Research on the effect of icing on aerodynamic performance of airfoil and power generation performance of wind turbine

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Abstract. In order to study the effects of icing on the aerodynamic performance of airfoils and the power generation performance of wind turbines, CFD (computational fluid dynamics) is used in this paper to simulate and analyze the airfoil before and after icing based on the numerical simulation of a NACA airfoil. Results of the analysis show that ice accretion on the airfoil causes the lift coefficient to decrease and the drag coefficient to increase, which results in a significant deterioration in the aerodynamic performance of the airfoil. To further verify the analysis results, real-time icing monitoring is carried out on a 1.5MW wind farm. Statistics show that after ice accretes on the blades, the power curve of the blades decreases overall, and the blades stall at a speed close to the rated wind speed.

1. Introduction
Wind is used as a resource in China mainly in the northeast, north and northwest regions of the country, as well as in the southeast coastal areas and the Yunnan-Guizhou Plateau. Most of the wind farms have harsh climate and very cold winters. When encountering weather conditions of low ambient temperature, high air humidity, supercooled water droplets in the air, freezing rain, or snow, wind turbine generators are extremely vulnerable to freezing, especially the exposed parts such as the wind turbine blades and the anemometer [1-3].

Icing on wind turbine blades alters the aerodynamic shape of the blades, causing changes in the aerodynamic performance of the airfoil; the amount of ice accretion varies on different parts of the blades, which increases the imbalance of the components, and makes the load uneven for the windwheel and other components [4-7]. This results in torque oscillation of the transmission chain, which affects the fatigue life of the transmission system. In addition, when the windwheel rotates, pieces of ice may fall off, which may cause injuries to personnel and damage equipment near the unit.

Based on the numerical simulation of airfoil icing, CFD simulation analysis of static pressure distribution, airflow streamline distribution, as well as lift and drag characteristics around the airfoil before and after icing is carried out. These results are then compared with the aerodynamic characteristics of clean airfoil, and the effect of icing on the aerodynamic performance of airfoil is analyzed. At the same time, combined with the icing monitoring system of a wind farm, the power curve of the blades after icing and the power generation of the unit are statistically analyzed.
2. Numerical simulation of icing

2.1. Conditions for numerical calculations of icing

In this paper, the FENSAP-ICE software is used to solve the ice accretion process of airfoil. First, the FENSAP module is applied to solve the compressible or incompressible Navier-Stokes (NS) equations or Euler equations to obtain the external flow field of the airfoil, and then the DROP3D module is used to solve the Euler equations for droplet motion. The impact characteristics of water droplets are calculated, and finally the ice accretion module ICE3D is used to solve the ice growth process.

The icing simulation results are verified via comparison with the experimental results of Shin, J [8] and Kong et. al [9] under the same meteorological conditions. The meteorological conditions for icing calculations are shown in Table 1.

Table 1. The meteorological conditions for icing calculations

| Item                               | Value  |
|------------------------------------|--------|
| Airfoil chord length (m)           | 0.5    |
| Air velocity (m/s)                 | 67     |
| Angle of attack (°)                | 4      |
| Atmospheric pressure (Pa)          | 101325 |
| Liquid water content (g/m³)        | 1g/m³  |
| Diameter of the water-drop (μm)    | 20     |
| Freezing temperature (°C)          | -4.4 - 19.4 |
| Freezing time (s)                  | 360    |

2.2. Calculation results and analysis of icing

Under the same meteorological conditions, the comparison between the icing simulation results and the experimental results obtained by Shin, J et al. is shown in Figures 1.

![Figure 1](image)

(a) $t = -4.4°C$  
(b) $t = -19.4°C$

Figure 1. Calculation results and analysis of icing

It can be seen from the comparison figures that the simulation results are in relatively good agreement with the experimental results; in addition, under different freezing temperature conditions, the ice shape on the airfoil surface varies. At -4.4°C, the ice shape is irregular, often angular or prismatic, while at -19.4°C, the ice shape tends to be more gentle and regular. This is because at a relatively high temperature (slightly below 0°C), when water droplets hit the airfoil surface, instead of freezing immediately, they form a water film that is able to flow, which forms clear ice with icicles; at a relatively low temperature, the icing rate increases, and when rain droplets hit the airfoil surface, they freeze quickly, forming frost-like ice that is smoother in shape.
3. Simulation analysis of the effect of ice shape on aerodynamic performance of airfoil

3.1. Conditions for simulation analysis calculations

The numerical model in this paper is established in Gambit 2.4, with the calculation domain shown in Figure 2 below. The total length is 45c, the height is 30c, and c=1 is the chord length of the airfoil. The incoming flow velocity V is set to 50m/s, with an angle of attack \( \theta \) of 10°; the air pressure \( P_0 \) is set to 101325Pa, the air density \( \rho \) is 1.225kg/m\(^3\), the air temperature \( T_0 \) is 288K, and the kinematic viscosity \( \nu \) is set to \( 1.79 \times 10^{-5} \)m\(^2\)/s.

![Figure 2. Calculation domain](image)

Through gambit modeling, the clean airfoil, the airfoil at -4.4°C with ice accretion, and the airfoil at -19.4°C with ice accretion are divided by the grid. The local enlarged grids around the airfoil are shown in Figures 3.

