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An Experimental Study on Adhesion Strength of Offshore Atmospheric Icing on a Wind Turbine Blade Airfoil

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Abstract: When wind turbines work in a cold and humid environment, especially offshore condition, ice accretion on the blade surfaces has a negative effect on the aerodynamic performance. In order to remove the ice from the wind turbine blade, the adhesive characteristics of atmospheric icing on the blade surface should be mastered under various conditions. The objective of this study is to evaluate the effects of offshore atmospheric conditions, including wind speeds, ambient temperatures and, especially, the salt contents on ice adhesion strength for wind turbine blades. The experiments were conducted on a NACA0018 blade airfoil under conditions including an ambient temperature of −3 °C~−15 °C, wind speed of 6 m/s~15 m/s and salt content of 1~20 mg/m^3. The results showed that salt content was the most important factor affecting the ice adhesion strength, followed by ambient temperature and wind speed. The interactive effect of wind speed and salt content, ambient temperature and salt content were extremely significant. The research can provide a reference for the anti-icing for offshore wind turbines.

Keywords: atmospheric icing; adhesion strength; wind turbine; offshore condition; wind tunnel test

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Citation: Mu, Z.; Li, Y.; Guo, W.; Shen, H.; Tagawa, K. An Experimental Study on Adhesion Strength of Offshore Atmospheric Icing on a Wind Turbine Blade Airfoil. *Coatings* **2023**, *13*, 164. https://doi.org/10.3390/coatings13010164

Academic Editors: Joachim Albrecht and Ioannis Karapanagiotis

Received: 17 November 2022
Revised: 26 December 2022
Accepted: 5 January 2023
Published: 11 January 2023

1. Introduction

Wind energy is one of the most widely used and commercially successful renewable energy sources in the world [1,2]. The wind turbine can operate stably under suitable environmental conditions. However, in cold and humid weather conditions, wind turbines meet serious icing problems [3]. Initial ice adhesion on the blade surface may cause a weight imbalance between turbine blades, affecting the aerodynamic characteristics and the power output of the wind turbine, and continued ice accretion can affect the structural loading of the rotor leading to accidents [4,5]. At present, offshore wind turbine has developed rapidly. However, some complex and extreme atmospheric conditions pose special challenges to the development of offshore wind turbines, such as icing. It is known that the type and characteristics of icing on the surface of the wind turbine blade are affected by many factors, such as wind speed, ambient temperature, super-cool water droplets, etc. [6,7]. However, compared with many research results on onshore wind turbine icing, the research on the icing characteristics of the offshore wind turbine blade is very few, and establishing the adhesion strength of ice on the blade airfoil surface will be the key for research on the anti-icing strategy design of offshore wind turbines.

Over years of research, by using icing wind tunnel tests and numerical simulation, scholars have basically found the distribution of icing on the blade surface under different environmental conditions. The effect of icing on the aerodynamic characteristics of the blade was investigated [8]. In order to solve icing problems, active de-icing methods have been used, such as mechanical vibration, physical heating and chemical fluid spray. Compared with the above methods, which suffer from low efficiency, high energy consumption and pollution, passive de-icing methods by introducing icephobic coatings are an effective alternative approach [9–11]. Moreover, regardless of the kind of anti-icing method, understanding the variation in adhesion strength between the ice and the surface of the wind turbine blade under various atmospheric environment conditions is the first step to clarifying the icing mechanism. The icing adhesion theory can be mainly divided into mechanical adhesion theory, electronic theory, adsorption theory and weak boundary layers theory [12–15]. All these studies have made a good exploration for revealing the mechanism of icing adhesion. However, due to the complex icing environment, there are still some differences between theoretical calculation and practice. The experimental method is still the most important and accurate means to obtain the ice adhesion strength on the blade surface. At present, for the convenience of experimental research, researchers usually simplify the object to a flat plate and cylinder [16,17]. The evaluation of the adhesion strength on the airfoil surface of wind turbine blades is quite few.

In addition, the above research were all tested under pure water. Compared with the onshore condition, the wind turbines under offshore conditions are exposed to sea fog all year round, which means that the content of liquid water in the environment is extremely high. Moreover, the sea fog splashed by the waves floats in the air, which makes the salt content in the sea air much higher than that on land. Therefore, it can be inferred that the most significant difference between offshore and onshore atmospheric conditions is that there will be a certain amount of salt in the sea air. Then, adding an appropriate amount of salt to the purified water to study the icing problem of the offshore wind turbines will provide the possibility for the study of offshore wind turbine icing.

