

Article

The Icing Characteristics of a 1.5 MW Wind Turbine Blade and Its Influence on the Blade Mechanical Properties

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Abstract: Ice accumulation significantly impacts the mechanical properties of wind turbine blades, affecting power output and reducing unit lifespan. This study explores the icing characteristics and their effects on a 1.5 megawatt (MW) wind turbine blade's mechanical properties under various conditions, including wind speeds of 5 m per second (m/s) and 10 m per second, temperatures of -5 degrees centigrade ($^{\circ}\text{C}$) and -10 degrees centigrade, and different liquid water contents, by using icing wind tunnel tests and structural statics analysis. The research reveals that ice predominantly forms in an irregular pattern on the leading edge of the blade. It is easy to produce corner ice and ice skating when the icing temperature and wind speed are higher, and the icing surface is rougher. When the other conditions remain unchanged, the decrease in temperature, an increase in wind speed, or a rise in liquid water content all lead to an increase in the average thickness of icing and the volume of icing at the leading edge, with the effect of the wind speed on the two being 147.8% and 147.9%, the effect of the liquid water content on the two being 39.9% and 53.5%, and the effect of the temperature on the two being 24.6% and 13.2%. The study finds that the blade tip experiences the maximum displacement in both iced and non-iced states, although the positions of peak equivalent stress and strain vary. The above study will also provide references for the design of new wind turbine blades and the anti-icing maintenance of wind turbine generator sets.

Keywords: wind turbine; blade; icing characteristics; mechanical properties; wind tunnel test



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1. Introduction

Wind energy, as a clean and renewable source, not only has an abundant reserve but also features flexible utilization methods. It has been widely developed globally [1]. Many wind turbine units have been installed in cold, humid coastal and mountainous areas to fully harness the wind resources available in nature [2–5]. With the increasing frequency of extreme weather events in recent years, such as cold waves, blizzards, and frost, the issue of wind turbine icing has become increasingly prominent [6].

Ice formation on wind turbines not only reduces their power generation capacity but, in severe cases, can increase the load on the unit, thereby shortening its lifespan. It also carries the risk of causing injuries due to ice shedding [7]. According to previous research, the study of wind turbine icing primarily involves wind tunnel tests and simulation modeling [8]. Some scholars, such as Lichun Shu and others [9], have conducted in-depth studies on the distribution of icing on wind turbines using experimental methods. They employed image processing techniques to quantitatively analyze ice accumulation on blades. Their findings indicate that under icing conditions, the rotational speed and power generation of wind turbines at the same wind speed are significantly reduced, and the wind turbines are more likely to experience rotor vibration or rotor rotation eccentricity. Yiqiang Han et al. [10] used scaled-down blade icing experiments to validate the similarity

between experimental results and simulation models. They discovered that light, moderate, and severe icing increase the torque requirements by 5%, 25%, and over 70%, respectively.

Liangquan Hu et al. [11] conducted ice simulation experiments on wind turbine blades under various conditions, demonstrating how liquid water content, temperature, and blade pitch angle affect icing thickness. They concluded that icing could reduce the load and fatigue damage on certain parts of the wind turbine by altering the rotor thrust and the torque at the blade root. However, asymmetric icing leads to unbalanced forces, increasing fatigue damage on the shaft, which is used for torque input to the gearbox. Yi Xian et al. [12] studied the phenomenon of supercooled water droplets impacting and freezing on the surface of wind turbines. They summarized the effects of simulated icing on the distribution of ice on wind turbines and found that icing has a minimal impact on the pressure load distribution near the blade root but significantly alters the load near the blade tip. Liangquan Hu et al. [13], using the NREL Phase VI wind turbine as their subject, investigated the effects of symmetric and asymmetric icing on wind turbine loads through icing simulation experiments. The results show that symmetric icing reduces the wind wheel torque and can decrease the force along the center of rotation, blade root torque, and tower base torque. Asymmetric icing causes an imbalance in the shaft, which is used for torque input to the gearbox shear force, increasing the fatigue load on the shaft. Rustem Manatbayev et al. [14], using FENSAP-ICE (Version 2019 R1) software, developed a new method for ice prediction simulation. This method showed that the torque coefficient of the blades significantly decreased after icing.

Previous scholars have conducted multifaceted research on the icing issues of wind turbines, but there are still relatively few studies on the icing morphology of intact blades through icing wind tunnel tests. Because of the limited size of the wind tunnel test space, it is impossible to carry out icing experiments on larger-scale blades. At the same time, the iced blade is a whole, so it is not easy and accurate to describe the local icing morphology and thickness, which is unfavorable to the in-depth study of the icing mechanism and the anti-icing method. Therefore, this paper proposes an experimental method for scaled-down segmentation of blades based on a small recirculating icing wind tunnel. This method can solve the problems of blade size and the depiction of icing morphology on the local cross-sections of blades by segmenting the blades at the key positions and performing icing experiments on the sections. Due to the fact that the blade icing has a smoother surface in the case of clear ice, the thickness of icing in the various cross-sections is more uniform. Through the verification, Catia V5-6R2019 software in the multi-section solid feature can be very good at reconstructing the icing model, and the error is within the range of 10% icing thickness, which ensures the accuracy of the test data.

This study also explores the differences in stress, strain, and tip displacement analyses between different blade iced models and non-iced blades, under two icing conditions. These studies will provide important references for subsequent wind turbine blade anti-icing studies, and will also contribute to the design of new wind turbine blades.

2. Research Methodology

2.1. Scaled-Down Model Establishment

The experiment uses a scaled model of a specific 1.5 MW wind turbine blade, originally 37.64 m in length. Due to experimental conditions, a scaled-down 3 m model was used. The scale of the model is 1/12.5. The irregular shape of the blade tip and root in horizontal-axis wind turbines makes it challenging to accurately depict the icing formation after icing experiments with the horizontal axis blade scaled-down model as a whole. Past experiments have shown issues with precision in reconstructing the icing on wind turbines using methods such as 3D reconstruction. Therefore, this study divides the 3 m scaled model of the 1.5 MW wind turbine blade, focusing on the section near the blade root where the chord length is at its maximum. The cross-section at the maximum chord length has a unique airfoil shape, and it is representative to study the icing characteristics of the airfoil in this cross-section as well as to accumulate data for the subsequent study of the influence

of icing on the blade lift resistance. The subsequent segmentation position is chosen to be equal-length segmentation, which will facilitate the generation of a uniform icing model. The specific segmentation is shown in Figure 1. Then, take the airfoils at both ends of the cross-section of each segmented section. These nine airfoils were 3D printed with high-strength resin material into 20 mm thick sections.

