NUMERICAL SIMULATION OF ICING EFFECT ON AERODYNAMIC CHARACTERISTICS OF A WIND TURBINE BLADE

by

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Icing accretion on wind turbine will degrade its performance, resulting in reduction of output power and even leading to accidents. For solving this problem, it is necessary to predict the icing type and shape on wind turbine blade, and evaluate the variation of aerodynamic characteristics. In this paper the icing types and shapes in presence of airfoil, selected from blade of 1.5 MW horizontal-axis wind turbine, are simulated under different ambient temperatures and icing time lengths. Based on the icing simulation results, the aerodynamic characteristics of icing airfoils are simulated, including lift and drag coefficient, lift-drag ratio, etc. The simulation results show that the glaze ice with two horns presents on airfoil under high ambient temperature such as –5 °C. When ambient temperatures are low, such as –10 °C and –15 °C, the rime ices with streamline profiles present on the airfoil. With increase in icing time the lift forces and coefficients decrease, and the drag ones increase. According to the variations of lift-drag ratios of icing airfoil, the aerodynamic performance of airfoil deteriorates in the presence of icing. The glaze ice has great effect on aerodynamic characteristics of airfoil. The research findings lay theoretical foundation for icing wind tunnel experiment.

Key words*: horizontal-axis wind turbine, icing, numerical simulation, aerodynamic characteristic*

Introduction

As a wind turbine operates in heavy humid and cold environment, icing presents on its blade surface. Icing can change the profile of blade and damage the aerodynamic characteristics of it, which reduces the lift force and increases the drag one. It results in the reductions of power coefficient and efficiency of wind turbine [1-3]. For solving the icing problem of wind turbines, it is necessary to research on the icing characteristic of airfoil of wind turbine blade, analyze the variations of lift and drag forces, and explore the effect law of icing on wind turbine [4, 5].

Now two kinds of research methods of icing on airfoil blades are used. They are simulation method and experimental method. Generally the effect of icing on performance of wind turbine is researched by simulation software. There are mainly two steps during exploration. At the first step the icing types and shapes at different positions of blade are obtained by icing simulation software [6, 7]. In foreign countries several kinds of icing simulation software, such as LEWIC, ONERA, IRC, FENSAP-ICE, and CANICE, have been utilized widely [8-10].

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Homola comparatively analyzed the aerodynamic performances of wind turbine blade before and after icing by TURBOICE [11]. A Quasi-3D numerical simulation method was developed for calculating the icing shape and distribution on a rotating blade of large-scale horizontal axis wind turbine under different icing conditions [12, 13]. However, the aforementioned calculation codes are almost developed for aircraft icing. Only CANICE can be used to simulate icing on wind turbine [14]. At the second step, the effect of icing on aerodynamic performance of wind turbine is analyzed by CFD simulation software based on icing result acquired at the first step. To summarize, it is difficult to predict icing procedure of wind turbine because of its complex airfoil blade, working and icing conditions.

In this paper the icing types and procedures under different ambient temperature conditions are obtained through numerical calculation codes of 2-D airfoil icing. Based on the results of icing simulations, the aerodynamic characteristics of the icing airfoil, such as lift and drag forces, lift and drag coefficients, are analyzed in order to obtain the variations of wind turbine performance. The research findings lay the theoretical foundation for experiment.

Simulation of icing

Selection of typical airfoil

The acquisition of icing type is the premise of researching on the effects of icing on aerodynamic performance of wind turbine. In this paper, a horizontal-axis wind turbine rotor with 1.5 MW is selected as research object. The computer model is shown in fig. 1.

