ABSTRACT

For researching on the rules of icing on wind turbine blade in different temperatures, a numerical simulation method has been established in this paper. Three kinds of sections of airfoils which are the blades of 1.5 MW wind turbine have been used for icing simulation. The simulations are carried out in four kinds of temperatures which are -8°C, -12°C, -16°C and -20°C. By this way the shapes and dimensionless areas of icing on blades have been analyzed. The results show that the shapes of icing on all kinds of airfoils change from horn ice to streamlined ice with decreasing of ambient temperature. When ambient temperature is -20°C, the shape of icing on the tip of one kind of airfoil become streamlined ice; the other ones are still small horn ice. The shorter tip of the airfoil is, the more greatly value of dimensionless area of icing varies with changing of temperature. The research finding provides theoretical basis and numerical reference to development of anti and deicing strategy for wind turbine blades.

Key words: Wind turbine; Icing; Numerical Simulation; Airfoil; Ambient temperature.

1. INTRODUCTION

Wind power technologies have been widely applied because of no pollution, blade is the important part of wind turbine to capture wind energy and its working characteristics determine the performance of the wind turbine. But in outdoor environment wind turbine blades often face icing problem. Icing on blades will change the aerodynamic characteristics and load distribution of wind turbine. It causes wind turbine working unstably and reducing output power, ultimately shorting
the lifespan of wind turbine blades \cite{1}. Researchers have done a lot of researches on icing on blades of wind turbine and the research methods include ice wind tunnel and numerical simulation. Now the numerical simulation method is widely used with the rapid development of computer technology \cite{2}. The simulation of icing on blade of wind turbine references to the research method of plane airfoil. The famous icing numerical simulation software includes the LEWICE and LEWICE3D developed by NASA \cite{3-4}, FENSAP-ICE developed by Canada \cite{5}, ONERA developed by France \cite{6} and the DRA developed by British \cite{7}. Ping Fu and Masoud Farzaneh have calculated the two-phase flow of air and water by using Fluent, and simulated icing on the NREL Phase VI blade model \cite{8}. Lasse Makkonen and Timo Laakso have used TURBICE to simulate the frosting and icing on wind turbine blade airfoils \cite{9}. Matthew C. Homola and Tomas Walleniu have analyzed the aerodynamic characteristics of airfoil before and after icing by TURBICE and Fluent \cite{10}. Barber and others have predicted the distribution of icing and studied the effects of icing position on wind turbine performance by Lewice \cite{11}. Mariya Dimitrova has simulated the icing process and calculated the power loss of blades due to icing at -6ºC by PROICET \cite{12}. Xian Yi have done a lot of researches on the icing by numerical simulation \cite{13}. Pinting Zhang has analyzed the aerodynamic characteristics of icing airfoil by combining Fluent and LEWICE to \cite{14}. Pengfei Ren has simulated the parameters of NREL Phase VI wind turbine before and after icing by Numeca \cite{15}.

In this paper three sections of airfoil from a 1.5MW horizontal axis wind turbine will be selected because of easily icing and the process of icing will be simulated based on previous research achievement. The researches will provide the theoretical basis and the data basis to study the prediction and anti-deicing system of icing on wind turbine.

2. MODEL AND SIMULATION METHOD

2.1 Wind turbine model

In this paper simulations of icing on the blades of a 1.5MW horizontal axis wind turbine have been conducted. The three-dimensional model of wind turbine is shown in Fig.1. The diameter of wind turbine rotor \(D\) is 83m. For simulation the three-dimensional rotating airfoil is transformed into a two-dimensional airfoil based on blade element theory as shown in Fig.2 and Fig.3. By this way the wind speed \(U_\infty\) and rotation speed \(\omega_F\) of blade are composed into speed \(W\). Then the speed \(W\) is rotated to an angle \(\psi\) around the point \(O\). At this position, icing on the airfoil can be calculated by simulation.

For simulation the sections of airfoil which have been selected in this paper are shown in Fig.4. The distances from hub of sections are 23.29 m, 32.04 m and 40.72 m respectively. The parameters of the three sections are shown in Table 1.
Figure 1. Wind turbine model.

Figure 2. Two-dimensional airfoil.

Figure 3. Transformed airfoil.

