

Article

Ice Distribution Characteristics on the DU25 and NACA63-215 Airfoil Surfaces of Wind Turbines as Affected by Ambient Temperature and Angle of Attack

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Abstract: Icing on wind turbines reduces power generation efficiency and leads to safety issues. Consequently, in this paper, ice distribution characteristics on DU25 and NACA63-215 airfoils at ambient temperatures and angles of attack are explored VIA numerical simulation. The findings indicate that when the ambient temperature changes in the range of 248–268 K, the ice distribution range on the upper surface of the DU25 airfoil (0–3.07 mm) is wider than that of the NACA63-215 airfoil (0–1.91 mm), while the ice distribution range on the lower surface of the DU25 airfoil (0–12.13 mm) is narrower than that of the NACA63-215 airfoil (0–15.18 mm) due to the discrepancy in droplet collection efficiency and droplet freezing rate caused by airfoil structure and ambient temperature, respectively. At an angle of attack of 0°, the ice distribution range on the upper surface of the DU25 airfoil is almost the same as that of the NACA63-215 airfoil. At an angle of attack of 8°, the ice distribution range on the upper surface of the DU25 airfoil (0–1.05 mm) is broader than that of the NACA63-215 airfoil (0–0.675 mm), whereas the ice distribution range on the lower surface of the DU25 airfoil (0–17 mm) is narrower than that of the NACA63-215 airfoil (0–20 mm) due to the discrepancy in droplet collection efficiency caused by droplet flow trajectory. The angle of attack has a much greater effect on the peak ice thickness than ambient temperature. This study will provide guidance for the anti-icing coating design of wind turbine blades.

Keywords: wind turbine; ice distribution characteristics; DU25 airfoil surface; NACA63-215 airfoil surface; icing conditions



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1. Introduction

Wind energy is the most promising renewable energy, mainly used in the field of wind power generation [1]. However, due to the frequent occurrence of extreme weather, ice formation occurs on the surface of wind turbine blades, which causes serious problems, including a decrease in power generation efficiency and a reduction in structural strength and lifetime [2–4]. Even worse, owing to centrifugal force, ice blocks on the surface of the blades may be shed, posing a threat to the safety of people in the surrounding area [5]. Therefore, exploring the ice distribution characteristics on blade surfaces is crucial for the anti-icing coating design of wind turbine blades.

The common methods for investigating the icing characteristics of wind turbine blades consist of icing wind tunnel experiments and numerical calculations. Experimentally, Li et al. [6] explored ice distribution characteristics on vertical-axis wind turbine blades under rotating conditions and found that non-uniform ice accumulation covered the entire blade, leading to variation in the blade airfoil. Shu et al. [7] reported that ice thickness increased sharply from the root to the middle of the wind turbine blade and then slowed down from the middle to the tip of the wind turbine blade. Gao et al. [8,9] examined the aerodynamic performance of iced blade airfoil under ice conditions and found a functional

relationship between aerodynamic performance and angle of attack. Jin et al. [10–12] compared the ice distribution characteristics on different airfoil surfaces and analyzed the aerodynamic performance of different iced blade airfoils for a wind turbine. It was found that the aerodynamic performance of the iced S832 airfoil exhibited a more significant decrease than that of the iced S826 airfoil. Hu et al. [13] proposed a novel method for detecting ice thickness on the surface of wind turbine blades and reported a measurement error of 2.62%–6.0%. Sundaresan et al. [14] analyzed the effects of angle of attack and Reynolds number on the aerodynamic performance of wind turbine blades, and it was found that the lift coefficient showed less variation for iced airfoil at the stall angle of attack under rime ice conditions. Han et al. [15] investigated the effect of ice accumulation on the mechanical properties of wind turbine blades; it was found that there was a positive correlation between stress–strain and rotational speed.

To summarize, owing to experimental size limitations, scaled-down models of most wind turbine blades were employed in the experiments. To make the research more meaningful, it is necessary to establish similarity between scaled models and full-scale models. However, due to the unclear icing physical mechanism on wind turbine blades during the experimental process, it is difficult to establish a similarity between scaled models and full-scale models.

Owing to the fact that numerical calculations can reveal the icing physical mechanism of wind turbine blades, many scholars use numerical calculation methods to investigate ice distribution characteristics on the blade surfaces of wind turbines. Ibrahim et al. [16] employed numerical simulation to investigate the influence of blade design on icing characteristics under ice conditions. Wang et al. [17] proposed a numerical calculation method to examine the water film distribution and ice shapes on a NACA0012 airfoil under environmental conditions; it was found that liquid water content had a significant effect on horn ice shapes. Sheidani et al. [18] presented a numerical calculation approach to reveal the mechanism of the effect of ice accretion on the wake characteristics of NACA0021 airfoils; it was found that ice accretion led to power coefficient reduction due to wake vortex separation. Lu et al. [19] employed a numerical method to examine the influence of the angle of attack on the ice shapes of a NACA0012 airfoil, it was found that the mass of ice accretion was large at low angles of attack (4° and 8°). Xu et al. [20,21] developed an icing model to reveal the mechanism of the effect of icing parameters on the icing characteristics of NACA0012 airfoils; it was found that ice shapes were influenced by droplet collection efficiency and freezing rate under different icing conditions. Wang et al. [22] employed a numerical method to analyze the effect of the angle of attack on the ice distribution characteristics of a DU97 airfoil; it was found that the peak ice thickness at the trailing edge increased with the increase in the angle of attack.

From the literature review on numerical simulation, it is clear that most researchers focus on the physical mechanism of the ice distribution characteristics of symmetrical airfoils. However, there are some limitations in the above studies, which include:

- (1) There are few studies on the physical mechanism of the ice distribution characteristics of asymmetric airfoil surfaces;
- (2) The effect of ambient temperature and angles of attack on the ice distribution mechanism of the DU25 and NACA63-215 airfoil surfaces has not been reported.

Therefore, the main objectives of this study are as follows: (1) the numerical calculation method is employed to reveal the physical mechanism of the ice distribution characteristics of asymmetric airfoil surfaces, including DU25 and NACA63-215 airfoils, and (2) the effects of ambient temperatures and angles of attack on the icing distribution mechanism are explored.

