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Numerical simulation on the aerodynamic effects of blade icing on small scale Straight-bladed VAWT

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Abstract

To invest the effects of blade surface icing on the aerodynamics performance of the straight-bladed vertical-axis wind turbine (SB-VAWT), wind tunnel tests were carried out on a static straight blade using a simple icing wind tunnel. Firstly, the icing situations on blade surface at some kinds of typical attack angle were observed and recorded under different cold water flow fluxes. Then the iced blade airfoils were combined into a SB-VAWT model with two blades. Numerical simulations were carried out on this model, and the static and dynamic torque coefficients of the model with and without icing were computed. Both the static and dynamic torque coefficients were decreased for the icing effects.

Keywords:icing; vertical axis wind turbine;numerical simulation ; wind tunnel test; aerodynamics

1.Introduction

Icing on wind turbine blade surface in cold and moist conditions is a serious problem, which will affect the performance of wind turbine greatly. By using the theory and technology of airplane, most of the researches including the numerical simulation and wind tunnel experiments on icing problem mainly focused on the horizontal axis wind turbine in the past [1]. The research of icing on vertical axis wind turbine is rather little. However, the straight-bladed vertical axis wind turbine (SB-VAWT) receives more and more attentions recently for its simple design, low cost, and good maintenance [2, 3]. Authors have also done some works on the performance effect of attachments on blade surface on the SB-VAWT to simulate the condition of icing on blade [4, 5].

To invest the effects of blade surface icing on the aerodynamics performance of the SB-VAWT, wind tunnel test and numerical simulation were carried out in this study. Firstly, the ice accretions on blade surface at some attack angles were observed under different water flow fluxes by using a simple icing wind tunnel. Then a small model of SB-VAWT with two blades with the iced airfoils obtained from wind

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tunnel tests were designed and induced into numerical simulation. Computations were carried out on the static and dynamic torque performances of the model with and without icing. The icing effects on the SB-VAWT were analyzed and discussed.

2.Methods Followed

2.1.Wind Tunnel Test

A blade with NACA0015 airfoil was designed and made for wind tunnel test. The size of span was 0.3 m and the chord was 0.3 m. The wind tunnel outlet used is 0.4×0.4 m^2 square. Fig. 1 shows the wind tunnel and experimental system. The wind tunnel drew the cold air from outdoor with the temperature between -10℃ to -4℃. The wind speed is 4 m/s. To support the moist environment, there is a water spray nozzle set in the outlet. The flow flux was set up as 0.5 L/min and 1L/min controlled by flow controller. The attack angles defined as Fig.2 used in the tests were 0 °, 15°, 30°, 45°, 135°, 150°, 165° and 180°.

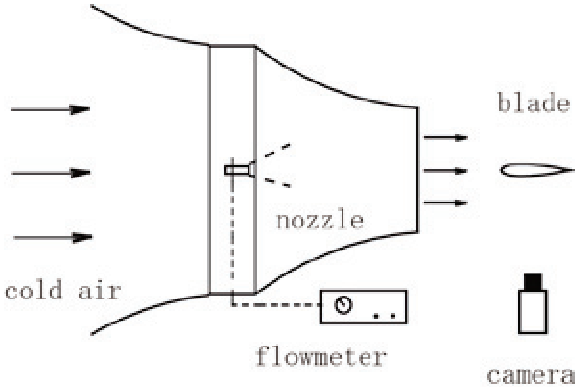


Figure 1. Schematic diagram of experimental system

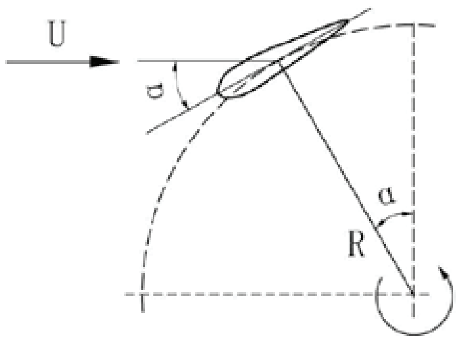


Figure 2. Definition of blade attack angle

2.2.Numerical Computational Method

The numerical simulation was carried out by using the Navier-Stokes equation based on the 2 dimensions incompressible steady flow. Numerical computations were carried out by the finite volume method with unstructured grid method. According to the conditions in the computation, the continuity equation and momentum equation were shown as below:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u_j)}{\partial x_j}=0 \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=\frac{\partial\left[\mu_e\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]}{\partial x_j}-\frac{\partial P}{\partial x_i}+S_i \tag{2}$$

Where ρ is fluid density (kg/m^3), the x_j is coordinate component, $u_i u_j$ is the average relative velocity components, μ_e is the significant viscosity coefficient, P is the pressure (Pa), S_i is the generated item.