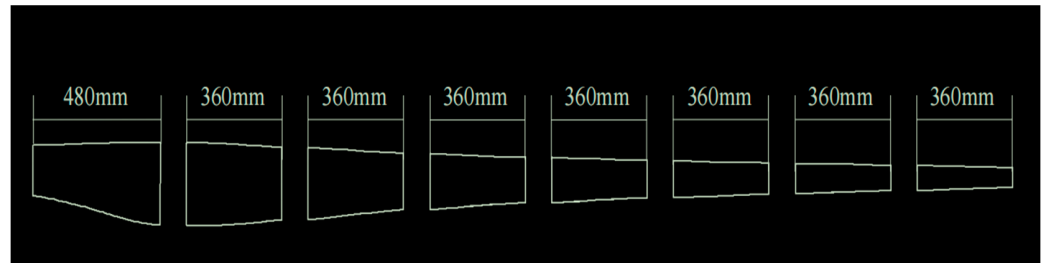


Figure 1. Division method for the 3 m scaled model of a 1.5 MW wind turbine blade.

2.2. Test System

The test was conducted using the small recirculating icing wind tunnel at Northeast Agricultural University, as shown in Figure 2. The test system consists of a refrigeration system, a spraying system, and a return wind tunnel. Meanwhile, there are several sets of fairing plates in the icing wind tunnel, which can ensure that the airflow in the wind tunnel is a stable laminar flow. The excess water droplets will flow into the drain under the wind tunnel on the fairing plates at the back of the test space, so that it is also conducive to ensuring the stability of the liquid water content in the test. It has been verified that a test space of 800 mm ensures the water droplets are distributed uniformly throughout the test space before impacting the section, and the 250 mm × 250 mm cross-section size allows for a wide range of blade icing tests. Therefore, the test space of the system is 800 mm in length with a cross-section size of 250 mm × 250 mm. Test wind speeds of the icing wind tunnel range from 0 to 20 m/s, temperatures from −20 to 0 °C; liquid water content (LWC) from 0.1 to 20 g/m³; air pump from 0 to 0.7 MPa air pressure; and mean volumetric diameter (MVD) of the cloud droplets from 20 to 100 μm.

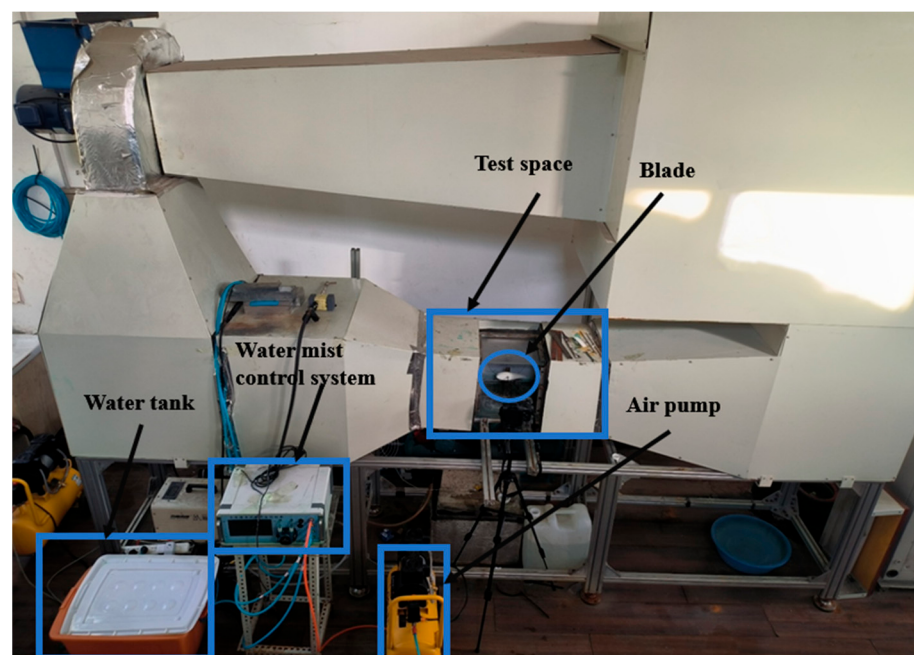


Figure 2. Small recirculating icing wind tunnel test system.

The test conditions in this small recirculating icing wind tunnel can cover most of the environmental conditions when real wind turbines are iced up, so the icing data obtained in this test system can represent the real wind turbine icing situation to some extent.

2.3. Experimental Plan

Temperature is one of the key factors affecting ice formation [15,16]. Previous studies have shown that different temperature conditions can affect icing characteristics and thickness. The 1.5 MW wind turbines selected for this experiment are onshore units and have been in actual operation for power generation, with some units being installed in certain wind farms in Guizhou, China. By checking the icing reports of wind turbines in the region, icing occurs more often at $-5\text{ }^{\circ}\text{C}$ and $-10\text{ }^{\circ}\text{C}$. Therefore, the experimental temperatures were set at $-5\text{ }^{\circ}\text{C}$ and $-10\text{ }^{\circ}\text{C}$. Since liquid water content as a variable is related to wind speed [17,18]. In order to obtain the best experimental comparison, an experimental plan, as shown in Table 1, was designed.

Table 1. Wind tunnel test conditions.

Ice Model	Temperature T ($^{\circ}\text{C}$)	Wind Speed U (m/s)	Liquid Water Content LWC (g/m^3)
1	-5	5	2
2	-5	5	4
3	-5	10	1
4	-5	10	2
5	-10	5	2
6	-10	5	4
7	-10	10	1
8	-10	10	2

Through the pre-test, it can be found that when the spray time reaches more than 5 min, the blade is easier to ice skate and produces more angular ice. It will have a greater impact on the later study of icing thickness and icing volume, so choose the icing time of 5 min. Meanwhile, the air pump air pressure is stable at 0.3 MPa, with the cloud equivalent particle size MVD through the laser particle sizer measurement for 24–36 μm .