In this paper, to replicate the natural icing characteristic of the wind turbine blade, atmospheric ice generated by water droplets in the dynamic flow field was produced in the wind tunnel. The effect and interactive effect of atmospheric conditions, including wind speed, ambient temperature and salt content on ice adhesion strength of wind turbine blade airfoil, was investigated. The experiments were carried out based on the NACA0018, a typical symmetrical airfoil under the offshore condition of China's Bohai Sea in winter. The maximum ice adhesion strength was obtained under the test conditions. This study can be a reference for research on the surface icing mechanism of offshore wind turbine blades and the development of icing protection technology.

2. Experiment and Methods

2.1. Test Blade Segment

An axial symmetrical blade segment with airfoil NACA0018 was selected in this paper, as shown in Figure 1. The blade airfoil is made of aluminum alloy because it has isotropy, good thermal conductivity and stability, which is widely used to investigate the adhesive characteristics of icing. According to the size of the tunnel outlet, the airfoil chord (c) was set as 150 mm. The thickness of the blade airfoil (h) is 20 mm. The roughness of the surface is 6.313 μm.

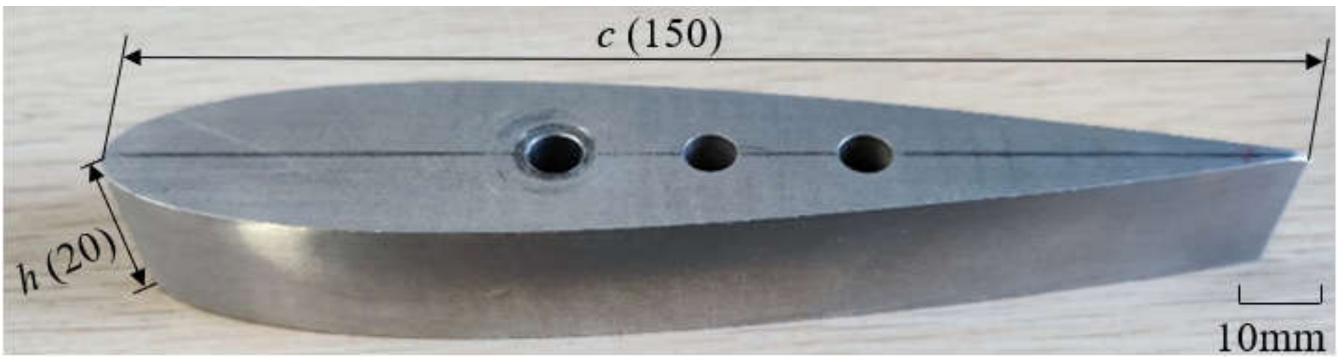

Figure 1. Blade segment sample.

2.2. Experiment System

The icing test was carried out in the wind tunnel with a return-flow air system, as shown in Figure 2. The cross area of the air duct at the test chamber is 250 × 200 mm. The test blade airfoil with an attack angle of zero degrees is held in the frame and placed within the inner duct of the wind tunnel. Based on the windward areas of the blade airfoil and the frame, the blockage area ratio of them to the cross area of the test chamber is 1.8%. The droplets with the given salt content were emitted into the cooled air flow and froze upon impact with the blade airfoil according to the experimental conditions. It should be noted that the temperature of salt droplets is regarded as the same as the ambient temperature in the test chamber. The detail information about the wind tunnel system can be found in our previous research [18].