2. Model

2.1. Mathematical Model

2.1.1. Airflow and Temperature Fields Model outside the Wind Turbine Blade

The prerequisite for exploring icing distribution characteristics on the wind turbine blade surface is to obtain airflow and temperature fields outside the wind turbine blade, which can be calculated according to mass, momentum, and energy conservation equations, which are written as follows [20,23]:

The mass equation is written as

$$\frac{\partial \rho_1}{\partial t} + \nabla \cdot (\rho_1 \vec{V}_1) = 0 \quad (1)$$

The momentum equation is written as

$$\frac{\partial (\rho_1 \vec{V}_1)}{\partial t} + \nabla \cdot (\rho_1 \vec{V}_1 \vec{V}_1) = \sigma^{ij} + \rho_1 \vec{g} \quad (2)$$

$$\sigma^{ij} = -\sigma^{ij} p_1 + \tau^{ij} \quad (3)$$

The energy equation is written as

$$\frac{\partial (\rho_1 E_1)}{\partial t} + \nabla \cdot (\rho_1 \vec{V}_1 H_1) = \nabla \cdot [k_1 (\nabla T_1) + V_i \tau^{ij}] + \rho_1 \vec{V}_1 \vec{g} \quad (4)$$

2.1.2. Droplet Flow Model

After determining the multi-physical fields outside the wind turbine blade, the next step is to calculate the flow characteristics of water droplets outside the wind turbine blade. Therefore, a droplet flow model was established according to Euler's formula to address the droplet distribution on the wind turbine blade considering the droplet volume fraction, which is represented as follows [24]:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{V}_2) = 0 \quad (5)$$

$$\frac{\partial (\alpha \vec{V}_2)}{\partial t} + \nabla \cdot (\alpha \vec{V}_2 \vec{V}_2) = \frac{C_D \text{Re}_2}{24K} \alpha (\vec{V}_1 - \vec{V}_2) + \alpha \left(1 - \frac{\rho_1}{\rho_2} \right) \frac{1}{\text{Fr}^2} \quad (6)$$

The dimensionless number in Equation (6) includes the Reynolds number, inertia parameter, and Froude number, which are expressed as follows:

$$\text{Re}_2 = \frac{\rho_1 d V_{1,\infty} \|\vec{V}_1 - \vec{V}_2\|}{\mu_1}, K = \frac{\rho_2 d^2 V_{1,\infty}}{18 L_\infty \mu_1}, \text{Fr} = \frac{\|V_{1,\infty}\|}{\sqrt{L_\infty g_\infty}} \quad (7)$$

The drag coefficient of water droplets in Equation (6) is based on an empirical correlation for flow around spherical droplets [25], which is given by

$$C_D = \left(\frac{24}{\text{Re}_2} \right) \left(1 + 0.15 \text{Re}_2^{0.687} \right), \text{Re}_2 \leq 1300 \quad (8)$$

$$C_D = 0.4, \text{Re}_2 \geq 1300 \quad (9)$$

2.1.3. Water Film and Ice Accretion Model

After determining the droplet flow characteristics outside the wind turbine blade, the next step is to calculate heat and mass transfer for water film and ice accretion. The water film velocity considering surface roughness is calculated by [26–29]

$$\vec{V}_f = \frac{y}{\mu_f} \vec{\tau}_{1,\text{wall}} \quad (10)$$

$$\tau_{1,\text{wall}} = \frac{1}{2} C_f \rho_1 V_\infty^2 \quad (11)$$

$$C_f = [3.476 - 0.707 \ln(k_s/s)]^{-2.46} \quad (12)$$

The mass equation includes mass transfer due to droplet impact, water evaporation, and ice accretion, which is written as [20]

$$\rho_f \left[\frac{\partial h_f}{\partial t} + \nabla \cdot (\vec{V}_f h_f) \right] = V_\infty \beta LWC - \dot{m}_{\text{evap}} - \dot{m}_{\text{ice}} \quad (13)$$

The energy equation includes heat transfer, phase change, ice accretion, convective heat flow, and radiant heat flow caused by water droplet impact, which is calculated by [20]

$$\begin{aligned} \rho_f \left[\frac{\partial h_f c_f \tilde{T}}{\partial t} + \nabla \cdot (\vec{V}_f h_f c_f \tilde{T}) \right] &= \left(c_f \tilde{T}_{2,\infty} + \frac{1}{2} \vec{V}_2^2 \right) V_\infty \beta LWC \\ &- 0.5 \dot{m}_{\text{evap}} (L_{\text{evap}} - L_{\text{sub1}}) + \dot{m}_{\text{ice}} (L_{\text{fus}} - c_{\text{ice}} \tilde{T}) + \sigma \varepsilon (T_\infty^4 - T_f^4) + \dot{Q}_h \end{aligned} \quad (14)$$

2.2. Computational Domain and Mesh

The computational domain of DU25 and NACA63-215 blade airfoils commonly used for wind turbine blades are shown in Figure 1. The chord length (C) and span length of the DU25 and NACA63-215 airfoils are 0.1 m and 0.02 m, respectively. The computational domain is meshed by structured elements, and the normal distance of the first layer grid is 0.01 mm, as shown in Figure 2. The y^+ of the grid is controlled to be around or below 1. The total number of grids in the flow field is 90945, which ensures high computational accuracy and improves computational efficiency.

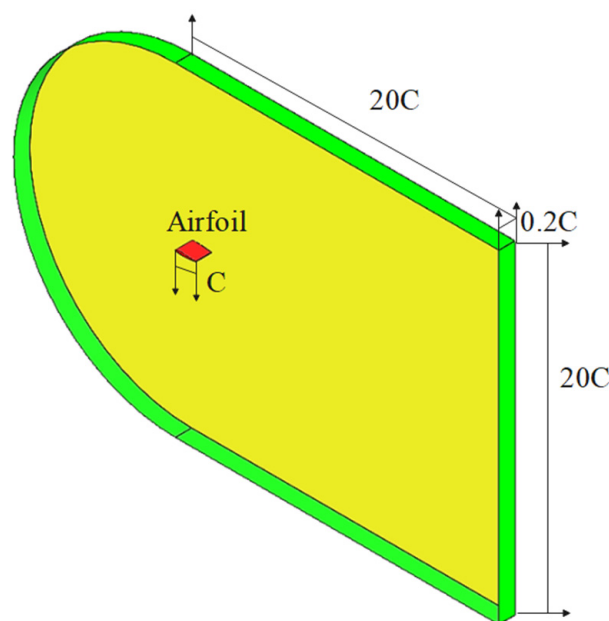


Figure 1. The computational domain.