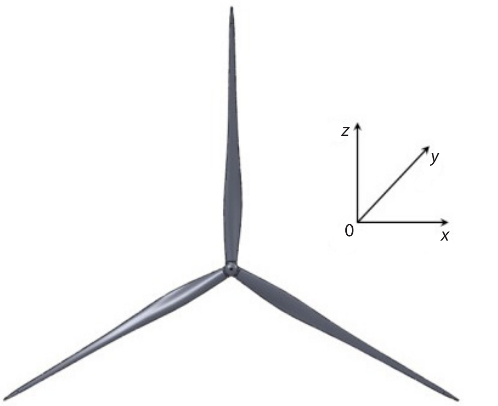

Figure 1. Rotor model for computation

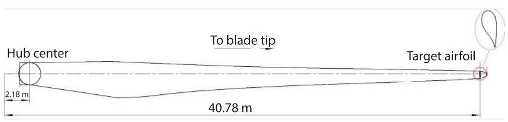

Figure 2. Sketch map of blade airfoil location

In this model the radius, R, of rotor is 42 m, and the rated rotational speed is 18.8 rpm. The typical airfoil object is the one at 40.78 m radial location from hub of rotor, which is shown in fig. 2. The reason for choosing this location is that the bulk of produced rotor torque and loss of rotor torque due to icing occur in this region. In other researches it was concluded that the ice load and associated loss of power increase towards the blade tip which have great influences on wind turbine performance [15].

In this paper a 2-D ice prediction code is used to predict the ice shape on airfoil. First, a co-ordinate system is established and the positions of airfoil in this co-ordinate system before and after transformation are shown in fig. 3. The transformation aims to set the direction of incoming flow speed into being horizontal, and the rotation angle of airfoil is equal to inflow angle, α.

The local operating condition at selected airfoil location is shown in tab. 1.

Table 1. Operating condition of airfoil

Chord length, c [m]	Speed of incoming flow, U_∞ [ms^{-1}]	Circular velocity, V [ms^{-1}]	Resultant velocity, W [ms^{-1}]	Inflow angle, α [°]
0.7	11	80.2	81	8

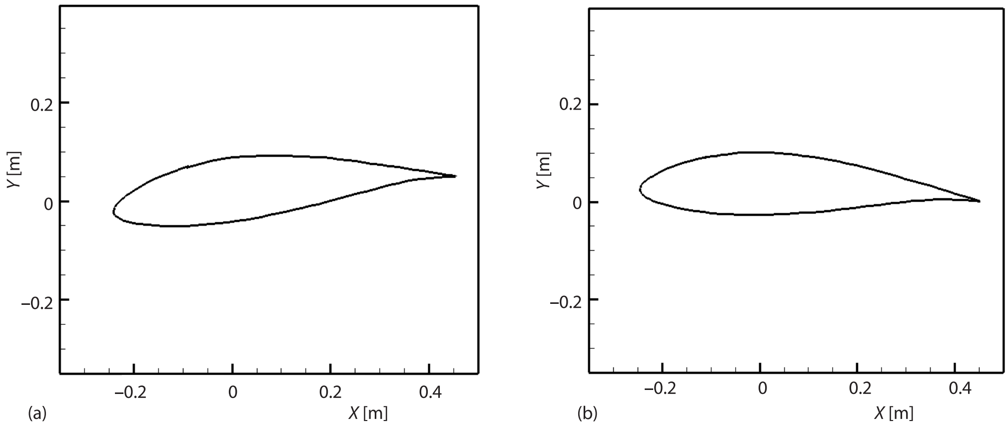

Figure 3. Position of airfoil in 2-D ice prediction code; (a) 2-D vector diagram of airfoil before transformation and (b) 2-D vector diagram of airfoil after transformation

Calculation of ice type

The procedure of ice prediction simulation has three-stages. They are air-flow field calculation, droplet impinging characteristic calculation and icing shape calculation. For air-flow field calculation the governing equation is the N-S equation. In this equation the convective flow item and source item are discretized by finite volume method, the time item is discretized by second-order implicit scheme, and the turbulence model is standard k-ε model. For droplet impinging characteristic calculation, the droplet trajectory equation is established and solved by Lagrange method and Runge-Kutta method, respectively. The Lagrangian equation:

$$M_d \frac{\mathrm{d}^2 \overrightarrow{x_d}}{\mathrm{d}t^2} = \left(\rho_d - \rho_a\right) V_d \vec{\mathrm{g}} + \frac{1}{2} C_D A_d \rho_a \left|\overrightarrow{u_a} - \overrightarrow{u_d}\right| \left(\overrightarrow{u_a} - \overrightarrow{u_d}\right) \tag{1}$$

where M_d is the quality of ice, t – the icing time, $\vec{x_d}$ – the thickness of ice in x-axis direction, ρ_d – the density of droplets, ρ_a – the density of air, $\vec{\mathrm{g}}$ – the gravitational acceleration, A_d – the frontal area of water droplet, W_d – the volume of water droplet, C_D – the drag coefficient, $\vec{u_a}$ – is local wind velocity, and $\vec{u_d}$ – the water droplet velocity.