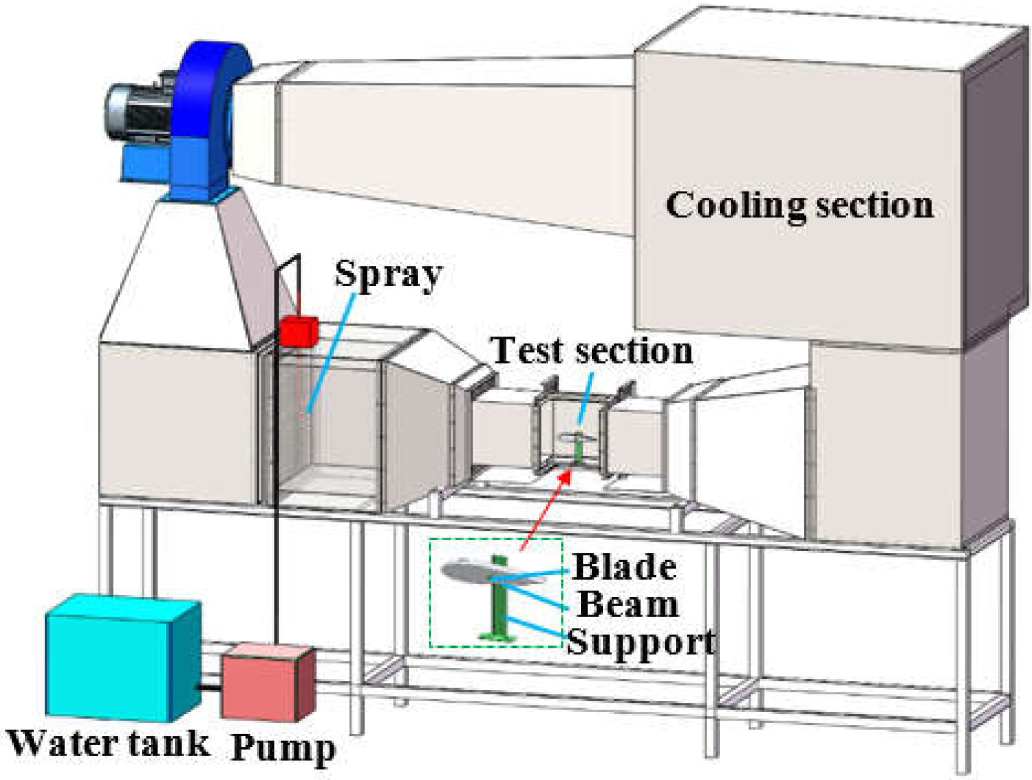

Figure 2. Icing wind tunnel experimental system.

After the icing period, the spraying system and tunnel wind were stopped. The test specimen was carefully removed from the tunnel and then mounted in the adhesion strength test device. The key to this process is to ensure the ice specimen along the leading edge is not damaged before the test begins. The adhesion strength of ice on the blade airfoil was measured by the self-built test device, as shown in Figure 3. It mainly consists of three components: the refrigeration unit, the measuring unit and the data acquisition unit. The whole device was put in a refrigerator to avoid the influence of changes in ambient temperature. The blade airfoil was fixed on a slider connected with two pressure sensors. It is driven by a hydraulic thruster at a gradual and steady pace. When the icing blade airfoil passes through the de-icing hole, the ice layer is detached from the airfoil under the action of shear force. The shear force is obtained by the sensor and recorded in real time. Each test was repeated 20 times, and the results were averaged and plotted with standard deviation to account for experimental error and natural variations.

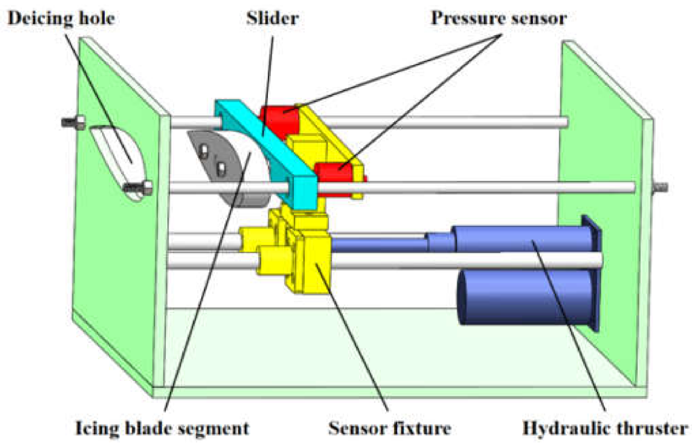

Figure 3. Measuring device of the adhesion strength of ice.

2.3. Experiment Condition

The LWC in the test chamber for the present study is in the range of 0.8~1.6 g/m^3, and the MVD is about 65 µm. In this research, the atmospheric condition is based on the offshore air condition of China's Bohai Sea in winter. The wind speed is in the range of 6~7 m/s usually, but in January, it is in the range of 10.8~13.8 m/s more than 20% of the time. The minimum temperature reaches −18 °C, and the maximum temperature is −3 °C. Regarding the salt content, it is in the range of 0.33~23.6 mg/m^3 [19–21]. Therefore, the range of variables selected is the ambient temperature of −3 °C~−15 °C, wind speed of 6 m/s~15 m/s and salt content of 1~20 mg/m^3. All the icing time in this paper is 6 min. The experimental schemes of the effect of individual variables on ice adhesion strength are listed in Tables 1–3.

Table 1. Experimental scheme of the effect of salt content on ice adhesion strength.

Wind Speed *U* (m/s)	Temperature *T* (°C)	Salt Content *C* (mg/m^3)
9	−9	1 4 8 12 16 20

Table 2. Experimental scheme of the effect of ambient temperature on ice adhesion strength.

Wind Speed *U* (m/s)	Temperature *T* (°C)	Salt Content *C* (mg/m^3)
9	−3 −6 −9 −12 −15	8

Table 3. Experimental scheme of the effect of wind speed on ice adhesion strength.

Wind Speed *U* (m/s)	Temperature *T* (°C)	Salt Content *C* (mg/m^3)
6 9 12 15	−9	8

In order to investigate the interactive effect of variables on adhesion strength, a central composite design (CCD) of three variables with five levels is selected, employing the

Design Expert software program (V10). The range of values for the independent variables is selected based on preliminary experiments and the offshore atmospheric condition of China's Bohai Sea. The variables and their levels are given in Table 4.

Table 4. Variables and their levels.