![Figure 3. Local enlarged grids around the airfoil](image)

3.2. CFD simulation results and analysis

3.2.1. Comparative analysis of static pressure around airfoil under different icing conditions

The results of static pressure around airfoil under different icing conditions are show in Figure 4. Compared with the clean airfoil, the negative pressure zone on the airfoil surface with clear ice is significantly reduced. Due to the effect of icicles at the leading edge of the airfoil, a high-speed airflow temporarily appears near the icicles, which causes the negative pressure zone to appear earlier, after which the flow velocity drops rapidly and the negative pressure zone diminishes. The surface of frost ice airfoil is regular, and the position of ice accretion is in most cases near the leading edge and pressure surface, which has little effect on the negative pressure zone of the airfoil. The negative pressure zone appears slightly earlier compared with that of clean airfoil.
3.2.2. Comparative analysis of airflow streamline distribution around airfoil under different icing conditions

It can be seen from Figure 5 (a) that due to the smooth surface of the airfoil, the airflow can maintain a good streamline around the clean airfoil with practically no separation vortex. Figures 5 (b) and 5 (c) illustrate the streamline distribution of airfoil with clear ice versus airfoil with frost ice. The surface of clear ice is irregular, and the position of ice accretion is near the leading edge and suction surface of the airfoil, especially the irregular icicles near the suction surface, which results in poor airflow uniformity and an early appearance of the separation zone; however, the surface of airfoil with frost ice has a relatively regular surface, and the position of ice accretion mainly concentrates on the leading edge and pressure surface, which has little effect on the suction surface. The separation zone of the trailing edge of the airfoil is smaller compared with that of the airfoil with clear ice.

3.2.3. Comparison of lift and drag characteristics of airfoil under different icing conditions

It can be seen from Table 2 below that after ice accretes on the airfoil surface, the airflow around the airfoil is separated earlier, which causes the lift coefficient to decrease and the drag coefficient to increase; the lift-to-drag ratio of the airfoil is therefore reduced. Compared with frost ice, the flow separation vortex caused by clear ice appears earlier and has a larger influence area, and the drop in the lift coefficient and the rise in the drag coefficient are both more significant. Consequently, the aerodynamic performance of airfoil can be deteriorated by different forms of icing, of which clear ice has a more severe negative effect on the aerodynamic performance of airfoil.

| aerodynamic coefficients | Clean airfoil | Clear ice airfoil | Frost ice airfoil |
|--------------------------|--------------|------------------|------------------|
| Lift coefficient         | 0.79         | 0.74             | 0.76             |
| Drag coefficient         | 0.019        | 0.081            | 0.062            |
| Lift-to-drag ratio       | 52.6         | 9.14             | 12.3             |

4. Effect of icing on the power curve of the unit

4.1. Icing monitoring system for wind turbine blades
In order to further understand the effect of icing on the aerodynamic performance of wind turbine blades, the following icing monitoring system is constructed as shown in Figure 6, which monitors the external environment of the wind turbine in real time by installing temperature, humidity and freezing-rain sensors on the unit. Corresponding data analysis is conducted based on signals from the aforementioned sensors to determine whether the blades are icing, and monitoring data of the turbine blade unit is compiled.

4.2. Icing monitoring results of wind turbine blades

Figure 7 shows the comparison of the average power curve of the blades after 5 minutes of icing with the dynamic power curve of the blades. It can be seen from the figure that after the blades are iced, the power of the unit decreases, and the blades stall close to the rated wind speed.

After the blades are iced, the lift coefficient decreases and the drag coefficient increases, which reduces the CP-λ curve of the blades. The decrease in the power coefficient of the wind turbine reduces the energy absorbed by the wind turbine at the same wind speed, resulting in a decrease in the overall power of the unit. According to the control strategy of the unit, after the windwheel reaches the rated speed, there will be a period which the torque increases. As the wind speed increases, the rated power will gradually be reached. During this process, the speed of the windwheel does not change but the wind speed increases, resulting in an increase in the angle of attack. The blades are more likely to stall during this process. In addition, the blades are iced at this time, which increases the angle of attack to a certain extent, and finally causes the blades to stall close to the rated wind speed.

By analyzing the statistics of power generation of the iced blades, it is found that within the monitored 23.5h, the power generation of the unit is 16,426kW, which suggests a loss of 800kW compared with the theoretical power generation of a normal unit; the power generation loss is 4.8%.
5. Conclusions and prospects

(1) Icing affects the flow field around the airfoil, causing the flow separation vortex to appear early, which results in a decrease in the lift coefficient and an increase in the drag coefficient of the airfoil, which in turn lowers the lift-to-drag ratio of the airfoil. Icing therefore leads to a decrease in aerodynamic performance of the airfoil. In addition, clear ice has a more severe negative effect on the airfoil than frost ice.

(2) After ice accretes on the airfoil, the power curve drops, and a stall occurs close to the rated wind speed. According to the statistics of the daily power generation of the unit, it is found that the power generation loss due to icing can reach 4.8%.

(3) Icing affects the aerodynamic performance of the airfoil, which in turn alters the CP~λ curve of the blades. However, if the normal airfoil control strategy is still adopted when there is ice accretion on the blades, the unit may not be able to operate under the optimal wind turbine power coefficient. This might be one of the factors leading to the decrease in the power curve; further studies are required to verify this hypothesis.

(4) At present, anti-icing coating is the most frequently adopted anti-icing technology, both domestically and internationally. Active de-icing methods that are more effective and safe still require further research and development.

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