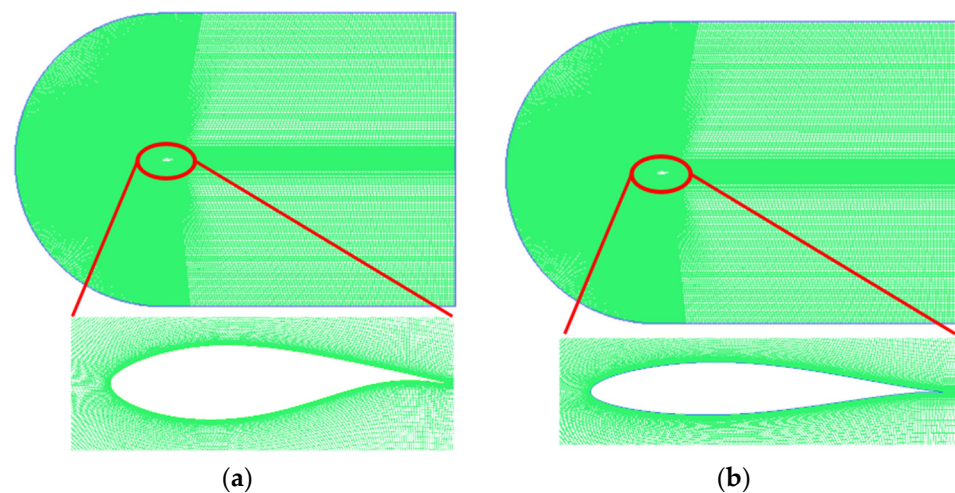


Figure 2. The computational mesh of the DU25 (a) and NACA63-215 (b) blade airfoils.

2.3. Boundary Conditions and Solution Method

The far-field boundary conditions and wall boundary conditions were employed on the external flow field and solid surface of a wind turbine blade airfoil for numerical simulations, respectively. The icing conditions of the wind turbine are reported in ref. [30], including the ambient temperature of 233–323 K, the wind speed of 3–25 m/s, the LWC of 0–5 g/m³, and the MVD of 10–5000 μ m. In this study, the icing conditions are given as follows: ambient temperature of 248–268 K, wind speed of 10 m/s, LWC of 1 g/m³, MVD of 20 μ m, angle of attack (0°, 4° and 8°), and icing time of 30 min. The specific parameters are presented in Table 1. The detailed solution method is reported in ref. [20].

Table 1. Boundary conditions.

Types	Values
Far-field	Pressure: 101,325 Pa
	Temperature: 248–268 K
	LWC: 1 g/m ³
	MVD: 20 μ m
	Speed: 10 m/s
Wall	No slip

2.4. Model Validation

The numerical simulation results were compared with experimental data in the NASA Icing Research Tunnel [31], and the icing conditions are given as follows: ambient temperature of 267 K, air speed of 102 m/s, LWC of 0.55 g/m³, MVD of 20 μ m, icing time of 420 s, and angle of attack of 4°. It can be observed from Figure 3 that the simulated ice distribution is in good agreement with the experimental data. The error of the vast majority of points was within 2%. As shown in Figure 3, most of the droplet diameters are very close to the median volume diameters, which leads to the ice thickness distribution caused by water film solidification in the experiment being close to that in the numerical simulation. Notably, it was found that the ice horns can appear on the leading edge of the blade airfoil. In the experiment, the droplet size was different. On the other hand, in the numerical simulation, the different droplet sizes are equivalent to the medium volume diameter of the droplets. The experimental results indicate that different droplet sizes can affect the water film distribution on the airfoil surface, freezing into the thickest ice accretion at the location where the droplet size is largest under icing conditions due to the variation in heat and mass transfer. The distribution characteristics of ice accretion on the airfoil surface caused by water film solidification are described using the medium volume diameter of droplets

in the numerical simulation. Therefore, this explains why the maximum error occurs at the horn ice.

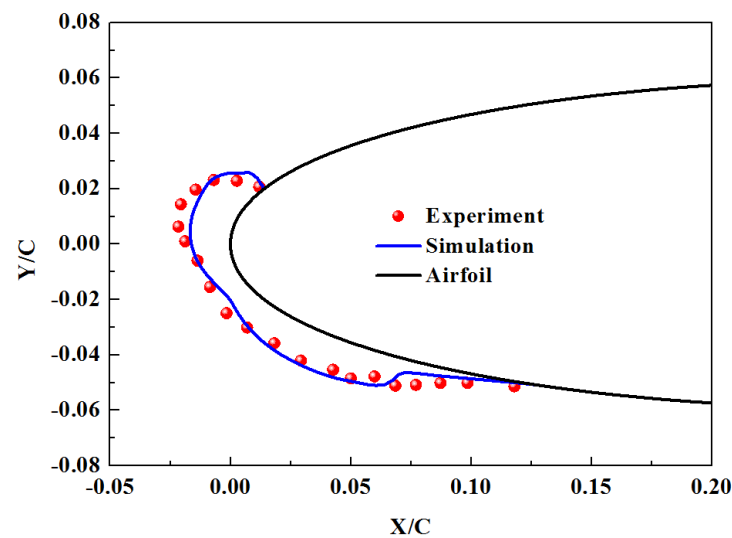


Figure 3. Comparison between the simulated values and the experimental values [21].

3. Results and Discussion

In this section, we describe icing simulations performed to analyze the ice distribution characteristics on DU25 and NACA63-215 airfoil surfaces at various ambient temperatures and angles of attack.

3.1. Effect of Ambient Temperature

Figures 4–6 depict the ice thickness distribution on DU25 and NACA63-215 airfoil surfaces at different ambient temperatures (248–268 K) for an angle of attack of 4° . For the upper surface, when the ambient temperature increases from 248 K to 268 K, the peak ice thickness on the leading edge of the DU25 and NACA63-215 airfoils decreases from 5.32 mm to 5.21 mm (2.1% reduction) and from 5.39 mm to 5.22 mm (3.2% reduction), respectively. For the lower surface, as the ambient temperature rises from 248 K to 268 K, the peak ice thickness on the leading edge of the DU25 and NACA63-215 airfoils drops from 6.21 mm to 5.91 mm (4.8% reduction) and from 6.52 mm to 6.12 mm (6.1% reduction), respectively. The peak ice thickness on the upper surface of the DU25 airfoil is almost the same as that of the NACA63-215 airfoil, while the peak ice thickness on the lower surface of the DU25 airfoil is smaller than that of the NACA63-215 airfoil. On the lower surface, it is noteworthy that the peak ice thickness on the trailing edge of the NACA63-215 airfoil (0.092 mm) is greater than that of the DU25 airfoil (0.077 mm). On the other hand, for the leading edge of the airfoils, the ice distribution range on the upper surface of the DU25 airfoil (0–3.07 mm) is wider than that of the NACA63-215 airfoil (0–1.91 mm), while the ice distribution range on the lower surface of the DU25 airfoil (0–12.13 mm) is narrower than that of the NACA63-215 airfoil (0–15.18 mm). Owing to the discrepancy in the geometric structure of the DU25 and NACA63-215 airfoils, the droplet flow trajectory outside various airfoils can exhibit significant differences, leading to a discrepancy in droplet collection efficiency distribution on DU25 and NACA63-215 airfoil surfaces. The ice accretion distribution on different airfoil surfaces caused by droplet freezing exhibits significant differences under icing conditions. For the trailing edge of airfoils, the ice distribution range of the DU25 airfoil (80.55–99.36 mm) is broader than that of the NACA63-215 airfoil (85.03–99.36 mm). This is ascribed to the fact that different airfoils can result in variation in droplet collection efficiency, freezing into non-uniform ice accretion under icing conditions.