Figure 4 shows the sections that we choose this option to study. Section 1 is 23.29m from the hub. Section 2 is 32.04m from the hub. Section 3 is 40.72m from the hub. Table I are the parameters of the three sections.

![Figure 4. Positions of airfoils.]

**TABLE I. PARAMETERS OF SECTIONS OF AIRFOILS.**

<table>
<thead>
<tr>
<th>Section number</th>
<th>Distance (r/m)</th>
<th>Chord length (c/m)</th>
<th>Flow rate (U_{\infty}/(m/S))</th>
<th>Circumferential speed (V/(m/S))</th>
<th>Synthetic speed (W/(m/S))</th>
<th>Inflow angle (\psi(°))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.29</td>
<td>1.60</td>
<td>11</td>
<td>48.77</td>
<td>50</td>
<td>12.7</td>
</tr>
<tr>
<td>2</td>
<td>32.04</td>
<td>1.12</td>
<td>11</td>
<td>67.10</td>
<td>68</td>
<td>9.3</td>
</tr>
<tr>
<td>3</td>
<td>40.72</td>
<td>0.69</td>
<td>11</td>
<td>85.29</td>
<td>86</td>
<td>7.3</td>
</tr>
</tbody>
</table>

2.2 Simulation method

In this paper, the air flow field is calculated by N-S equation which has the characteristic of low-velocity viscous flow and solved based on the Simple method. The motion equation of water droplets is established by the Lagrangian method and solved based on Runge - Kutta method. Based on the control body theory, the icing process which droplets impact on blade is solved by mass and energy conservation equations.

According to the mass conservation, the weight of current control equals to the difference between weight going into the control body and the leaving ones. The equation is:

\[
m'_{in} + m'_{im} - m'_{ou} - m'_{oa} = m'_{so} \tag{1}
\]

The formula (1) is usually given as:
\[ m'_{\text{ou}} = (1 - f) \left( m'_{\text{im}} + m'_{\text{m}} \right) - m'_{\text{va}} \]  

(2)

Where, \( m'_{\text{in}} \) is mass of water flow from upstream into control body, \( m'_{\text{m}} \) is supercooled droplets impacting on the blade, \( m'_{\text{va}} \) is the mass of water transforming into steam by evaporation or sublimation, \( m'_{\text{ou}} \) is the mass of water droplets which is not freezes and flow into downstream, \( m'_{\text{so}} \) is the mass of water which was changed to ice, \( f \) is the icing ratio.

The surface energy of the control body is subdivided into eight items. According to the first law of thermodynamics, the energy balance equation is:

\[ E_{\text{so}} + H_{\text{va}} + H_{\text{ou}} - H_{\text{in}} - H_{\text{im}} = Q_{\text{f}} - Q_{\text{c}} - Q_{\text{k}} \]  

(3)

Where, \( E_{\text{so}} \) is the energy of water during freezing, \( H_{\text{va}} \) is the heat of evaporation of water droplets or ice surface, \( H_{\text{ou}} \) is the energy of droplets out the body, \( H_{\text{in}} \) is the energy of droplets into the body, \( H_{\text{im}} \) is the impact kinetic energy into the water heat flux, \( Q_{\text{f}} \) is the energy of air friction heating, \( Q_{\text{c}} \) is the convective hot flow of wall and the environment, \( Q_{\text{k}} \) is the heat between ice and water.

2.3 Conditions and meshing

In this paper, four different ambient temperatures such as -8°C, -12 °C, -16°C and -20°C are selected as temperature conditions to simulate the process of icing on the three airfoils. The other ambient parameters are same in different temperature conditions. The LWC (Liquid Water Content) is 0.5g/m³, MVD (Medium Volume Droplet Diameter) is 45μm, icing time is 120min.

According to above theory the relevant procedures have been filed and the selected airfoil is meshed finely. The results are shown in Fig.5.

3. RESULTS AND DISCUSSION

3.1 Icing distribution

The distributions of icing on the leading edges along different sections of the blade are shown in Fig.6. The ratio of length of chord selected in the graphs is 30%.

According to Fig.6 (a) the shape of icing on Section 1 airfoil is given. At -8°C the shape of icing is horn shape ice and the lower horn has an obvious trend flowing backward. When the temperature is -12°C, the upper and lower horns are more
obvious and contract inward. When the temperature continues decreasing such as -16°C and -20°C, the upper and lower surfaces of horns remain unchanged. The depressed part in the middle of shape of icing is gradually obvious. At -20°C streamlined ice appears obviously in the middle part, but there is still a small horn ice.