The κ–ε turbulence model was used as the turbulence model. Turbulent kinetic energy k (m^2/s^3) and turbulent energy dissipation rate ε, were inducted. The constraint equations were expressed as follows:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+\rho(P_k-\varepsilon) \tag{3}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho\frac{\varepsilon}{k}(C_1 P_k-C_2\varepsilon) \tag{4}$$

Where P_k is the turbulent kinetic energy generated item, and it is defined as:

$$P_k=\frac{\mu_t}{\rho}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{5}$$

Figure 3 shows wind turbine model with the iced airfoils obtained from wind tunnel test and the flow field around the model for computation. The iced airfoil at 0 deg and the one at 180 deg were combined as one model, and the iced airfoil at 45 deg and the one at 135 deg were combined as another model. The diameter of the model was 0.7 meter and flow field was 2.8 m×2.8 m.

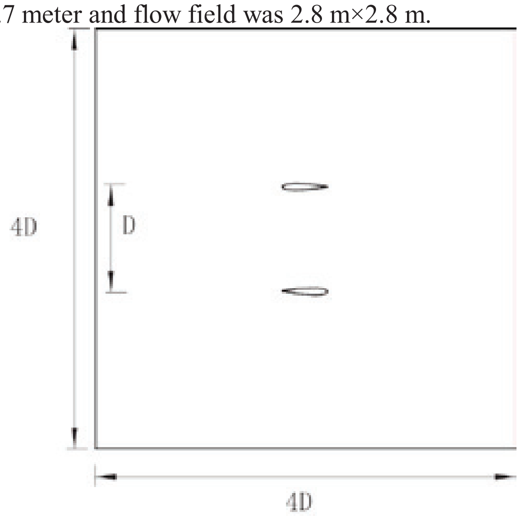


Figure 3. Schematic diagram of experimental system

3.Resaults and Discussions

3.1.Wind Tunnel Test Results

Figure 4 shows the photos of icing on the leading edge and trailing edge of the test blade at different attack angles under the wind speeds of 4m/s and the flow flux of 1L/min. According to the results, there are icing on blade surface at all attack angles. However the amount of icing on blade surface is quite different. The icing amount increases with the attack angle increases. On the other hand, the icing area on upper surface is lager than the down side. With the increasing of attack angle, the icing on down side reduces.

3.2.Numerical Computaion Results

Figure 5 shows the static torque coefficients (C_{ts}) of the model at four attack angles. The C_{ts} was defined as blow.

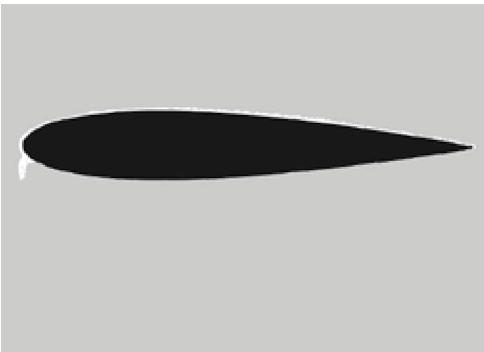
$$C_{ts} = \frac{T_s}{\frac{1}{2}\rho ARU^2} \tag{6}$$

Where T_s is static torque (N·m), ρ is air density (kg/m^3), A is wind turbine swept area (m^2), and U is wind speed (m/s).

According to the result, the starting torques of the SB-VAWT model with icing on blade at the attack angle of 0 deg for both two water flow fluxes are almost the same with the model with no icing. However, at other attack angles, the static torque coefficients of the model with iced blade become smaller than the model without icing, especially for the larger water flow flux pattern at 30 deg. Therefore, it can conclude that the icing on blade will reduce the static torque performance of the SB-VAWT.