According to the mass conservation, the variation of current weight in control body equals to the difference between mass of water going into control body and the leaving ones. The surface energy of control body is comprised of eight items, according to the First law of thermodynamics. By this way the droplet trajectory and impingement position in each moment and impinging characteristic with airfoil can be calculated. Then the amount of super-cooled water captured by airfoil and ice shape can be calculated. The process satisfies the conservation of mass and energy.

Theoretical model of simulation

For wind turbine icing, the key factors affecting icing distribution on blade under rated operating conditions are environmental parameters, such as environmental temperature, T, liquid water content (LWC), medium volume diameter (MVD), and icing time, t. In this paper, three cases of working conditions are selected for simulating ice shape, and each case has four icing time lengths. The simulation parameters are listed in tab. 2.

Table 2. Research scheme of simulation

Working conditions	Ambient temperature, T [°C]	LWC [gm^{-3}]	MVD [μm]	Icing time, t [min]
Case 1	–5	0.15	20	30, 60, 90, 120
Case 2	–10	0.15	20	
Case3	–15	0.15	20	

Based on the ice prediction code, 12 kinds of ice shapes are obtained, which are shown in figs. 4-6.

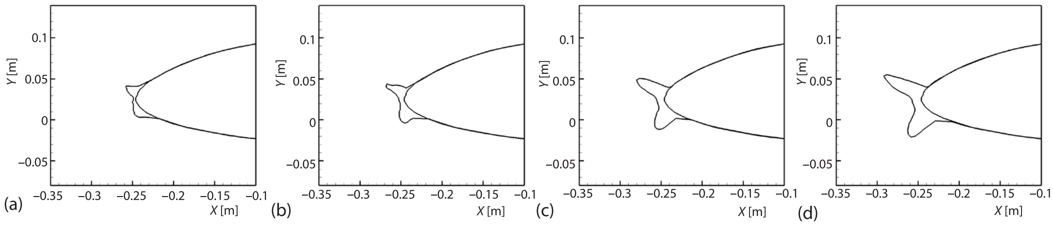

Figure 4. Ice shapes at different moments under ambient temperature of –5 °C; (a) 30 minutes, (b) 60 minutes, (c) 90 minutes, and (d) 120 minutes

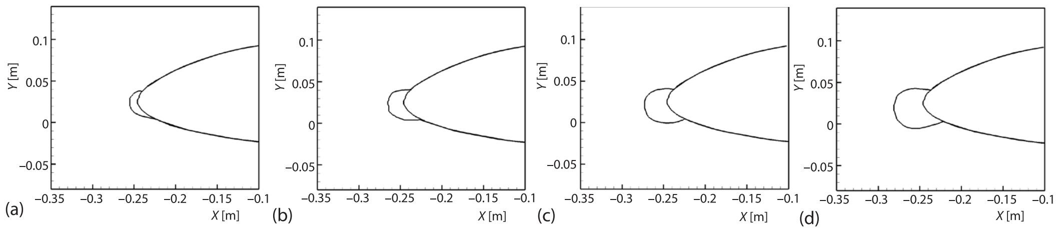

Figure 5. Ice shapes at different moments under ambient temperature of –10 °C; (a) 30 minutes, (b) 60 minutes, (c) 90 minutes, and (d) 120 minutes