Level	Variable		
	Wind Speed U x_1 (m/s)	Ambient Temperature T x_2 (°C)	Salt Content C x_3 (mg/m^3)
1.682	14	−4	19.75
+1	12	−6	16
0	9	−9	10.5
−1	6	−12	5
−1.682	4	−14	1.25

In the response surface analysis, the quadratic polynomial regression model is usually used to approximate the functional relationship. The second-order polynomial of the following form of the model can be expressed as:

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ii} x_i^2 + \sum_{i \neq j=1}^{3} \beta_{ij} x_i x_j \quad (1)$$

Among them, Y is the dependent response; β_i, β_{ii} and β_{ij} represent the regression coefficients of the process variables; and x_i and x_j are coded independent variables.

According to the above experimental condition, a typical shape of icing and de-icing blade airfoil is shown in Figure 4. In order to quantitatively analyze the icing characteristic of the blade of the wind turbine, the adhesion strength is calculated as follows:

$$\tau = \frac{F}{S} \quad (2)$$

where F is the external shear force acting upon the unit model, S is the de-icing area of the blade that is removed from the blade airfoil and τ is the ice adhesion strength. The area is obtained by multiplying the arc length of the adhesion ice removed from the airfoil (L) and the thickness of the blade airfoil (h).

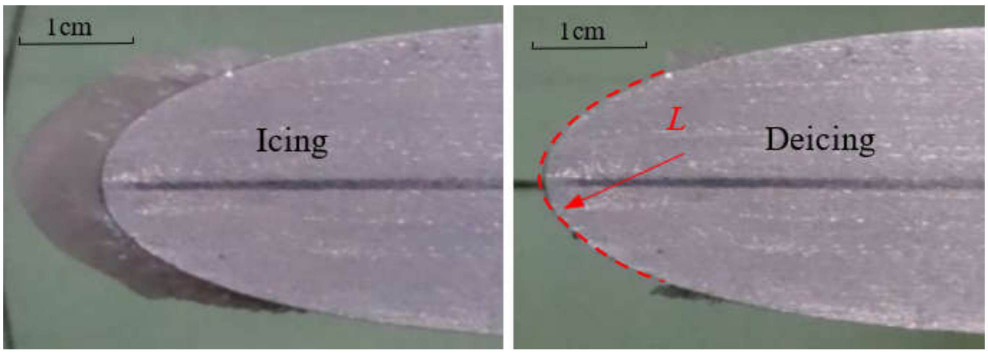

Figure 4. De-icing area for ice adhesion strength.

3. Results and Discussion

3.1. Icing Shape

In order to observe the difference of icing on the surface of the airfoil, icing shapes under various conditions are given in Figure 5. In fact, droplet freezing is nothing more than a first-order liquid–solid phase transition initiated by the nucleation and growth of the nucleus of the new phase into three-dimensional ice crystals [22], but it can be seen that the icing types are quite different. Figure 5a shows that icing event occurs under all kinds of salt content. With the increase in salt content, the type of ice changed from mixed ice to glaze ice. Figure 5b shows that the ambient temperature has a significant effect on the icing type. With the decrease in temperature, the type of ice changed from glaze ice to mixed ice and rime ice at last. Figure 5c shows that the wind speed did not have a significant effect on the change in icing type, and the type of ice is all mixed ice. With the increase in the wind speed, more blade surface area is covered by rime ice. Above all, the icing characteristics are quite different under various atmospheric conditions. It was once pointed out that ice type is an important parameter in the ice adhesion process [23,24]. In the following part, the adhesion strength of ice on the blade airfoil was tested. Moreover, the effect and interactive effect of atmospheric conditions on the ice adhesion strength were also discussed.