Figure 6 and Fig. 7 show the dynamic torque coefficients (C_T) of the model under different the tip speed ratios (λ). They are expressed as follows:

$$C_t = \frac{T}{\frac{1}{2}\rho ARU^2} \tag{7}$$



0 deg

135 deg

15 deg

30 deg

45 deg

150 deg

165 deg

180 deg

Figure 4. Iceing on blade surface at different attack angles at U=4/s

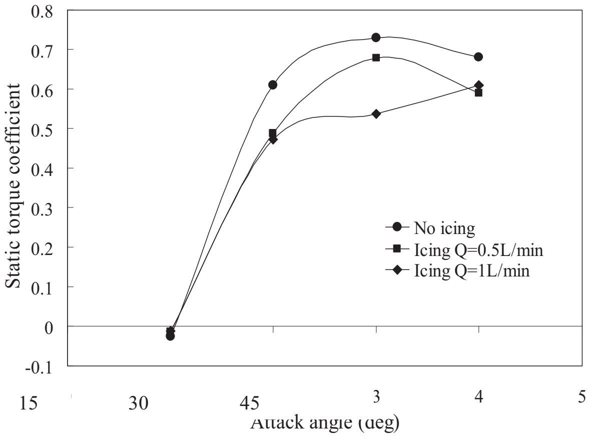


Figure 5. Ice accretion on blade at the attack angle of 0 degree

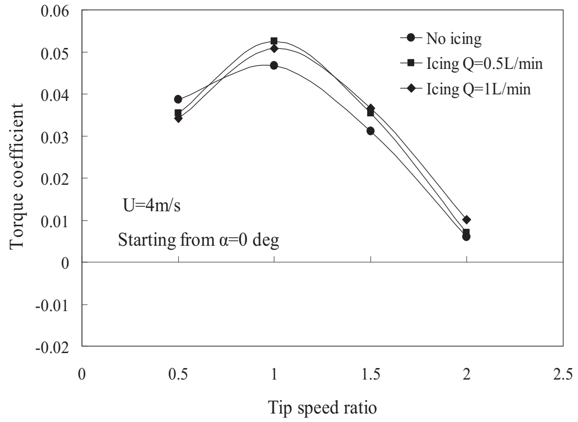


Figure 6. Ice accretion on blade at the attack angle of 180 degree

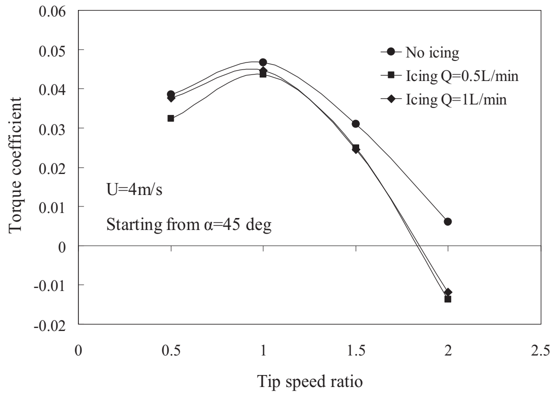


Figure 7. Ice accretion on blade at the attack angle of 180 degree

$$\lambda = \frac{\omega R}{U} \tag{8}$$

Where T is dynamic torque (N・m), and ω is the angular velocity of the blade.

According to the Fig. 6, the maximum torque coefficient of the model with icing blade (0 deg and 180 deg) is larger than the model without icing. This means that icing on blade at small attack angle will not affect the turbine performance. However, for the model with icing blade at 45 deg and 145 deg (see Fig.7), the torque coefficients for the model with icing blade under both the two types of water flow flux are smaller than the model without icing. Based on these results, it can be said that larger icing amount on blade surface will greatly affect the dynamic performance of SB-VAWT.

4.Conclusions

To investigate the condition of ice accretion on the blade surface and the performance effects on the straight-bladed vertical axis wind turbine, wind tunnel tests and numerical simulations were carried out. Under the condition of this study, the results can be summarized as below:

The icing occurs on static blade at all attack angles test in the study and the icing amounts are different at different attack angle. The static torque performance of the SB-VAWT model combined by iced blade greatly reduced. For the dynamic torque performance, although small icing amount on blade has little effect, the larger icing amount decreased the performance.

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