2.4. Experimental Method

In order to ensure that the initial conditions before the icing experiment are the same for all sections and closer to the real temperature simulated by the test, before each experiment, the nine sections were wiped dry and pre-cooled in a $-20\text{ }^{\circ}\text{C}$ freezer for one hour. When the experiment began, the parameters of the icing wind tunnel were adjusted to the conditions listed in Table 1. After the experimental conditions stabilized, one of the sections was taken out of the freezer in numerical order, fixed in the test space at a 0 degree angle of attack, and pre-cooled for 30 s to bring its temperature in line with the experimental temperature. Then, the spray system parameters were adjusted to the corresponding conditions, and the spray system was turned on for the experiment. The spray system mixed water droplets with the air in the wind tunnel and impacted the leading edge of the section. When the experiment reached 5 min, the spray system was turned off, and the icing condition on the section surface was photographed with a high-definition camera, as shown in Figure 3. Using high-precision vernier calipers to measure the thickness of icing at the leading edge of each section, three measurements were averaged and recorded. The resulting photographs were then imported into CAXA CAD 2018 software to draw the icing profile of the section at that time, as shown in Figure 4. The experiments showed that the icing formed was clear ice.

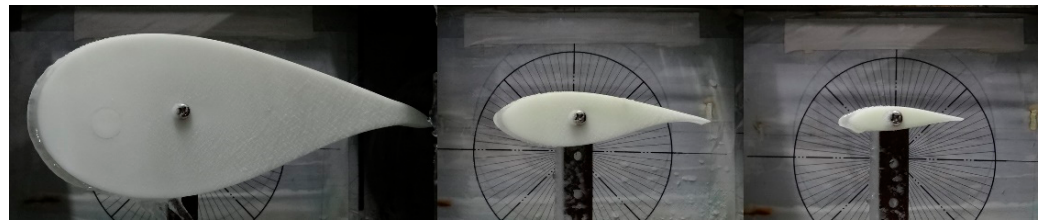


Figure 3. Icing images from the wind tunnel test.

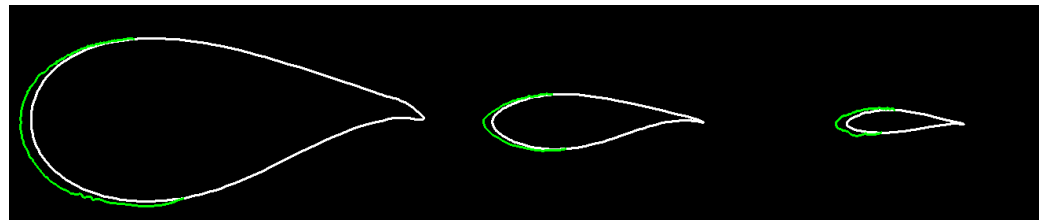


Figure 4. Iced blade profile diagram.

The icing conditions were converted into ice shape diagrams using CAD, resulting in nine icing profiles for each test condition. Following the blade segmentation method shown in Figure 1, the entire blade's ice model diagram was created using the multi-section solid feature in Catia, as shown in Figures 5 and 6.

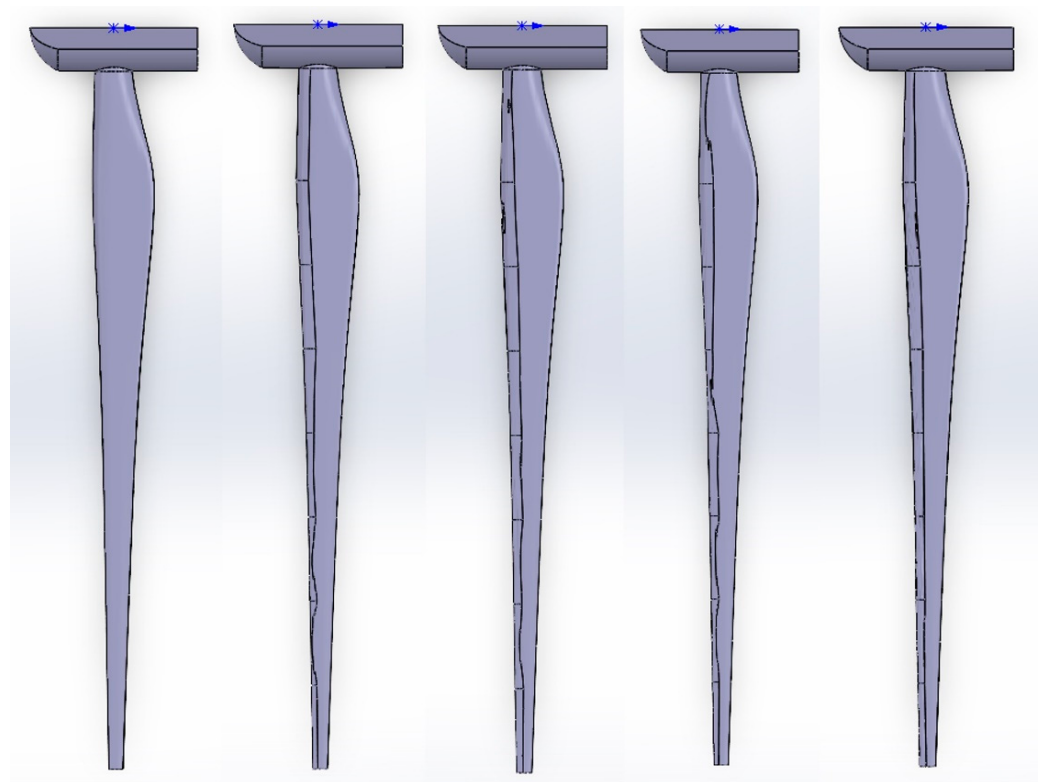


Figure 5. Ice model 1–4 diagram.