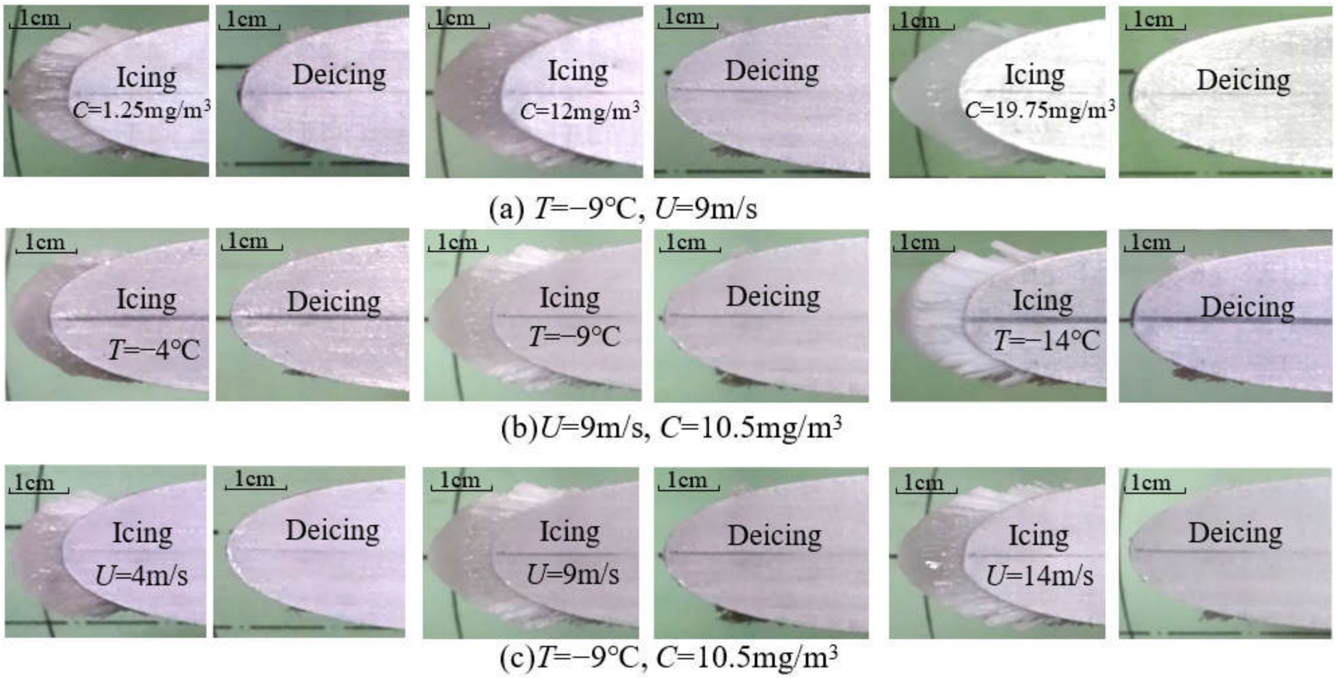

Figure 5. Shape of icing and de-icing blade airfoil under various conditions.

3.2. Effect of Individual Variables on Ice Adhesion Strength

The effect of salt content on ice adhesion strength is shown in Figure 6a. The adhesion strength between the ice and airfoil surface decreased sharply at first and then gradually declined. The corresponding values are 161.8 ± 13.6, 64.7 ± 8.4, 29.9 ± 3.6, 26.9 ± 2.8, 20.2 ± 2.1 and 14.5 ± 2.2 kPa, respectively. This is because the ice consists of salt-free ice and the so-called brine pockets that contain saline water [25]. Upon cooling, some brine is evidently forced out of the brine pockets and must eventually be expelled out of the ice. As a result of this brine expulsion, a layer of high salt concentration forms on the ice surface. When ice is adhered to a structure and cooled, a concentrated salt layer also forms at the ice–airfoil interface. Kulinich [15] found that the larger ice–solid area that is corresponding to the higher ice adhesion strength. The reduction in effective solid–solid contact area at the ice–airfoil interface causes the decline of the adhesion strength. The higher the salt content, the more brine was expelled out, and the smaller the contact area of the ice and airfoil, the lower the adhesion strength.