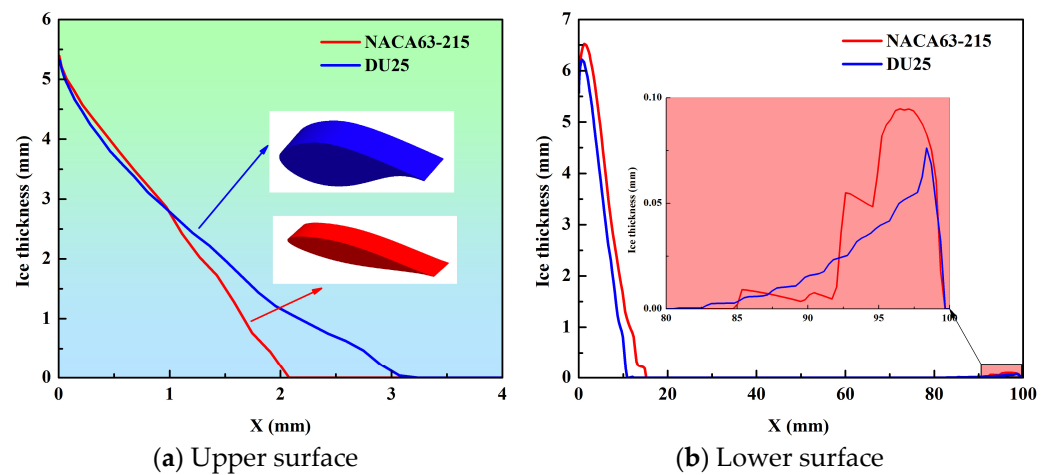


Figure 4. Ice distribution on airfoil surfaces at an ambient temperature of 248 K.

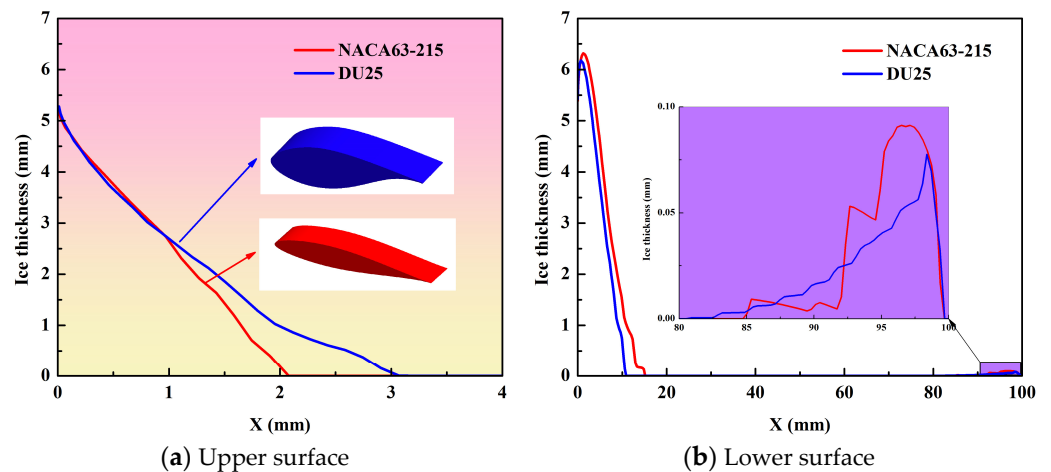


Figure 5. Ice distribution on airfoil surfaces at an ambient temperature of 258 K.

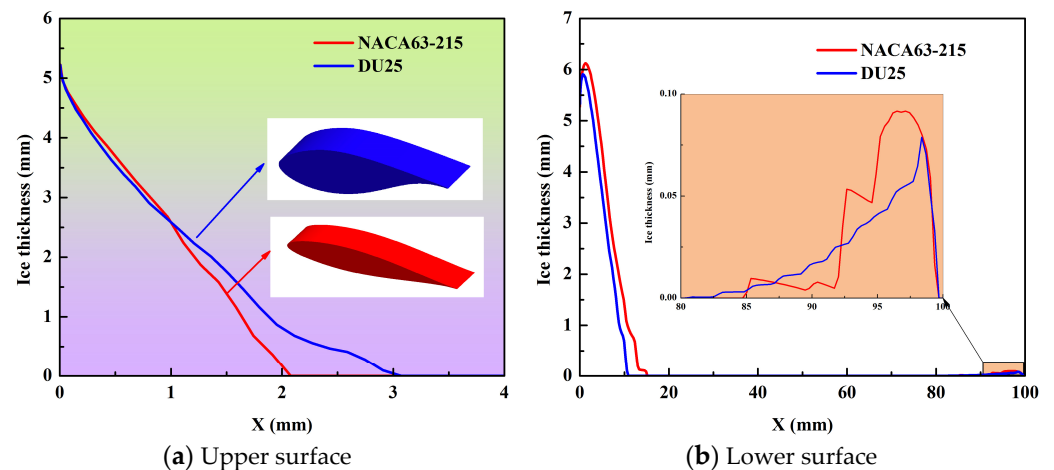


Figure 6. Ice distribution on airfoil surfaces at an ambient temperature of 268 K.