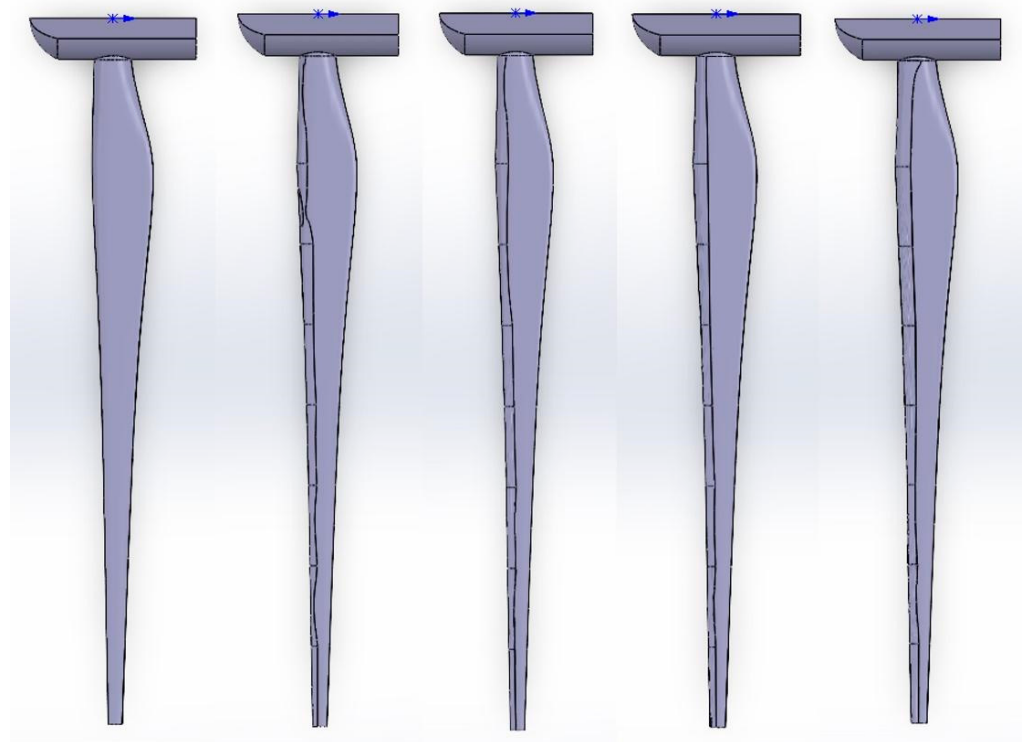


Figure 6. Ice model 5–8 diagram.

In Figures 5 and 6, the top of the blade root shows the origin and axis of the ice model. From the wind tunnel test's icing images and ice model diagrams, it is evident that under the conditions of Table 1, icing primarily occurs on the leading edge of the blades, forming clear, irregularly shaped ice. Decreasing temperature, increasing wind speed, or increasing liquid water content all contribute to an increase in the extent and amount of ice formation.

2.5. Analysis of Wind Tunnel Test Results

As can be seen from Figure 6, the icing of the blade is mainly distributed at the leading edge of the blade under the working conditions in Table 1, and the shape of the icing is irregular. By removing the un-iced blade model in Catia V5-6R2019 software, the ice model of the blade as a whole can be obtained, and Figure 7 shows the ice model 7 and ice model 8 ice-shape diagrams.

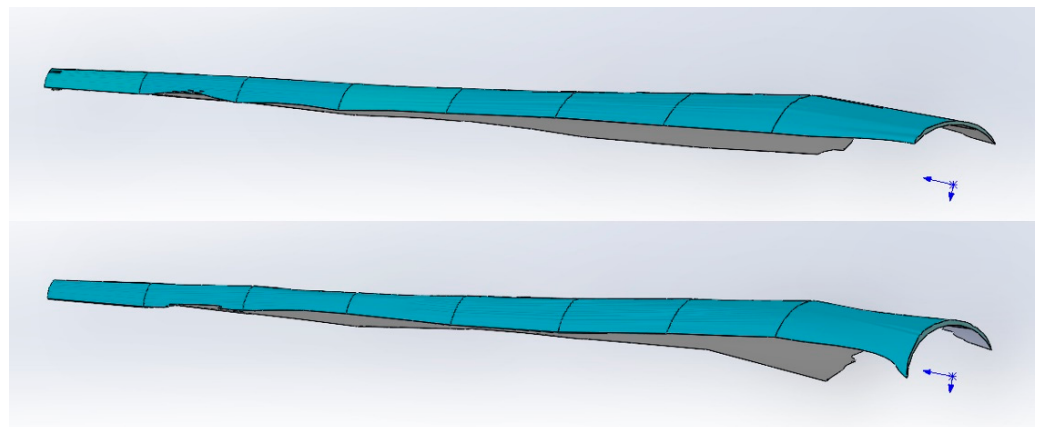


Figure 7. Ice model 7–8 ice-shape diagrams.

By analyzing the ice-shape diagrams of ice models 1–8 through the software, the icing volume of the ice model can be obtained while measuring the leading edge icing thickness of the nine sections under each test condition, calculating the average icing thickness of the leading edge of ice models 1–8, and organizing the icing volume and the average icing thickness of the leading edge to obtain the table of icing volume and average icing thickness of the leading edge of ice models 1–8 shown in Table 2.

Table 2. Ice model 1–8 icing volume and average icing thickness at leading edge.

Ice Model	Test Condition (T/U/LWC)	Average Icing Thickness at Leading Edge/mm	Icing Volume/m ³
1	−5 °C 5 m/s 2 g/m ³	2.261	3.856×10^{-4}
2	−5 °C 5 m/s 4 g/m ³	2.648	5.728×10^{-4}
3	−10 °C 5 m/s 2 g/m ³	2.942	4.014×10^{-4}
4	−10 °C 5 m/s 4 g/m ³	5.577	7.351×10^{-4}
5	−5 °C 10 m/s 1 g/m ³	4.623	6.436×10^{-4}
6	−5 °C 10 m/s 2 g/m ³	5.641	9.521×10^{-4}
7	−10 °C 10 m/s 1 g/m ³	5.242	7.429×10^{-4}
8	−10 °C 10 m/s 2 g/m ³	7.239	9.989×10^{-4}

Based on the data in Table 2, it is possible to plot the average icing thickness analysis of the leading edge of ice models 1–8 in Figure 8 along with the icing volume analysis of ice models 1–8 in Figure 9.