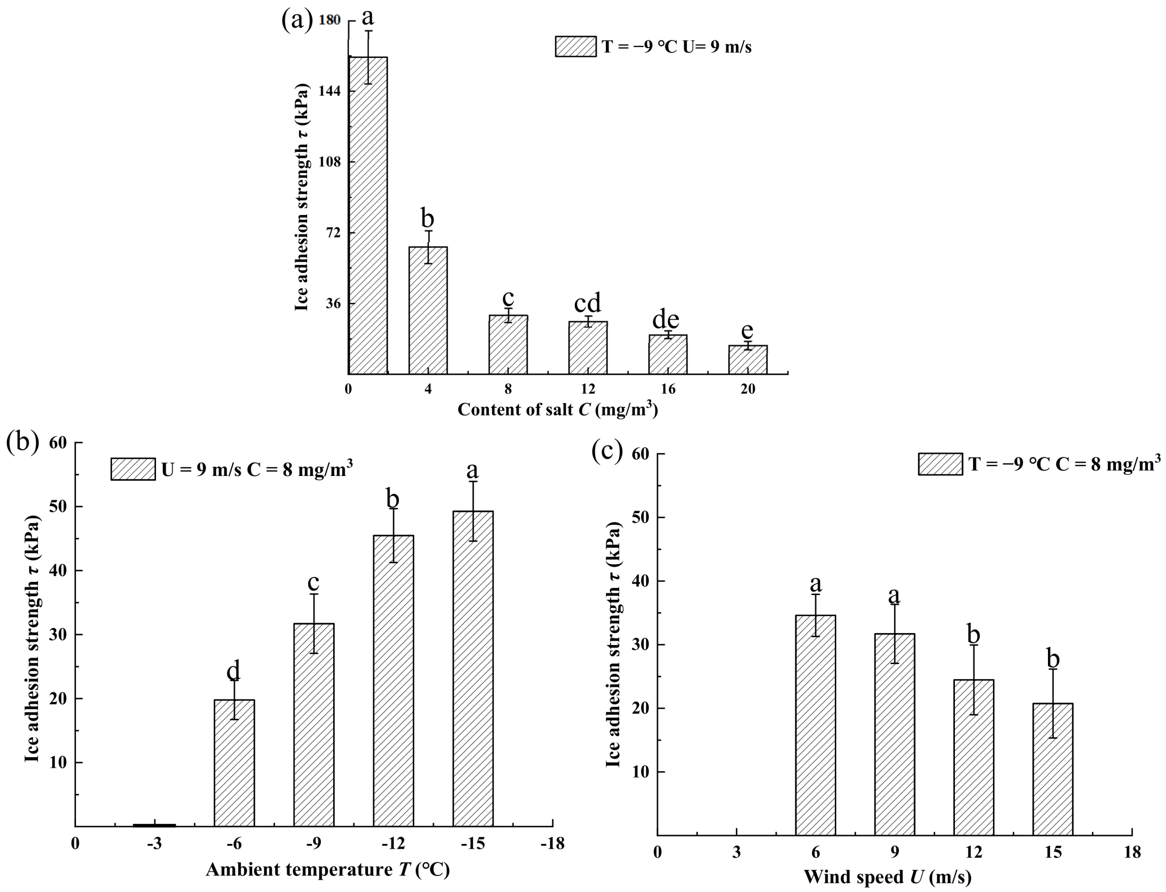

Figure 6. Effect of variables on ice adhesion strength: (**a**) salt content, (**b**) ambient temperature, (**c**) wind speed.

For the effect of ambient temperature, as shown in Figure 6b, the ice adhesion strength on the blade airfoil surface increases with the decrease in ambient temperature. The corresponding values are 0, 19.8 ± 3.1, 31.7 ± 4.6, 45.5 ± 4.2, 49.3 ± 4.7, respectively. According to the mechanical adhesion theory, the occurrence of adhesion is due to the interaction between the ice and the surface of the blade airfoil [26]. On the micro scale, peak–valley with different shapes are distributed on the surface of the blade airfoil. When the super-cool water droplet impacts the cold blade airfoil surface, it takes up the space of the peak–valley. The droplets rapidly cool down under the effect of convection heat transfer in the dynamic flow field. Upon cooling, the droplets and the blade airfoil contract together. However, the thermal expansion coefficient of ice is higher than that of aluminum, causing the shrinkage of ice volume is greater than that of the peak–valley under the same ambient temperature. Then the ice and the peak–valley squeeze and interlock each other. With the decrease in ambient temperature, the difference between the volume shrinkage of ice and peak–valley on the surface of the blade airfoil increases, which leads to an increase in the extrusion stress between them. Therefore, the ice adhesion strength on the blade surface increases with the decrease in ambient temperature.

In Figure 6c, the ice adhesion strength on the blade airfoil surface decreases with the increase in wind speed. The corresponding values are 34.6 ± 3.3, 31.7 ± 4.6, 24.5 ± 5.5 and 20.7 ± 5.4, respectively. A forced flow requires less time for the solid–liquid interface to reach a given solid volume [27]. The reason is that the forced convection heat transfer on the blade airfoil surface increases with the increase in wind speed. More heat is carried away by the airflow per unit of time. As a result, the temperature of the ice layer on the blade airfoil is relatively low, which is close to the surface of the airfoil. Therefore, the volume shrinkage of the ice and the peak–valley decreases, causing the extrusion stress between them decreases.

3.3. Interactive Effect of Variables on Ice Adhesion Strength

According to the above analysis, the salt content, wind speed and ambient temperature all have effects on the ice adhesion strength, and the interactive effect of different variables on the ice adhesion strength is still not clear. Hence, it is necessary to investigate the variation in adhesion strength under different variable combinations, but there are many combinations of the variables. It is time-consuming and labor-consuming to carry out all the tests. Fortunately, response surface methodology (RSM) can yield the required outcomes whilst minimizing the number of resources utilized. In addition, the interaction between the variables could be obtained, allowing for an in-depth understanding of the process and identification of the "key roles" [28]. Therefore, in the following part, a central composite design (CCD) of three variables with five levels is selected, employing the Design Expert software program (V10). The variable level combinations and responses of the experiments are shown in Table 5. According to the ANOVA results shown in Table 6, a second-order polynomial equation is highly conspicuous ($p < 0.01$) for the response. No significant lack of fit, and the high R^2 (0.9875) values show that most of the variability can be explained by the variables tested. After calculating the contribution ratio of factors affecting the ice adhesion strength, it is found that salt content is the most important factor, followed by ambient temperature, and wind speed is the least important. Their contribution ratios are 2.954, 2.306 and 2.212, respectively.