3.2. Effect of Angle of Attack

The icing characteristics on the airfoil surface ARE not only affected by the ambient temperature but also by the angle of attack. The premise of exploring icing characteristics is to understand the droplet collection efficiency on various airfoil surfaces at different angles of attack. The droplet collection efficiency on DU25 and NACA63-215 airfoil surfaces at

different angles of attack (0 – 8°) is displayed in Figure 7. It is obvious that the peak droplet collection efficiency on the surface of the NACA63-215 airfoil (0.72) is higher than that of the DU25 airfoil (0.59). Owing to the discrepancy in the geometric shapes of airfoils, droplet flow trajectories outside various airfoils can exhibit significant differences, which leads to a discrepancy in droplet collection distribution on airfoil surfaces. At an angle of attack of 0° , the peak droplet collection efficiency appears at the stagnation point. With an increase in the angle of attack, the peak droplet collection efficiency moves toward the lower surface of airfoils. Significantly, the peak droplet collection efficiency on the DU25 airfoil exhibits a larger offset than that of the NACA63-215 airfoil. This is significantly different from symmetric airfoils [20]. On the other hand, the distribution range of droplet collection efficiency on the DU25 airfoil surface is wider than that of the NACA63-215 airfoil. Owing to the fact that the impact area of incoming droplets on the DU25 airfoil surface is wider than that on the NACA63-215 airfoil, the distribution range of droplet collection efficiency on the DU25 airfoil surface is wider than that of the NACA63-215 airfoil. In fact, a wide distribution range of droplet collection efficiency on DU-series airfoils was reported by Wang et al. [22], and a narrow distribution range of droplet collection efficiency on NACA63-series airfoils was reported by Guet et al. [32]. In addition, with increasing angle of attack, there is droplet impingement on the trailing edge of airfoils. This is due to the fact that the discrepancy in airfoils can lead to a change in droplet flow characteristics.

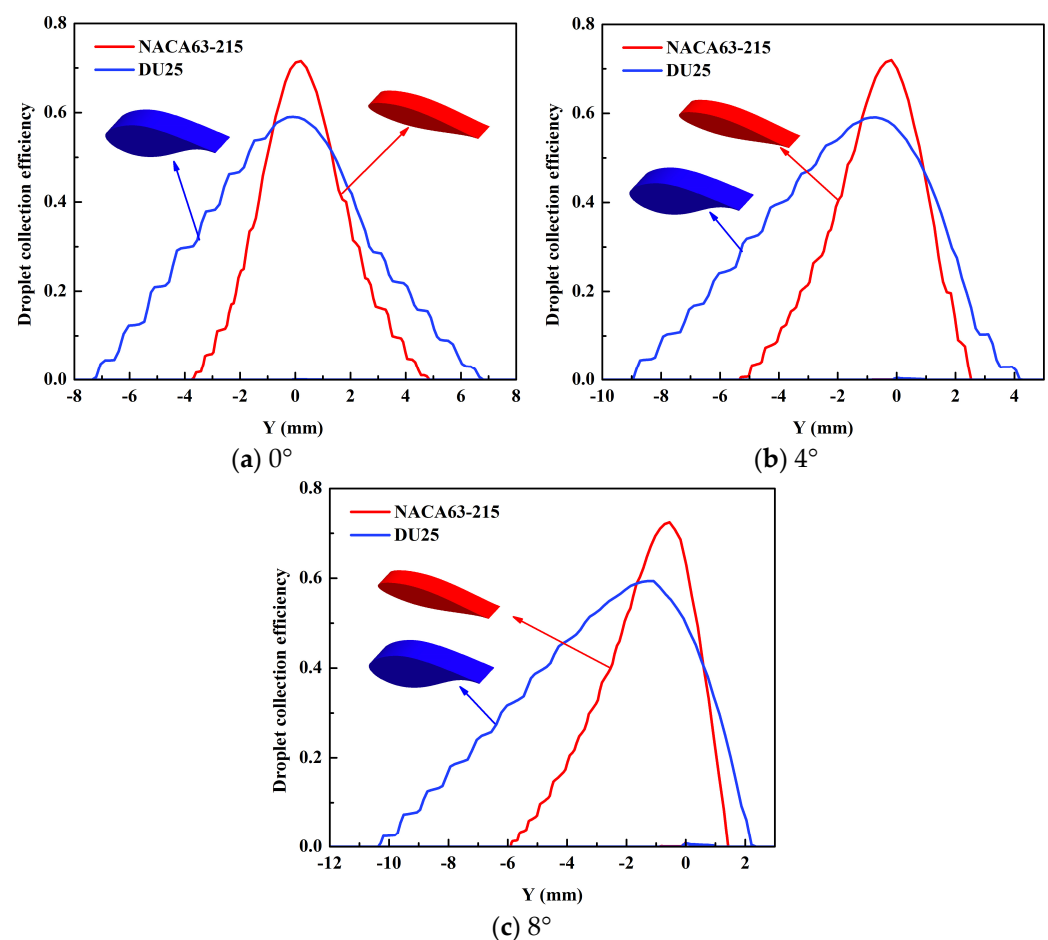


Figure 7. Droplet collection efficiency on airfoil surfaces at different angles of attack.

After understanding the droplet collection efficiency on various airfoil surfaces, the next step is to explore the influence of the angle of attack on ice distribution characteristics. Figures 8 and 9 depict the ice thickness distribution on DU25 and NACA63-215 airfoil

surfaces at different angles of attack (0° – 8°) for an ambient temperature of 258 K. For the upper surface, when the angle of attack increases from 0° to 8° , the peak ice thickness on the leading edge of the DU25 and NACA63-215 airfoils decreases from 5.64 to 4.78 mm and from 5.91 to 4.01 mm, respectively. It is clear that the peak ice thickness on the NACA63-215 airfoil (32.1% reduction) decreases more dramatically than that of the DU25 airfoil (15.2% reduction). At an angle of attack of 0° , the peak ice thickness on the NACA63-215 airfoil is larger than that of the DU25 airfoil. However, at an angle of attack of 8° , the peak ice thickness on the NACA63-215 airfoil is smaller than that of the DU25 airfoil. For the lower surface, as the angle of attack increases from 0° to 8° , the peak ice thickness on the leading edge of the DU25 and NACA63-215 airfoils varies in the range of 5.75 to 6.53 mm (13.6% increase) and 5.82 to 6.68 mm (14.8% increase), respectively. The peak ice thickness on the lower surface of the DU25 airfoil is smaller than that of the NACA63-215 airfoil. It is evident that the peak ice thickness on the lower surface of airfoils increases, which is in contrast with that on the upper surface. It is noteworthy that the peak ice thickness on the trailing edge of the NACA63-215 airfoil (0.18 mm) is greater than that of the DU25 airfoil (0.14 mm).