As can be seen in Figures 8 and 9, since the icing rate increases with the decrease in temperature after the supercooled water droplets hit the blade surface, the temperature decreases, the average icing thickness at the leading edge of the blade increases, and the icing volume of the blade increases, while the other conditions remain unchanged.

Regarding water droplets in the icing process, there is heat conduction, convection heat transfer and thermal radiation, and other energy transfer processes. When the wind speed increases, the convection heat transfer rate increases, which leads to the water droplets dissipating heat faster, thus increasing the icing rate. As the wind speed increases, the average icing thickness of the blade leading edge of the blade increases, the blade icing volume increases.

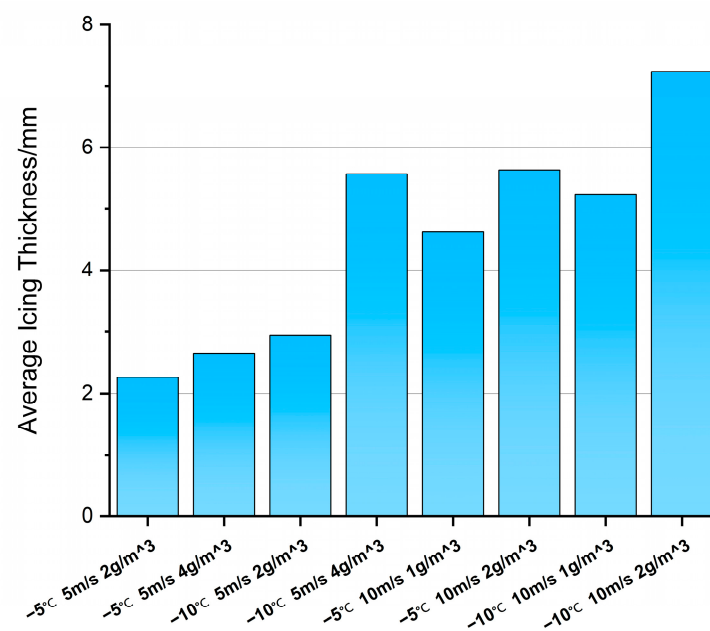


Figure 8. Average icing thickness at leading edge of ice model 1–8 analysis bar chart.

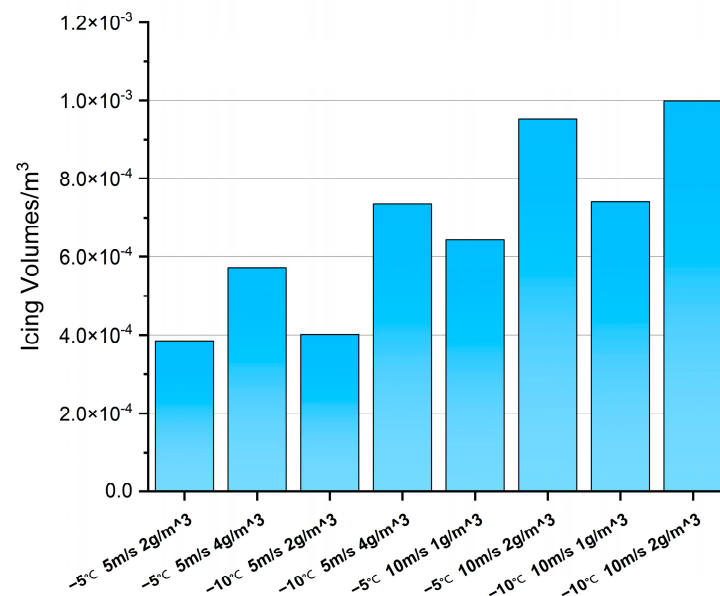


Figure 9. Ice model 1–8 icing volume analysis bar chart.

Liquid water content indicates the mass of liquid water in a unit volume of air. When the liquid water content increases, it means that there will be more water droplets hitting the blade surface at the same time, so the increase in liquid water content will lead to an increase in icing rate, and the average icing thickness of the leading edge of the blade and the icing volume of the blade will also increase accordingly.

Meanwhile, the data can be analyzed to indicate that when other conditions are the same, the wind speed increases from 5 m/s to 10 m/s, the average leading edge icing thickness increases by 147.8%, and the average icing volume increases by 147.9%; when other conditions are the same, the liquid water content doubles, the average leading edge icing thickness increases by 39.9%, and the average icing volume increases by 53.5%; and when other conditions are the same, the temperature decreases from $-5\text{ }^{\circ}\text{C}$ to $-10\text{ }^{\circ}\text{C}$. $-5\text{ }^{\circ}\text{C}$ to $-10\text{ }^{\circ}\text{C}$, the average increase in leading edge icing thickness is 24.6%, and the average increase in icing volume is 13.2%.

Therefore, under the conditions selected in this experiment, the increase in wind speed had the greatest effect on icing volume and the average icing thickness at the leading edge, followed by the increase in liquid water content, and the decrease in temperature had the least effect.

3. Structural Mechanics Analysis of Scaled-Down Model

3.1. Three-Dimensional Modeling and Mesh Division of Blade Scaled-Down Model

A scaled-down 3 m model of the wind turbine blade was created using Catia V5-6R2019 software, and the model was meshed using Icem 19.0 software. The mesh division of the model is shown in Figure 10. The blade structure is subjected to wind loads, vibration loads, and rotational loads. To conduct a structural mechanics simulation under wind-vibration combined load conditions, a comprehensive assessment of the mesh division is required. Considering the large geometric dimensions of the model and its solid nature, both computational accuracy and efficiency were taken into account. To ensure mesh quality, tetrahedral meshes with a minimum size of 20 mm were used. The study performed finite element mesh division on the non-iced model, as well as evenly distributed ice models 7 and 8, followed by a mesh independence verification.



Figure 10. Mesh division of the blade model.

3.2. Setting of Computational Conditions

Boundary conditions were set for the geometric model based on structural constraints. The structure is symmetrical; hence, symmetric constraints were used in the analysis. Fixed and rotational constraints were applied at the position of the axis of rotation. The corresponding boundary constraints at each location are shown in Figure 11.