Table 5. Results of the experiment.

	Wind Speed *U* x_1/(m/s)	**Ambient Temperature *T*** x_2/(°C)	**Salt Content *C*** x_3/(mg/m^3)	**Ice Adhesion Strength** τ/kPa
1	4	−9	10.5	41
2	9	−9	10.5	37
3	9	−9	1.25	107.1
4	12	−6	5	33
5	6	−6	16	8.1
6	9	−9	10.5	29.1
7	12	−6	16	14.9
8	9	−9	10.5	36.3
9	9	−9	10.5	32.6
10	9	−4	10.5	11.6
11	6	−12	16	16
12	6	−12	5	87.5
13	12	−12	5	71.6
14	9	−14	10.5	45.1
15	9	−9	10.5	35.1
16	14	−9	10.5	17.5
17	12	−12	16	17.8
18	9	−9	19.75	15.5
19	9	−9	10.5	34.2
20	6	−6	5	56.4
21	9	−9	10.5	29.6
22	9	−9	10.5	31.6
23	9	−9	10.5	34.6

Table 6. Analysis of the regression coefficients to the polynomial equation for ice adhesion strength.

Origin of Variance	Sum of Squares	*Df*	Mean Squares	*F* Value	*p* Value
x_1	361.07	1	361.07	28.98	<0.0001 **
x_2	1371.12	1	1371.12	110.06	<0.0001 **
x_3	8753.45	1	8753.45	702.63	<0.0001 **
x_1x_2	0.78	1	0.78	0.063	0.8062
x_1x_3	286.80	1	286.80	23.02	0.0003 **
x_2x_3	433.28	1	433.65	34.81	<0.0001 **
${x_1}^2$	53.31	1	53.31	4.28	0.0591
${x_2}^2$	73.44	1	73.44	5.90	0.0304 *
${x_3}^2$	1433.92	1	1433.92	115.10	<0.0001 **
Model	12775.10	9	1419.46	113.94	<0.0001 **
Residual	161.96	13	12.46		
Lack of fit	98.83	5	19.77	2.51	0.1193
Pure error	63.12	8	7.89		
All terms	12937.05	22			

** Extremely significant at $p < 0.01$; * Significant at $p < 0.05$.

The results in Table 6 indicate that, in this case, linear terms of wind speed, ambient temperature and salt content are extremely significantly different ($p < 0.01$). The interaction terms of wind speed and salt content, ambient temperature and salt content are extremely significantly different ($p < 0.01$). The quadratic terms of ambient temperature are significantly different at ($p < 0.05$), and the quadratic terms of salt content are extremely significantly different at ($p < 0.01$). The predicted model for the ice adhesion strength can be described by the following equation in terms of actual factors under the tested conditions. The polynomial equation generated after removing insignificant terms of the models is as follows:

$$\tau = 73.54 - 5.52x_1 - 12.30x_2 - 10.46x_3 + 0.36x_1x_3 + 0.45x_2x_3 - 0.24x_2^2 + 0.31x_3^2 \quad (3)$$

Figure 7a shows the interactive effect of ambient temperature and salt content. When the salt content is at a high level, the effect of ambient temperature on ice adhesion strength is not obvious compared with that of a low level. This is because when the salt content is at a low level, the effective solid–solid contact area at the ice–airfoil interface does not change obviously with a variation in ambient temperature. At this time, the ice adhesion strength is mainly affected by ambient temperature, but with further increase in salt content, upon icing, more brine is expelled out, causing the effect contact area of the ice and airfoil changing smaller. At this time, the adhesion strength of ice is low and almost not affected by ambient temperature.

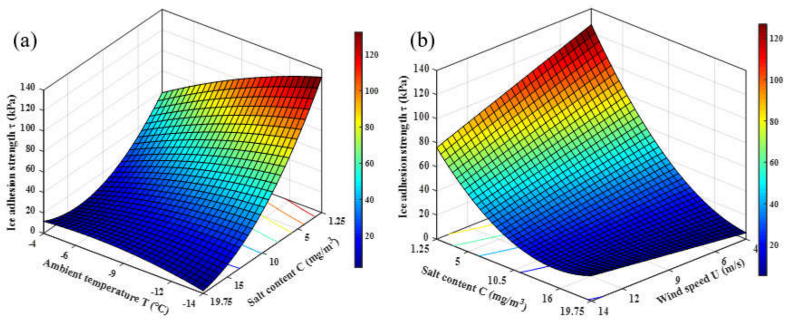

Figure 7. Effect of interactive effect of variables on ice adhesion strength: (**a**) effect of ambient temperature and salt content on ice adhesion strength; (**b**) effect of wind speed and salt content on ice adhesion strength.