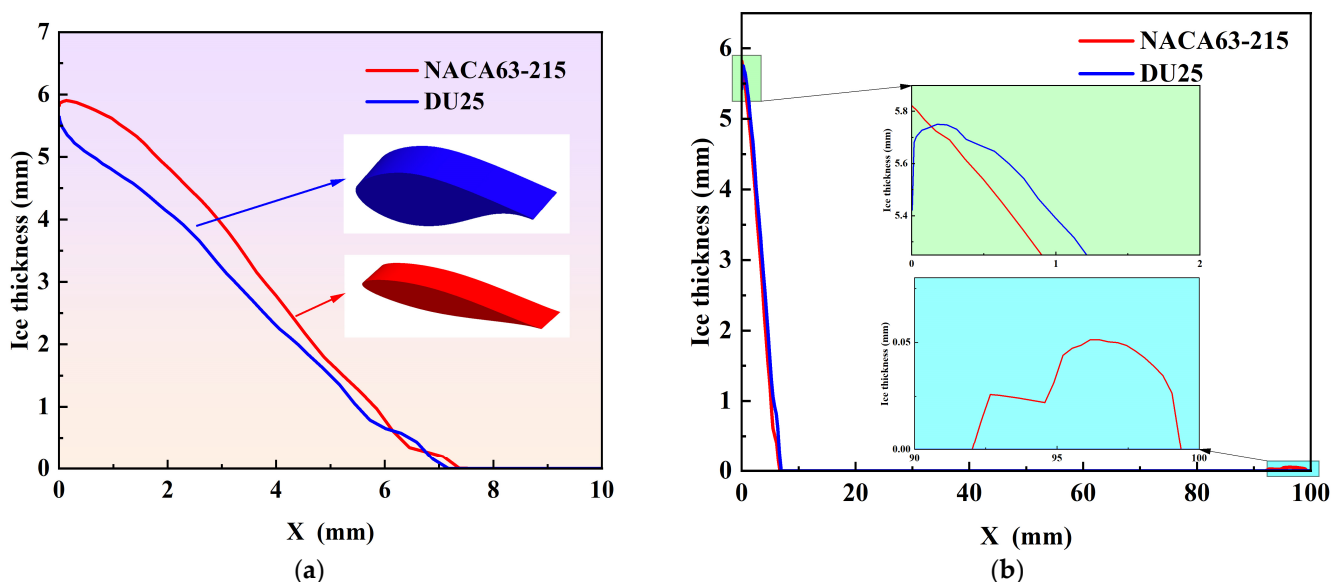


Figure 8. Ice distribution on the airfoil upper surface (a) and lower surface (b) at an angle of attack of 0° .

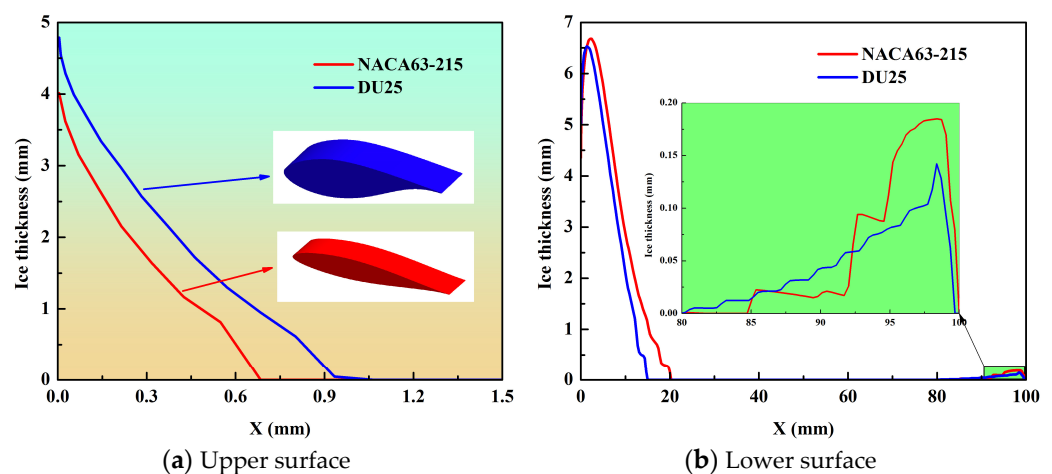


Figure 9. Ice distribution on the airfoil surfaces at an angle of attack of 8° .

On the other hand, for the leading edge of airfoils, the ice distribution range on the upper surface of the DU25 airfoil is almost the same as that of the NACA63-215 airfoil

at an angle of attack of 0° . At an angle of attack of 8° , the ice distribution range on the upper surface of the DU25 airfoil is broader than that of the NACA63-215 airfoil, whereas the ice distribution range on the lower surface of the DU25 airfoil is narrower than that of the NACA63-215 airfoil. This is due to the fact that different airfoils and angles of attack can cause non-uniform droplet collection efficiency, freezing into various ice shapes under icing conditions.

3.3. Coupling Effect of Ambient Temperature and Angle of Attack

After analyzing the influence of a single factor on icing characteristics, the influence of coupled factors on the peak ice thickness on the surfaces of the DU25 and NACA63-215 airfoils was further explored, including ambient temperature and angle of attack.

Figure 10a illustrates the peak ice thickness on the surfaces of the DU25 airfoil under various icing conditions. It was observed that the peak ice thickness changes more significantly at ambient temperatures of 258–268 K than at ambient temperatures of 248–258 K. This is due to the discrepancy in the droplet freezing rate caused by ambient temperature. In addition, the angle of attack has a much greater effect on the peak ice thickness than ambient temperature. This is ascribed to the fact that the influence of the droplet collection rate caused by angles of attack is greater than that of the droplet freezing rate caused by ambient temperature.

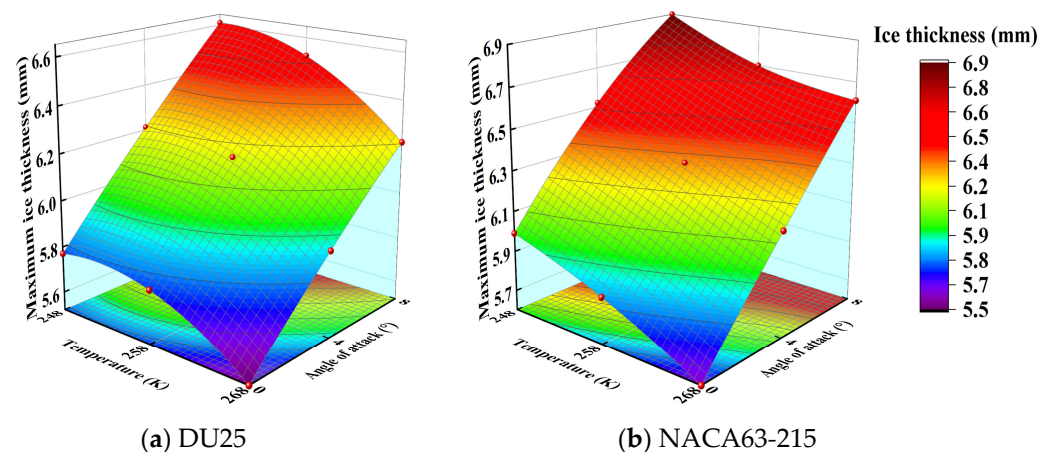


Figure 10. The maximum ice thickness on airfoil surfaces.