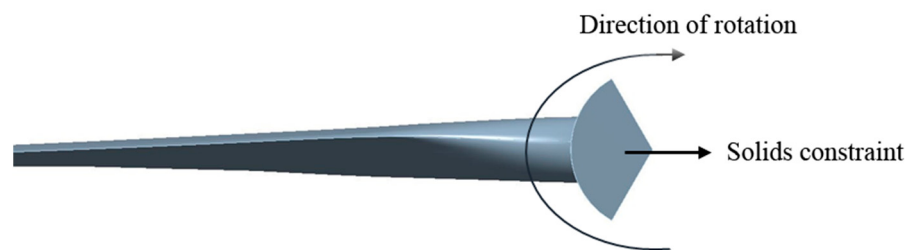


Figure 11. Boundary constraints of the blade.

The material selected for the blade structure is fiber cloth. The mechanical properties of the material, such as elastic modulus, Poisson's ratio, density, and other parameters, are shown in Table 3.

Table 3. Mechanical properties of blade material.

Material Name	Density	Longitudinal Tensile/ Compressive Modulus	Transverse Tensile/ Compressive Modulus	Poisson's Ratio
Fiber cloth	1.923 g/cm ³	31 Gpa	14 Gpa	0.5

The operational conditions selected for the analysis of the blade structure's mechanical characteristics are shown in Table 4.

Table 4. Operational conditions for the analysis of blade structure mechanical characteristics.

Condition Number	Wind Speed (m/s)	Rotational Speed (rpm)	Tip Speed Ratio	Blade Pitch Angle (°)
1	3	6.2	9	0
2	4	8.3	9	0
3	5	10.4	9	0
4	6	12.5	9	0
5	7	14.6	9	0
6	8	16.7	9	0

3.3. Scaled-Down Model Structural Mechanics Analysis Results

A static strain analysis was performed on the wind turbine blade structure at a wind speed of 8 m/s and a rotational speed of 16.7 rpm, both with and without icing conditions. The structural response over 10 s, with a time step of 0.05 s and 2000 calculation steps, was analyzed. Due to the structure's symmetry, one-third of the blade structure was chosen for illustration. The key positions for maximum deformation and maximum equivalent stress are shown in Figures 12 and 13. The place of maximum stress reflects the location where the blade is most susceptible to damage during rotation.

Comparing Figures 12 and 13, it is evident that the non-iced blade undergoes maximum deformation at the blade tip, with the maximum equivalent stress and strain occurring at about one-third of the blade length. Due to the elongated structure of the blade and the minimum chord length at the tip, this results in the tip being more susceptible to deformation, and again, the blade deforms the most at the tip after icing. Icing of the blades increases the weight of the blades, which results in stronger centrifugal forces acting on the iced blades as they rotate. Besides, the weight of the ice model is mainly concentrated near the leaf root due to the larger chord length at the leaf root, which leads to a shift in the center of gravity of the blade towards the root of the blade. The maximum equivalent stress is about halfway along the blade at this point. Further analysis of the blade's structural mechanics response before and after icing under five other rotational speed conditions was conducted, yielding the results shown in Table 5.

Table 5 shows the calculation results of equivalent stress, equivalent strain, and tip displacement for the non-iced blade and ice models 7 and 8 at the six rotational speeds in the table. Since the same material is used for both the scaled-down 3 m model of the blade and the original blade, the maximum allowable stress of the material is 360 MPa through the preliminary study [19], which is greater than the maximum equivalent stress of 190 MPa obtained from the scaled-down model of the analysis. Therefore, there is no risk of damage to the material. From the data in Table 5, we can obtain the comparative diagrams of equivalent stress, equivalent strain, and blade tip displacement analyzed in Figures 14–16.

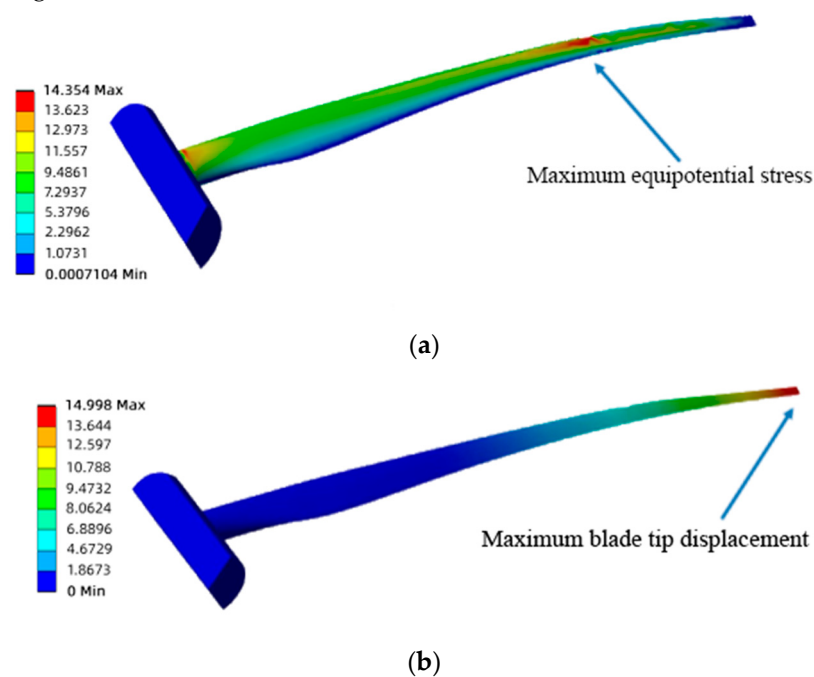


Figure 12. (a) Maximum equipotential stress of the non-iced blade; (b) maximum blade tip displacement of the non-iced blade.