According to Fig.6 (b) the shape of icing on Section 2 airfoil is given. At -8°C the horn shape ice is more obvious than Section 1 airfoil and the size increases. When the temperature is -12°C, the upper and lower horn ices shrink towards to the middle part and spread to the front of the airfoil. When the temperatures are -16°C and -20°C, the outer surface of icing remains unchanged and the central depressed part inflates outwards. Horn shape ice gradually transforms into the streamlined ice. When the temperature is -20°C the streamlined ice appears obviously, but there is still a small horn shape ice.

According to Fig.6(c) the shape of icing on Section 3 airfoil is given. At -8°C the horn shape ice are more obvious than former ones, upper and lower horn shape ice is larger and there is a trend of flowing to backwards to trailing edge. When the temperatures are -12°C, -16°C and -20°C respectively, the shapes of outer surfaces of the upper and lower horn shape ices change a little. The middle part of icing also increases outward. At -20°C, it grows up to be a streamlined ice.

In summary, the shapes of icing on three kinds of airfoils change from horn shape ice to streamlined shape ice with decreasing of ambient temperature as the other conditions are same. In the process of icing, the outlines of upper and lower surfaces of horn shape ice remain unchanged and the middle depressed part gradually increases. When temperature decreases to an extent, shapes of icing change into streamlined one. The size of icing on airfoil increases from section 1 to section 3. The reason is that father from hub the section is, higher the peripheral speed is. Then more water droplets are captured by airfoil at the same time, so the ice shape is larger.
3.2 Icing Area

In this paper the dimensionless icing area ηs is used to analyze the shape of icing by simulation which is proposed by Yan Li \cite{16}. The dimensionless icing area is:

$$\eta_s = \frac{S}{S_b}$$

(4)

Where, \(S\) is the icing area, \(S_b\) is the airfoil chord length.

The change situation of dimensionless icing area along with temperature is shown in Fig.7. It shows that the values of dimensionless icing area increases from Section 1 to Section 3. The change law and reason are identical with above ones. Father from hub the section is, higher the peripheral speed is. More water droplets are captured by airfoil at the same time. The dimensionless icing area is used to analyze the sensitivity of the airfoil to temperature changes. From -8\(^\circ\)C to -12\(^\circ\)C dimensionless icing area on Section 1 airfoil increases rapidly. Then the curve is smooth. The values of dimensionless icing areas of Section 2 and Section 3 fluctuate a little. According to above law it shows that shape of icing on small cross section airfoil is sensitive to ambient temperature. It concludes that farther from hub the airfoil is, more ice generates. It causes higher torque at blade root. If icing on this part, it will affect the aerodynamic characteristics and output power of the wind turbine.

3.3 Discussion

According to above analysis, the ice shapes on three sections of wind turbine blade changed from horn ice shape to streamline shape with the ambient temperature decreased under the conditions of other parameters were the same. The closer the section from the blade tip, the more ice generates. The anti-deicing system can be optimized or designed based on the rules of icing distribution. Such as the electric heater installed in blade of wind turbine, according to the rules obtained by this
research, the energy to melt ice is different in different sections, so the electric heater system can be designed different section installs different power of electric heater. This paper offered the train of thought and framework for further deep research on blade icing of wind turbine.

4. CONCLUSION

In order to explore the effects of icing on different cross section airfoils at different temperatures, a 1.5MW wind turbine blade is used to simulate the icing process by numerical simulation. Conclusions are acquired as follows:

(1) With decreasing of temperature, the type of ice changes from horn shape ice to streamlined shape ice on all kinds of airfoils. At -20°C only streamlined shape ice generates on surface of airfoil of section 3 and small horn shape ice still exists on airfoils of Section 1 and Section 2. It shows that process of icing on different airfoils is different in the same operating conditions. When the temperature decreases to an extent, the shape of icing will transform into streamlined ice.

(2) The sensitivity at different cross-sectional positions to temperature is different, smaller the cross section of blade is, larger the change of icing area. This research proposes a theoretical basis and numerical support for design of anti-deicing strategy of wind turbine blades.

REFERENCES