Figure 10b illustrates the peak ice thickness on the surfaces of the NACA63-215 airfoil under various icing conditions. It is obvious that the peak ice thickness changes more significantly at ambient temperatures of 258–268 K than at ambient temperatures of 248–258 K at an angle of attack of 0° . At ambient temperatures of 258–268 K, due to the fact that the freezing rate of droplets is not 100%, different ambient temperatures can affect the droplet freezing rate, and unfrozen water film formed on the surface of the airfoil interacts with ice accretion, leading to significant variation in ice thickness. However, at ambient temperatures of 248–258 K, owing to the fact that the freezing rate of droplets is almost 100%, ice thickness is not significantly affected by ambient temperatures. This phenomenon is similar to the reference [20]. However, with an increase in the angle of attack, the peak ice thickness changes more significantly at ambient temperatures of 248–258 K than at ambient temperatures of 258–268 K at an angle of attack of 8° . This is because the effect of the droplet collection rate caused by angles of attack is greater than that of the droplet freezing rate caused by ambient temperature. Moreover, with an increase in the angle of attack, the peak ice thickness changes almost linearly. The angle of attack has a much greater effect on the peak ice thickness than ambient temperature. This is because the angle of attack affects the droplet flow trajectory, and different angles of attack can lead to large discrepancies in ice thickness due to the variation in droplet collection efficiency. On the other hand, ambient temperature affects the freezing rate of droplets, especially under

rime ice conditions, due to the almost 100% freezing rate; the thickness of ice accretion is minimally affected by ambient temperature.

4. Conclusions

In this study, a numerical simulation was used to investigate the effects of ambient temperature and angle of attack on the ice distribution characteristics of different airfoil surfaces for a wind turbine. The following conclusions were deduced:

1. For the upper surface, when the ambient temperature increases from 248 K to 268 K, the peak ice thickness on the leading edge of the DU25 and NACA63-215 airfoils is diminished by 2.1% and 3.2%, respectively.
2. For the lower surface, the peak ice thickness on the leading edge of the DU25 and NACA63-215 airfoils drops by 4.8% and 6.1%, respectively.
3. For the leading edge of airfoils, the ice distribution range on the upper surface of the DU25 airfoil (0–3.07 mm) is wider than that of the NACA63-215 airfoil (0–1.91 mm), while the ice distribution range on the lower surface of the DU25 airfoil (0–12.13 mm) is narrower than that of the NACA63-215 airfoil (0–15.18 mm).
4. For the trailing edge of airfoils, the ice distribution range of the DU25 airfoil (80.55–99.36 mm) is broader than that of the NACA63-215 airfoil (85.03–99.36 mm).
5. For the upper surface, when the angle of attack increases from 0° to 8°, the peak ice thickness on the NACA63-215 airfoil (32.1% reduction) reduces more dramatically than that of the DU25 airfoil (15.2% reduction).
6. For the lower surface, the peak ice thickness on the surface of the DU25 airfoil is smaller than that of the NACA63-215 airfoil.
7. At an angle of attack of 0°, the ice distribution range on the upper surface of the DU25 airfoil is almost the same as that of the NACA63-215 airfoil.
8. At an angle of attack of 8°, the ice distribution range on the upper surface of the DU25 airfoil (0–1.05 mm) is broader than that of the NACA63-215 airfoil (0–0.675 mm), whereas the ice distribution range on the lower surface of the DU25 airfoil (0–17 mm) is narrower than that of the NACA63-215 airfoil (0–20 mm).
9. The angle of attack has a much greater effect on the peak ice thickness than ambient temperature.

In our follow-up study, the effect of airfoil design characteristics on the ice accumulation patterns of wind turbine blades will be explored, including camber and thickness. Afterward, wind turbine blade designs will be optimized, which can provide a reference for the anti/de-icing design of wind turbines.

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Nomenclature

c	chord length (m)	T	temperature (K)
c_f	specific heat capacity of the water film (J/kg K)	$\tilde{T}$	the interface equilibrium temperature (°C)
c_{ice}	specific heat capacity of the ice (J/kg K)	$\vec{V}$	velocity (m/s)
C_D	drag coefficient	y	distance normal to the wall (m)
C_f	friction coefficient	Greek symbols	
d	characteristic length (m)	α	droplet volume fraction
k	thermal conduction coefficient (W/m K)	β	droplet collection efficiency
k_s	surface roughness (m)	ε	emissivity
K	inertia parameter	μ	dynamic viscosity (Pa s)
L	latent heat (J/kg)	τ	shear stress (kg/m s ²)
E	internal energy (J/kg)	Subscripts	
Fr	Froude number	1	air
h_f	water film thickness (m)	2	droplet
H	internal enthalpy (J/kg)	evap	evaporation
LWC	liquid water content (g/m ³)	fus	fusion
Re	Reynolds number	f	water film
$\dot{m}$	mass rate per unit area (kg/m ² ·s)	ice	Ice
$\dot{Q}_h$	heat flux (W/m ²)	subl	sublimation
$\vec{g}$	gravity vector (m/s ²)	∞	free stream
t	time (s)		