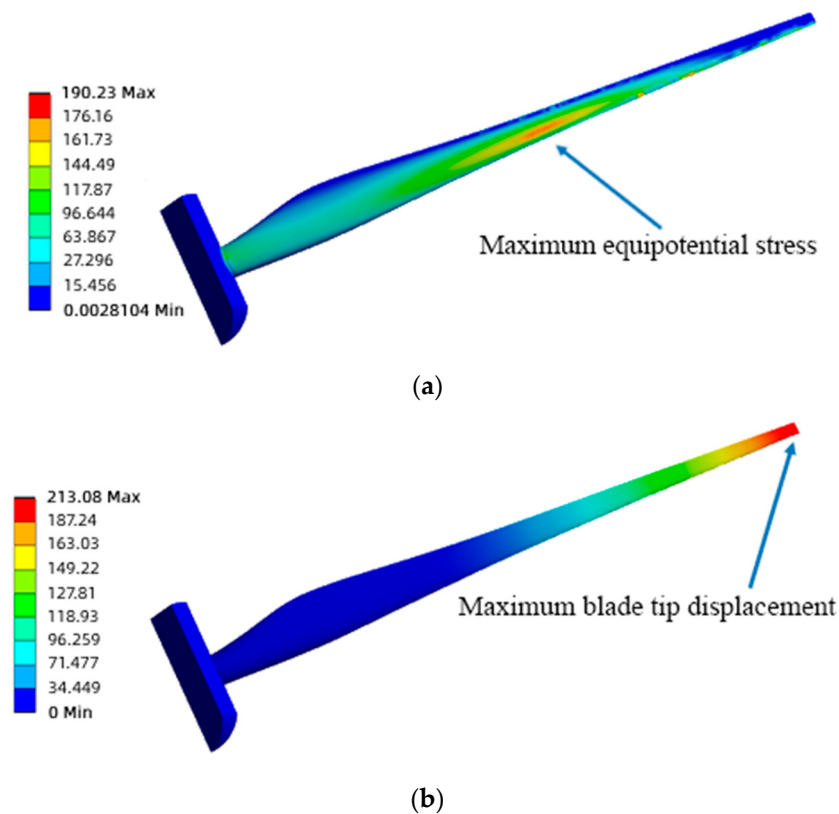


Figure 13. (a) Maximum equipotential stress of the iced blade; (b) maximum blade tip displacement of the iced blade.

Table 5. Response results of non-iced blade and ice models 7 and 8.

Rotation Speed /rpm	Stress/MPa			Strain mm/mm			Displacement/mm		
	Non-Iced	Ice Model 7	Ice Model 8	Non-Iced	Ice Model 7	Ice Model 8	Non-Iced	Ice Model 7	Ice Model 8
6.2	25	166	181	1.47×10^{-5}	9.69×10^{-5}	1.64×10^{-4}	21	132	207
8.3	27	168	184	1.55×10^{-5}	9.81×10^{-5}	1.65×10^{-4}	24	134	209
10.4	16	171	186	9.62×10^{-6}	9.94×10^{-5}	1.66×10^{-4}	21	135	210
12.5	27	173	188	1.56×10^{-5}	1.01×10^{-4}	1.67×10^{-4}	19	136	211
14.6	14	174	189	7.96×10^{-6}	1.01×10^{-4}	1.68×10^{-4}	15	137	212
16.7	14	175	190	7.96×10^{-6}	1.02×10^{-4}	1.69×10^{-4}	15	138	213

From Figures 14–16, due to the increased weight of the iced blade, while icing changes the aerodynamic characteristics of the blade, ice models 7 and 8 exhibit higher equivalent stress and strain compared to the non-iced blade at the same rotational speeds, and the blade tip displacement is also greater.

The maximum stresses and strains of the non-iced blades were obtained at 8.3 rpm and 12.5 rpm, with the maximum tip displacement reached at 8.3 rpm. Moreover, the maximum stresses, strains, and tip displacements tended to decrease slightly at higher speeds, so more attention should be paid to the low-speed region.

When the rotational speed increases, the blades are subjected to greater centrifugal force and lift force, and at the same time, since the icing volume of the ice model 8 is larger than that of the ice model 7, the icing weight of ice model 8 is greater, and the stresses and strains borne by the blades increase accordingly. Ice model 8 shows higher equivalent stress, strain, and blade tip displacement than ice model 7 at the same speed; The structural stress of ice models 7 and 8 on the blade body gradually increases, ranging between 166 and 190 MPa, with the maximum stress at 190 MPa. The strain gradually increases, ranging from 9.69×10^{-5} to 1.69×10^{-4} , with the maximum strain at 1.69×10^{-4} . Ice models 7 and 8 also had a slowly increasing trend in tip displacement, which was in the range of 132–213 mm, with a maximum tip displacement of 213 mm.

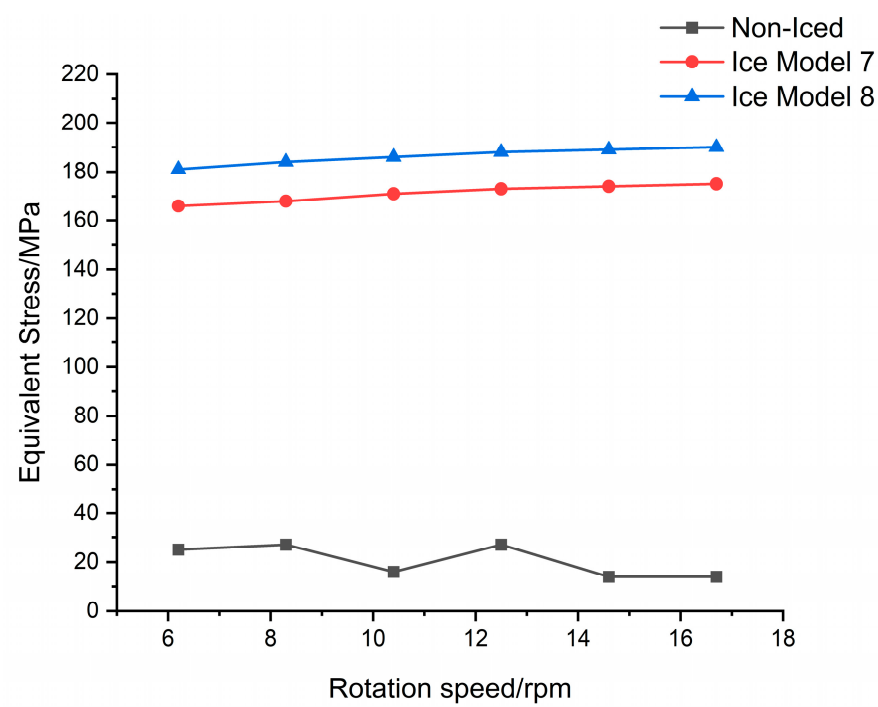


Figure 14. Equivalent stress analysis diagram.