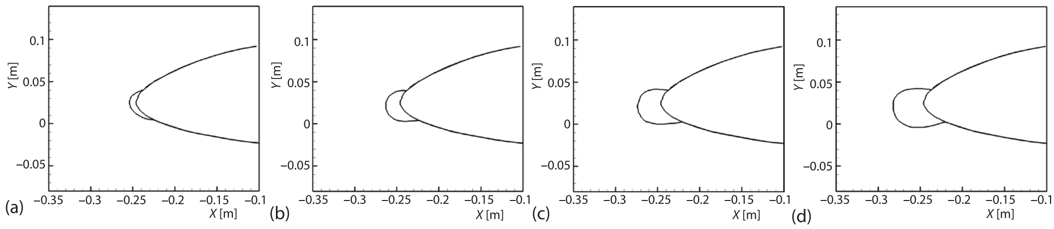

Figure 6. Ice shapes at different moments under ambient temperature of –15 °C; (a) 30 minutes, (b) 60 minutes, (c) 90 minutes, and (d) 120 minutes

From figs. 4-6, the ice layers in three cases grow layer by layer. When the ambient temperature is high such as –5 °C, the ice shape is horned. In contrast, the ice shape is arc with streamline profile as ambient temperature is low such as –10 °C and –15°C. The reason for these results is that when ambient temperature is high, the type of ice is glaze ice. In this condition the water droplets impinging on the blade surface could not freeze immediately. They flow and collect together to form horned icing shape. On the contrary, the water droplets freeze on the blade surface immediately under low temperature condition and the icing shape is arc with streamline profile.

Simulation on aerodynamic characteristics of icing airfoil

Simulation process

Based on simulation results of icing on airfoil, the software FLUENT is used to analyze the aerodynamic characteristics of icing airfoil. The governing equation is N-S equation and the turbulence model is a k-ε model in simulation. The meshing result of icing airfoil in flow field is shown in fig. 7.

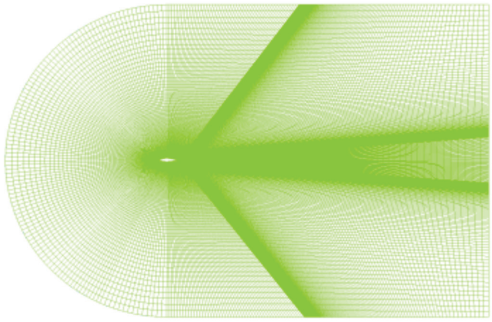

Figure 7. Meshing result of icing airfoil in flow field

Simulation results

After aerodynamic characteristic simulation, the lift coefficients, C_L, and drag coefficients, C_D, of icing airfoils under different conditions are analyzed. The definitions of them are expressed mathematically:

$$C_L = \frac{F_L}{\frac{1}{2}\rho_a v_a^2 S} \tag{2}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho_a v_a^2 S} \tag{3}$$

where F_L is the lift force, F_D – the drag force, v_a – the speed of air-flow, and S – the wind area of airfoil.

Furthermore, the lift-drag ratios of airfoils are also calculated. The definition of it is the ratio of lift coefficient to drag one and its mathematical expression:

$$K = \frac{F_L}{F_D} = \frac{C_L}{C_D} \tag{4}$$

where K is the ratio of lift/drag coefficient.

The variations of lift coefficients of icing airfoils under different conditions are shown in fig. 8. From fig. 8, it is concluded that the lift coefficients in three cases of conditions all decrease with increase in icing time. However, the lift coefficient in –5 °C case decreases dramatically, and the ones in –10 °C and –15 °C cases change similarly and decrease slowly. The reason for these results is that when the icing temperature is higher such as –5 °C, the ice shape has two horns from fig. 4. The horns increase with increase in icing time. They destroy the profile of airfoil and make the incoming flow separate with blade surface. The aerodynamic characteristics degrade dramatically. That's why the lift coefficient decreases dramatically. In contrast, the ice shapes in –10 °C and –15 °C cases have any horn and the stagnation-lines of them are arcs. They have a few worse effects on aerodynamic characteristics of blade and the lift coefficients decrease a little.