References

1. Chehouri, A.; Younes, R.; Ilinca, A.; Perron, J. Review of performance optimization techniques applied to wind turbines. *Appl. Energy* **2015**, *142*, 361–388. [\[CrossRef\]](#)
2. Lamraoui, F.; Fortin, G.; Benoit, R.; Perron, J.; Masson, C. Atmospheric icing impact on wind turbine production. *Cold Reg. Sci. Technol.* **2014**, *100*, 36–49. [\[CrossRef\]](#)
3. Zhang, Y.; Tang, N.; Niu, Y.; Du, X. Wind energy rejection in China: Current status, reasons and perspectives. *Renew. Sustain. Energy Rev.* **2016**, *66*, 322–344. [\[CrossRef\]](#)
4. Zhang, T.; Lian, Y.; Xu, Z.; Li, Y. Effects of wind speed and heat flux on de-icing characteristics of wind turbine blade airfoil surface. *Coatings* **2024**, *14*, 852. [\[CrossRef\]](#)
5. Douvi, E.; Douvi, D. Aerodynamic characteristics of wind turbines operating under hazard environmental conditions: A review. *Energies* **2023**, *16*, 7681. [\[CrossRef\]](#)
6. Li, Y.; Wang, S.; Liu, Q.; Feng, F.; Tagawa, K. Characteristics of ice accretions on blade of the straight-bladed vertical axis wind turbine rotating at low tip speed ratio. *Cold Reg. Sci. Technol.* **2018**, *145*, 1–13. [\[CrossRef\]](#)
7. Shu, L.; Li, H.; Hu, Q.; Jiang, X.; Qiu, G.; McClure, G.; Yang, H. Study of ice accretion feature and power characteristics of wind turbines at natural icing environment. *Cold Reg. Sci. Technol.* **2018**, *147*, 45–54. [\[CrossRef\]](#)
8. Gao, L.; Liu, Y.; Hu, H. An experimental investigation of dynamic ice accretion process on a wind turbine airfoil model considering various icing conditions. *Int. J. Heat Mass Transf.* **2019**, *133*, 930–939. [\[CrossRef\]](#)
9. Gao, L.; Liu, Y.; Zhou, W.; Hu, H. An experimental study on the aerodynamic performance degradation of a wind turbine blade model induced by ice accretion process. *Renew. Energy* **2019**, *133*, 663–675. [\[CrossRef\]](#)
10. Jin, J.Y.; Virk, M.S. Study of ice accretion along symmetric and asymmetric airfoils. *J. Wind. Eng. Ind. Aerodyn.* **2018**, *179*, 240–249. [\[CrossRef\]](#)
11. Jin, J.Y.; Virk, M.S. Study of ice accretion and icing effects on aerodynamic characteristics of DU96 wind turbine blade profile. *Cold Reg. Sci. Technol.* **2019**, *160*, 119–127. [\[CrossRef\]](#)
12. Jin, J.Y.; Virk, M.S. Experimental study of ice accretion on S826 & S832 wind turbine blade profiles. *Cold Reg. Sci. Technol.* **2020**, *169*, 102913.
13. Hu, Q.; Xu, X.; Leng, D.; Shu, L.; Jiang, X.; Virk, M.; Yin, P. A method for measuring ice thickness of wind turbine blades based on edge detection. *Cold Reg. Sci. Technol.* **2021**, *192*, 103398. [\[CrossRef\]](#)
14. Sundaresan, A.; Arunvinthan, S.; Pasha, A.A.; Pillai, S.N. Effect of ice accretion on the aerodynamic characteristics of wind turbine blades. *Wind. Struct.* **2021**, *32*, 205–217.
15. Han, Y.; Lei, Z.; Dong, Y.; Wang, Q.; Li, H.; Feng, F. The icing characteristics of a 1.5 MW wind turbine blade and its influence on the blade mechanical properties. *Coatings* **2024**, *14*, 242. [\[CrossRef\]](#)
16. Ibrahim, G.M.; Pope, K.; Muzychka, Y.S. Effects of blade design on ice accretion for horizontal axis wind turbines. *J. Wind. Eng. Ind. Aerodyn.* **2018**, *173*, 39–52. [\[CrossRef\]](#)
17. Wang, Q.; Xiao, J.; Zhang, T.; Yang, J.; Shi, Y. A new wind turbine icing computational model based on free wake lifting line model and finite area method. *Renew. Energy* **2020**, *146*, 342–358. [\[CrossRef\]](#)

18. Sheidani, A.; Salavatidezfouli, S.; Stabile, G.; Gerdroodbary, M.B.; Rozza, G. Assessment of icing effects on the wake shed behind a vertical axis wind turbine. *Phys. Fluids* **2023**, *35*, 095135. [\[CrossRef\]](#)
19. Lu, H.; Xu, Y.; Li, H.; Zhao, W. Numerical study on glaze ice accretion characteristics over time for a NACA 0012 Airfoil. *Coatings* **2024**, *14*, 55. [\[CrossRef\]](#)
20. Xu, Z.; Zhang, T.; Li, X.; Li, Y. Effects of ambient temperature and wind speed on icing characteristics and anti-icing energy demand of a blade airfoil for wind turbine. *Renew. Energy* **2023**, *217*, 119135. [\[CrossRef\]](#)
21. Xu, Z.; Zhang, T.; Lian, Y.; Feng, F. A parametric study on the effect of liquid water content and droplet median volume diameter on the ice distribution and anti-icing heat estimation of a wind turbine airfoil. *Results Eng.* **2024**, *22*, 102121. [\[CrossRef\]](#)
22. Wang, C.; Lin, W.; Lin, X.; Wu, T.; Meng, Z.; Cai, A.; Xu, Z.; Li, Y.; Feng, F. The influence of angle of attack on the icing distribution characteristics of DU97 blade airfoil surface for wind turbines. *Coatings* **2024**, *14*, 160. [\[CrossRef\]](#)
23. Hannat, R.; Morency, F. Numerical validation of conjugate heat transfer method for anti-/de-icing piccolo system. *J. Aircr.* **2014**, *51*, 104–116. [\[CrossRef\]](#)
24. Ahn, G.B.; Jung, K.Y.; Myong, R.S.; Shin, H.B.; Habashi, W.G. Numerical and experimental investigation of ice accretion on rotorcraft engine air intake. *J. Aircr.* **2015**, *52*, 903–909. [\[CrossRef\]](#)
25. Clift, R.; Grace, J.R.; Weber, M.E. *Bubbles, Drops, and Particles*; Academic Press: New York, NY, USA, 1978.
26. Beaugendre, H.; Morency, F.; Habashi, W.G. Development of a second generation in-flight icing simulation code. *J. Fluids Eng. Trans. ASME* **2006**, *128*, 378–387. [\[CrossRef\]](#)
27. Fouladi, H.; Habashi, W.G.; Ozcer, I.A. Quasi-steady modeling of ice accretion on a helicopter fuselage in forward flight. *J. Aircr.* **2013**, *50*, 1169–1178. [\[CrossRef\]](#)
28. Tompson, B.E.; Marrochello, M.R. Rivulet formation in surface-water flow on an airfoil in rain. *AIAA J.* **1999**, *37*, 45–49. [\[CrossRef\]](#)
29. Beaugendre, H.; Morency, F.; Habashi, W.G.; Benquet, P. Roughness implementation in FENSAP-ICE: Model calibration and influence on ice shapes. *J. Aircr.* **2003**, *40*, 1212–1215. [\[CrossRef\]](#)
30. Battisti, L. *Wind Turbines in Cold Climates*; Springer: Dordrecht, GX, The Netherlands, 2015.
31. Shin, J.; Bond, T.H. Results of an Icing Test on a NACA0012 Airfoil in the NASA Lewis Icing Research Tunnel. In Proceedings of the 30th Aerospace Sciences Meeting & Exhibit, Reno, NV, USA, 6–9 January 1992; pp. 1–19.
32. Guet, J.; Reggio, M.; Teyssedou, A. Implementation and Application of the Lattice Boltzmann Method Using Matlab. *Eng. Appl. Comput. Fluid Mech.* **2011**, *5*, 117–126. [\[CrossRef\]](#)

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