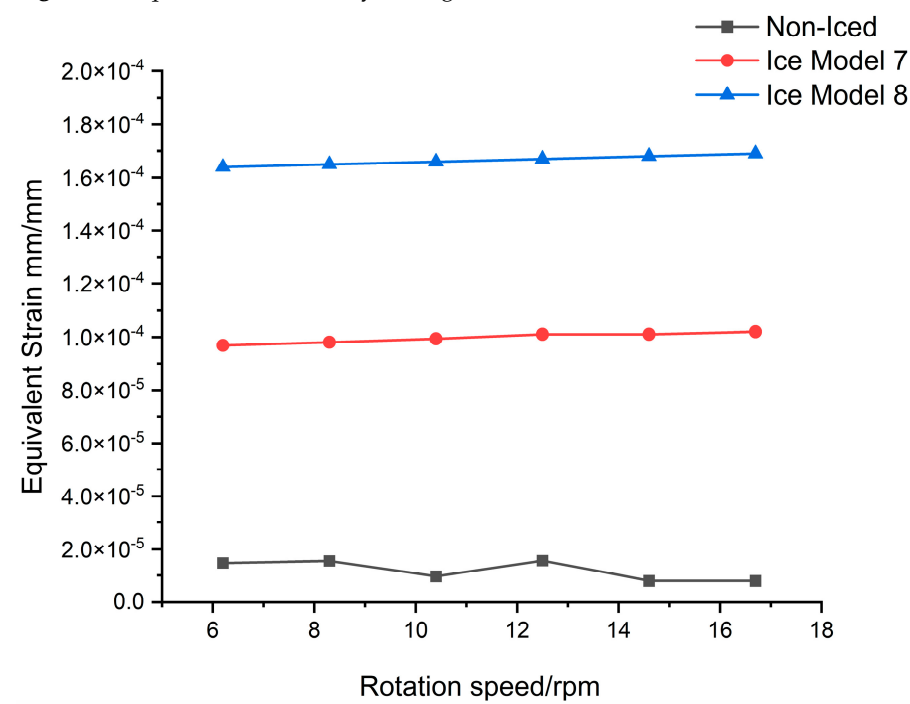


Figure 15. Equivalent strain analysis diagram.

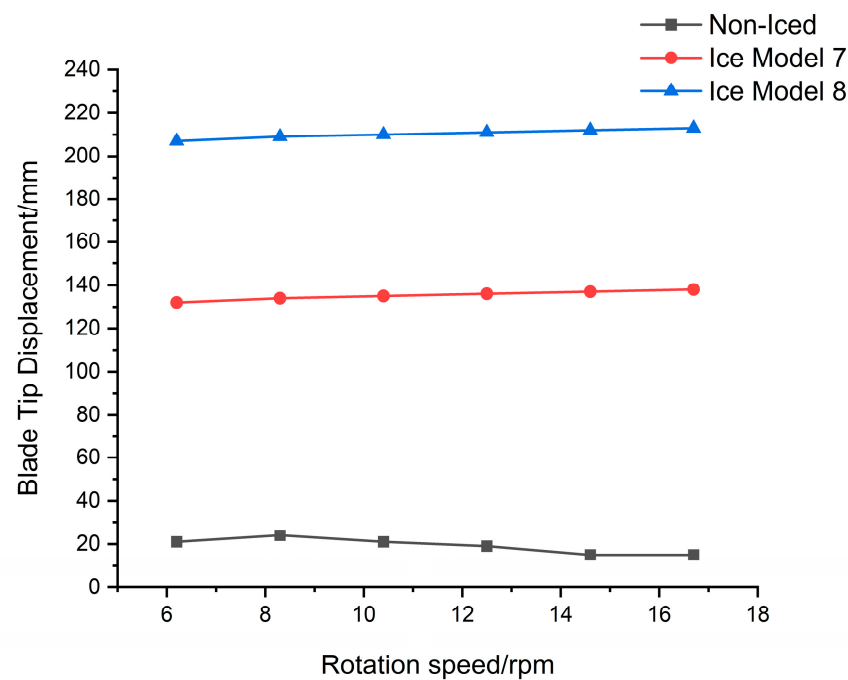


Figure 16. Blade tip displacement analysis diagram.

4. Conclusions

In this paper, the icing characteristics of 1.5 MW wind turbine blades are investigated by icing wind tunnel tests at different temperatures, wind speeds, and liquid water contents. The influence of icing on the mechanical properties of the blades is also explored. The following conclusions were drawn:

- (1) The blade icing under the test conditions in this paper is mainly distributed at the leading edge of the blades, and all of them are clear ice with irregular icing shapes. Meanwhile, at higher icing temperatures and wind speeds, it is easy to produce angular ice with ice skating and rougher icing surfaces.
- (2) Temperature, wind speed, and liquid water content all affect the blade icing rate. From the experimental data, it can be concluded that when other conditions remain unchanged, lowering the temperature, increasing the wind speed, or increasing the liquid water content will increase the average icing thickness at the leading edge of the blade, and the icing volume of the blade will increase.
- (3) When all other conditions remained consistent, doubling the wind speed, doubling the liquid water content, and doubling the temperature increased the leading edge icing thickness by an average of 147.8 per cent, 39.9 per cent and 24.6 per cent, respectively, and increased the icing volume by an average of 147.9 per cent, 53.5 per cent and 13.2 per cent, respectively.
- (4) Due to the weight increase in the iced blade and the change in aerodynamic characteristics of the blade by icing, the equivalent stress and strain of the iced blade are larger than that of the non-iced blade at the same rotational speed, and the tip displacement has the same law.
- (5) The icing volume and thickness of the blade are larger due to the stronger centrifugal force; the stress and strain are larger under the same rotational speed, and the stress and strain increase with the increase in rotational speed.
- (6) This thesis investigates the icing characteristics of leaves and the mechanical changes in leaf structures before and after icing. In the follow-up research, the influence of icing on the dynamic modal analysis of leaves will be explored. This is of great importance for the investigation of the effects of icing on wind turbine blades.

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