When the ambient temperature is at a high level, the ice adhesion strength decreases with the increase in salt content. While the ambient temperature is at a low level, the effect of salt content on ice adhesion strength is enhanced. This is because when the ambient temperature is higher, more brine is expelled out with the increase in salt content, causing a decrease in ice adhesion strength. However, when the ambient temperature is lower, the forced convection heat transfer on the surface of the blade airfoil is larger, causing the droplet icing quickly.

The interactive effect of wind speed and salt content can be seen in Figure 7b. It shows that when the salt content is at a high level, the effect of wind speed on the ice adhesion strength is not obvious, but when the salt content is at a low level, the effect of wind speed on ice adhesion strength is enhanced. This is because when the salt content is small, the effective solid–solid contact area of the ice–airfoil interface does not change obviously with the change in wind speed. The ice adhesion strength is mainly affected by wind speed. When the ice content is at a high level, more brine is expelled out, causing the effect contact area of the ice and airfoil changing smaller. At this time, the adhesion strength of ice is low and almost not affected by wind speed.

When the wind speed is at a high level, the decrease in salt content leads to an increase in adhesion strength. When the wind speed is at a low level, the effect of salt content on the adhesion strength is enhanced. This is because when the wind speed is low, the forced convection heat transfer on the airfoil surface of the blade is lower. The salt expelled is less than that with high salt content, so the adhesion strength is higher. When the wind speed is high, the forced convection heat transfer on the blade airfoil surface increases, and the heat taken away by the wind per unit of time increases. At this time, the salt expelled out is less than that with high salt content but more than that with low salt content and low wind speed.

Finally, to provide data reference for the anti-icing technology of offshore wind turbines, the maximum ice adhesion strength within the test conditions is determined, as shown in Table 7, by running the solutions menu of the numerical optimization program built into the Design Expert software. The maximum ice adhesion strength is 150 kPa when the wind speed is 4 m/s, the ambient temperature is −14 °C, and the salt content is 1.4 mg/m^3. Validation experiments were performed under the given test condition. The measured value of ice adhesion strength is 148 ± 7.8 kPa, which is found to be close to the predicted values within the acceptable limits of error percentage (3.7–7%). It demonstrates that the regression equations could predict the ice adhesion strength from the response surface.

Table 7. Predicted and measured icing adhesion strength under maximum icing conditions.

Maximum Icing Condition	Predicted Value	Measured Value
Wind speed U = 4 m/s	150 kPa	148 ± 7.8 kPa
Salt content C = 1.4 mg/m^3		
Ambient temperature T = −14 °C		

4. Conclusions

In this study, the effect and interactive effect of different offshore atmospheric conditions, including wind speeds, ambient temperatures and the salt contents on ice adhesion strength of a NACA0018 airfoil for a wind turbine, is researched by icing wind tunnel test. The main results are summarized and listed as follows:

(1) Under the test conditions in this study, the icing occurs on the surface of the test blade. Compared with the wind speed, salt content and ambient temperature have significant effects on the icing type. With the increase in salt content, the type of ice changed from mixed ice to glaze ice. While with the decrease in temperature, the type of ice changed from glaze ice to mixed ice and then rime ice.

(2) Salt content is the most important factor that affects the ice adhesion strength, followed by ambient temperature and wind speed. Salt content directly affected the amount of brine expelled out, resulting in the variation in the effective solid–solid contact

area at the ice–airfoil interface, thus affecting the adhesion strength. The regression characteristics of the three factors on the ice adhesion strength are obtained.

(3) The maximum ice adhesion strength is about 150 kPa according to the results of test and regression analysis when there is a certain salt concentration in the offshore wind, which can provide an experimental reference for the research and the development of icing protection technology for offshore wind turbines. Except for the adhesion characteristic, the effect of ice accretion on the aerodynamic performance of wind turbines under offshore conditions is deserved to be considered in the future.

Author Contributions: Conceptualization, Z.M. and Y.L.; Formal analysis, Z.M. and W.G.; Funding acquisition, Y.L.; Investigation, Z.M.; Methodology, Z.M., W.G. and H.S.; Software, Z.M.; Supervision, Y.L.; Validation, K.T.; Visualization, K.T.; Writing—original draft, Z.M.; Writing—review and editing, Z.M., Y.L. and K.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (NSFC) [grant number 51976029].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

C	Salt content (mg/m^3)
c	Blade airfoil chord (mm)
F	External shear force acting upon the unit model (N)
h	Thickness of the blade airfoil (mm)
L	Arc length of the adhesion ice removed from the airfoil (mm)
LWC	Liquid water content (g/m^3)
MVD	Medium volume diameter (μm)
S	De-icing area of ice on the blade (m^2)
T	Ambient temperature (°C)
t	Ice adhesion strength (kPa)
U	Wind speed (m/s)

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