The variations of drag coefficients of icing airfoils under different conditions are shown in fig. 9. From fig. 9, it is concluded that the drag coefficients in three cases of conditions all increase along with icing time. However, the drag coefficient in –5 °C case increases dramatically, and the ones in –10 °C and –15 °C cases change similarly and increase slowly. The changing trends are opposite to the ones of lift coefficients. The reason is that the ice shape with two horns under –5 °C increases the frontal area of blade largely, which is proportional to drag force and drag coefficient of blade. In contrast, the arc icing shapes in –10 °C and –15 °C have smaller frontal areas and the drag coefficients increase slowly.

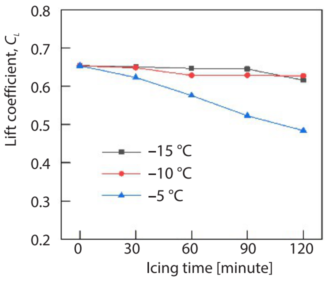

Figure 8. Curves of lift coefficients under different conditions

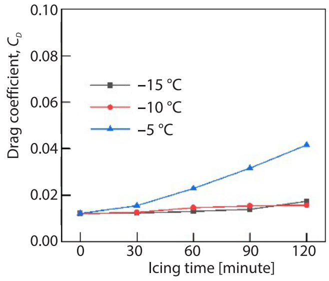

Figure 9. Curves of drag coefficients under different conditions

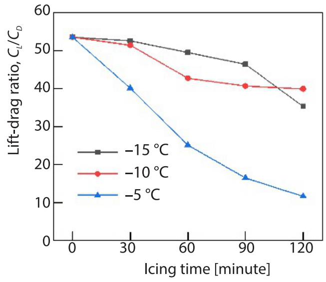

Figure 10. Curves of lift/drag ratios under different conditions

The resultant force acting on wind turbine blade includes lift force and drag force. The variation of aerodynamic characteristic of wind turbine blade cannot be described only by lift force or drag one. Therefore, it is necessary to analyze the variations of lift-drag ratios under different ambient temperatures and icing time conditions. The variations of lift-drag ratios in three cases are shown in fig. 10. This parameter is used to evaluate the aerodynamic characteristic of wind turbine with lift type blades in depth. From fig. 10, all the lift-drag ratios in three cases decrease with increase in icing time. It is concluded that the aerodynamic characteristics of wind turbine blades in three cases degrade as ice layer presents on blade surface. However, the horned icing shape under –5 °C condition has great effect on degradation of aerodynamic characteristic. Therefore, the performance of wind turbine degrades with increase in icing temperature.

For quantitatively analyzing the effect of icing on aerodynamic characteristic of wind turbine blade, two parameters are defined in this paper. They are declining rate of lift coefficient and rising rate of drag coefficient, respectively:

$$\eta = \frac{C_{L1} - C_{L2}}{C_{L1}} \times 100\%$$
$$\eta' = \frac{C_{D1} - C_{D2}}{C_{D1}} \times 100\% \tag{5}$$

where η is the declining rate of lift coefficient, η' – the rising rate of drag coefficient, C_{L1} and C_{L2} are the lift coefficients of adjacent acquisition icing times, and C_{D1} and C_{D2} – the drag coefficients of adjacent acquisition icing times.

The declining rates of lift coefficients in three cases are shown in fig. 11. From fig.11, the parameter of abscissa is the period of icing time. In this paper a total of four periods of icing time are selected. They are 0~30 minutes, 30~60 minutes, 60~90 minutes, and 90~120 minutes, respectively. According to fig. 11 the declining rate of lift coefficient under –5 °C is higher than the ones in other cases. It means that horned icing shape deteriorates the aerodynamic characteristic of airfoil dramatically. In addition, the declining rate of lift coefficient during the whole icing procedure is 25.92% under –5 °C, and the ones under –10 °C and –15 °C are 4.06% and 5.87%, respectively.

