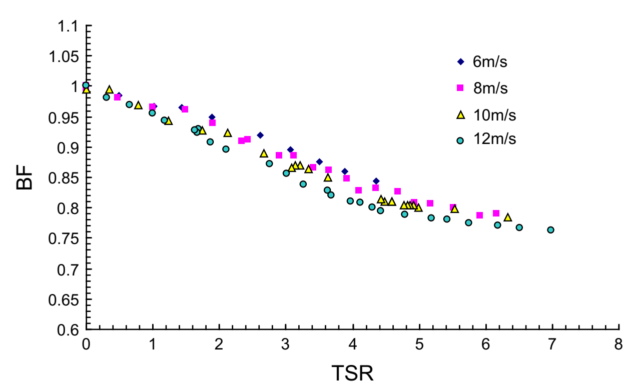


Fig. 4. Relationships between BF and TSR under four different wind speeds for 12 blades, $\beta = 7.5°$ and BR = 28.3%.

similar among the four measured air velocities, indicating that the tunnel blockage effect is less dependent on the freestream velocity than the other more dependent ones are.

The pitch angle (β) has a large effect on BF. Fig. 4 shows the relationships between BF and TSR under four different β for six blades, $U_\infty = 10$ m/s and BR = 28.3%. These results indicate that the smaller the β is, the smaller the BF is. Other investigated freestream velocities produced similar results. The blockage corrections were 31% (BF = 0.69) and 25% (BF = 0.75) for $\beta = 5°$ and 7.5°, respectively, but only 7% (BF = 0.93) for $\beta = 15°$. No blockage correction was necessary for $\beta = 25°$. The pitch angle is closely related to the incident angle of the airflow into the blades, and thus, is closely related to

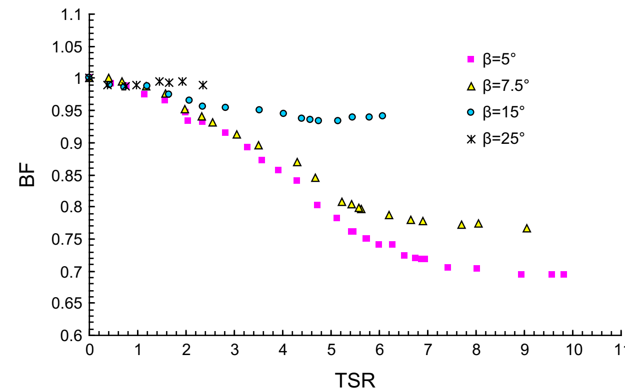


Fig. 5. Relationships between BF and TSR under four different β for six blades, $U_\infty = 10$ m/s and BR = 28.3%.

the energy attracted from the airflow by the blades. Fig. 5 shows a typical relationship between C_P and TSR under six different β for 12 blades, $U_\infty = 8$ m/s, and BR = 28.3% for different β, where the C_P has been corrected for the tunnel blockage effect, that is $C_P = C_{PF}$. This figure indicates that the smaller the β is, the larger the maximum C_P ($C_{P,max}$) is. The $C_{P,max}$ occurs at larger TSR for smaller β. For example, the $C_{P,max}$ is approximately 0.45 at TSR = 5.3 for $\beta = 5°$, while the $C_{P,max}$ is around 0.11 at TSR = 1.8 for $\beta = 25°$. A large β means the angle between the airflow and the blade chord line is relatively small. Thus, the airflow easier reaches the right angle of attack of the blade than a small β. The blades, thus, start to rotate early and produce power at smaller TSR. As the blade rotating speed increases, the angle between the relative airflow and the blade chord line becomes smaller and even negative. In this case, the blades may stall, and produce less power. On the contrary, at a small β, the airflow approaches the blade with a large angle, and has greater difficulty reaching the right angle of attack. In this case, the blades do not rotate and begin producing power at a small TSR. As the blade rotating speed increases, the angle between the airflow and the blade decreases, and finally reaches the right angle of attack. Thus, a small β causes a large rotating speed, allowing the blades to produce more power and collide with the air particles more frequently. As a result, the blockage effect is large for small β, and the BF is small.

This study also investigates the effects of the blockage ratio (BR) on BF. Fig. 6 presents the relationships between BF and TSR under three different BR (28.3%, 20.2% and 10.2%) for six blades, U_∞ = 10 m/s and $\beta = 7.5°$. As expected, the larger the BR is, the smaller the BF is. The blockage correction is 24% (BF = 0.76) for BR of 28.3%, while it is less than 5% (BF = 0.95) for BR of 10.2%. This result confirms that no blockage correction for a BR less than 10% in literatures is acceptable. Finally, Figs. 3–6 also show that the tunnel blockage effect is small at small TSR for all of the investigated conditions. For example, there are only up to 2% and 5% blockage corrections at TSR = 0.5 and 1.5, respectively. Thus, using rotor blockage ratio less than 10%, and running the tests at small TSR are methods to reduce the tunnel blockage effect. Also, using open jet wind tunnels [6–8] can also reduce the tunnel blockage effect.

To verify the accuracy of the obtained data conducted in this research, this study examines the performance of other blades measuring 21.2 cm long, with root and tip chord lengths of 2.5 cm and 2 cm, respectively, and a BR of 17.5%. The relationships between BF and TSR were examined under three different β for six blades and $U_\infty = 10$ m/s, and Fig. 8 shows the results. Bahaj et al. [5] conducted their power and trust measurements of marine current turbines in a cavitation tunnel. The BR was approximately 17.5%, and the blades were twisted with the main pitch angles between 0° and 7.5°. The correction of power coefficient due to the tunnel blockage

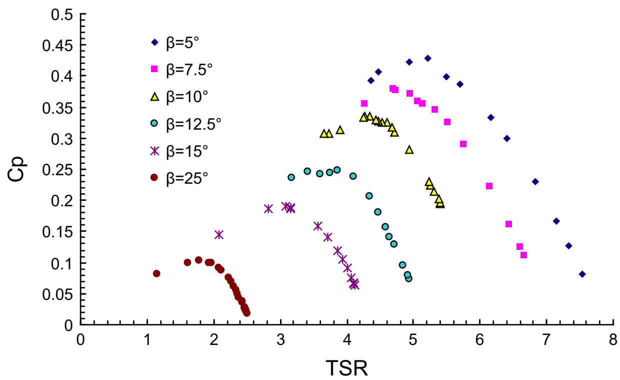


Fig. 6. Relationships between C_P and TSR under six different β for 12 blades, U_∞ = 8 m/s and BR = 28.3%.

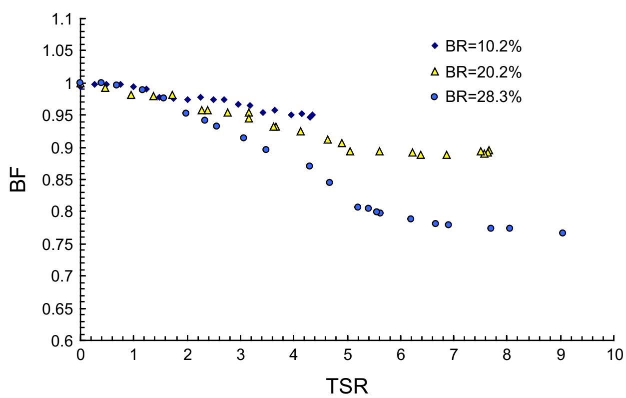


Fig. 7. Relationships between BF and TSR under three different BR for six blades, U_∞ = 10 m/s and β = 7.5°.

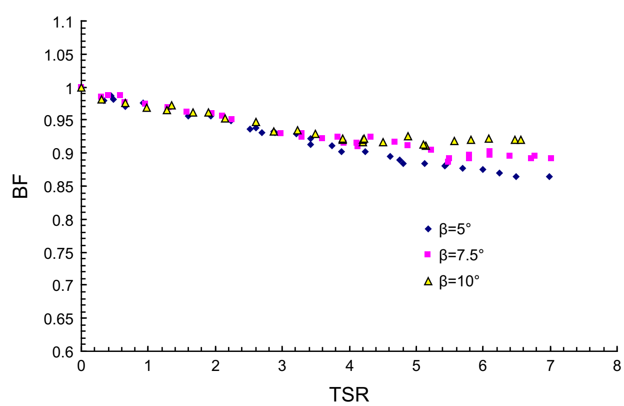


Fig. 8. Relationships between BF and TSR under three different β for six blades, U_∞ = 10 m/s and BR = 17.5%.

was 18% for TSR around 6. Fig. 7 shows that the blockage correction was around 15% for β = 5°, which suggests that the results obtained in this study are reasonable. Since the objective of this project is to develop a small horizontal-axis wind turbine with rotor diameter less than 75 cm. Thus, the results obtained in this study can be directly applied to the real world applications.

4. Conclusions

This research provides quantitative results for the effects of tunnel blockage on the power coefficients of small horizontal-axis wind turbines in wind tunnel tests under different tip speed ratios (TSR), rotor pitch angles (β), tunnel blockage ratios (BR), and air freestream velocities (U_∞). Results indicate that the tunnel blockage effects and, thus, the blockage factor (BF) are largely dependent on TSR, BR, and β, and weakly dependent on U_∞. The blockage effects increase as TSR and BR increase, and as β decreases. The blockage correction of turbine power coefficient was 31% (BF = 0.69) for β = 5°, BR = 28.3%. The tunnel blockage effect is small for small TSR, and BF approaches a constant value at a certain TSR, at which point the blades act like a solid wall. This study also shows that no blockage correction is necessary for β = 25°, and the blockage correction is less than 5% for BR less than 10% and for TSR less than 1.5.

Acknowledgement

This research was sponsored by the National Science Council of the Republic of China under Contract NSC98-2221-E-032-042-MY3.

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