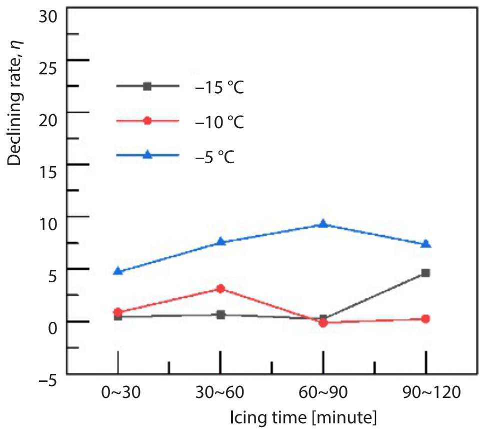

Figure 11. Declining rates of lift coefficients in three cases

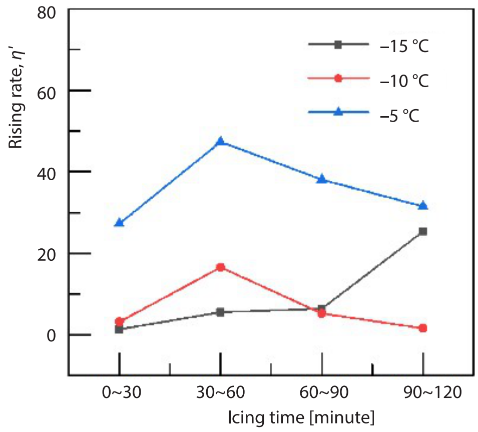

Figure 12. Rising rates of drag coefficients in three cases

The rising rates of drop coefficients in three cases are shown in fig. 12. From fig. 12, the rising rate of drag coefficient under –5 °C condition is higher than the ones in other cases. The reason is that horned ice shape with larger frontal area enforces the drag force of airfoil. With increase in icing time, the rising rate of drag coefficient increases first and then decreases. The maximum value is 38.09%. It is concluded that the amount of icing increases obviously in the period of 30~60 minutes icing time. In contrast, the rising rates of drag coefficients in –10 °C and –15 °C increases slowly during icing time. It is shown that arc icing shape with streamline profile has smaller effect on degradation of aerodynamic characteristic of blade. To summary, with the increase in icing time, all drag coefficients in three cases have upward trends, the aerodynamic characteristics get worse.

Conclusion

In this paper, the icing shape on airfoil blade and its effect on aerodynamic characteristics of airfoil have been researched by simulation method. The main conclusions are listed as follows. For a 1.5 MW horizontal-axis wind turbine rotor selected in this study, when ambient temperature is –5 °C, the icing type is glaze ice and icing shape is horned. In contrast, the icing type is rime ice and icing shape is arc with streamline profile as ambient temperatures are –10 °C and –15 °C. The lift forces and lift coefficients in three cases decrease with increase in icing time. On the contrary, the drag forces and drag coefficients increase along with icing time. According to changing trends of lift-drag ratios, the aerodynamic characteristics of airfoil deteriorate in the presence of icing especially for glaze ice. The glaze ice results in degradation of aerodynamic characteristics dramatically. The declining rate of lift coefficient in the whole icing period of 120 minutes is 25.92% under –5 °C condition. In contrast, the ones under –10 °C and –15 °C conditions are 4.06% and 5.87%, respectively. It is also concluded that the horned ice shape under glaze ice condition deteriorates aerodynamic characteristics dramatically.

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Nomenclature

A_d – frontal area of water droplet, [m^2]
C_D – drag coefficients
C_L – lift coefficient
c – chord length, [m]
F_d – drag force, [N]
F_L – lift force, [N]
$\vec{g}$ – gravitational acceleration, [ms^{-2}]
K – ratio of lift/drag coefficient
M_d – quality of ice, [kg]
R – radius, [m]
S – wind area of airfoil, [m^2]
T – temperature, [°C]
t – icing time, [minute]
U_∞ – speed of incoming flow, [ms^{-1}]
$\vec{u_a}$ – frontal area of water droplet, [m^2]
$\vec{u_d}$ – water droplet velocity, [ms^{-1}]
V_d – volume of water droplet, [m^3]
v_a – speed of air-flow[ms^{-1}]
$\vec{x_d}$ – thickness of ice in x-axis direction, [m]

Greek symbols

α – inflow angle, [°]
η – declining rate of lift coefficient
η' – rising rate of drag coefficient
ρ_d – density of droplets, [kgm^{-3}]
ρ_a – density of air, [kgm^{-3}]

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