Experimental Research on Adhesion Strength of Ice Accretion on Leading Edge of Symmetric Airfoil

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(Received 26 March 2023; revised 15 April 2023; accepted 24 April 2023)

Abstract: When aircraft operate in a cold and humid environment, ice accretion occurs on the leading edge of wing at times, which threatens the flight safety. For developing anti-icing and de-icing technologies, it is necessary to explore the adhesive characteristic of ice covering on the blade airfoil surface. In this paper, a measurement system of ice adhesion for blade airfoil is designed and built. And an evaluation method of ice adhesion strength for the blade airfoil is proposed. The distribution and adhesion strength of ice on the blade segment with airfoil of NACA0018 are recorded and measured under different conditions. The experiment results show that icing time is less significant to the ice adhesion strength. As the ambient temperature decreases, the adhesion strength of ice on the blade airfoil surface increases, but the growth rate decreases. In addition, when the wind speed increases, the adhesion strength of ice on the blade airfoil surface decreases. The research findings provide a reference for deeply exploring the adhesion mechanism of ice covering on blade airfoil.

Key words: aircraft; ice; adhesion; evaluation method; wind tunnel experiment

CLC number: V19 **Document code:** A **Article ID:** 1005-1120(2023)02-0230-09

Nomenclature

F / N	Adhesion force
LWC/ (g·m^{-3})	Liquid water content
L_1 / m	Iced arc length of the airfoil
L_2/ m	Length of wingspan
MVD /μm	Medium volumetric diameter
Ra /μm	Surface roughness
S / m^2	Adhesive area of ice removed from the blade surface
T/℃	Ambient temperature
t/min	Icing duration time
U/(m·s^{-1})	Wind speed
τ/Pa	Adhesion strength

0 Introduction

Icing is a universal phenomenon in the natural world. However, the icing on roads, aircraft, power transmission lines, wind turbines[1-2], and buildings easily causes accidents and economic losses[3-4]. In the aircraft industry, icing is one of the major threats to the flight safety of aircraft[5-6]. In a cold and humid weather, the aircraft's surface is easily icing. Ref.[7] found that the icing on aircraft reduced lift and elevator effectiveness, and increased drag. In order to research and develop effective anti-icing and de-icing systems, the adhesion mechanism between ice and substrate material must be explored.

The research methods of adhesion mechanism mainly include theoretical and experimental research. The theoretical research draws lessons from adhesion theories, including mechanical, electrical, and wetting theories[8-9]. These theories explain the adhesion between ice and substrate from different viewpoints but have not formed into a uniform adhesion theory. In this regard, experimental research is

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How to cite this article: SHEN He, LI Yan, GUO Wenfeng, et al. Experimental research on adhesion strength of ice accretion on leading edge of symmetric airfoil[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2023, 40(2): 230-238.

http://dx.doi.org/10.16356/j.1005-1120.2023.02.011

a crucial way to explore the adhesion mechanism of ice on the substrate surface. In experimental research, the impact ice experiment is easier to acquire results similar to the natural environment conditions, compared with the non-impact ice experiment[10]. In the impact ice experiment, the plate and column samples have received extensive attention[11-12]. For example, Ref.[13] studied the effect of ambient and substrate temperature on the adhesion strength of ice covering the plate surface. Ref.[14] studied the adhesive property of glaze and rime ice on aluminum electrical conductors. However, the geometrical shapes of the plate, column, and airfoil are different. The effect of the geometrical shape of substrate material on adhesion strength has not been explored. Therefore, it is essential to study the adhesive property of ice on the blade airfoil surface. Ref.[15] studied the adhesive property of ice on the blade airfoil. Nevertheless, the blade airfoil material in Ref.[15] used fiberglass, which was more suitable for wind turbine rather than aircraft. In Ref.[15], a simple measurement device of ice adhesion for blade airfoil was designed, but it did not report the detail of acquiring adhesive areas on the blade surface. The adhesive areas of ice are vital to calculate the result of adhesion strength. In addition, the ambient temperature is also an important factor in the adhesion strength of ice. In Ref.[15], only two temperatures were selected, −5 ℃ and −15 ℃. More ambient temperatures should be focused on in the experimental research. The icing time and wind speed also may be important factors for ice adhesion strength. Therefore, extensive research should be carried out on ice adhesive properties for blade airfoil.

For this purpose, the ice adhesion measure system is designed and built in this paper. The evaluation method of ice adhesion strength is proposed for blade airfoil. Experiments are conducted on the ice adhesion strength of 6061 aluminum alloy blades of NACA0018 airfoil under different icing time, environmental temperatures, and wind speeds. The experimental results are compared with those of other studies. It can provide reference for the study of the ice adhesion mechanism of blade airfoils.

1 Experiment

1.1 Experimental blade

The experimental blade is the 6061 aluminum alloy blade of the NACA0018 airfoil, as shown in Fig.1. The NACA0018 airfoil is a symmetric airfoil with a higher power coefficient, which is widely used in research. Aluminum material has isotropic and heat transfer stability characteristics and is broadly used in the aircraft industry. Therefore, the 6061 aluminum alloy blade of the NACA0018 airfoil is selected to research ice adhesive properties in this paper. The parameters of the experimental blade are as follows: The chord length is 150 mm, the wall thickness is 2 mm, the wingspan length is 20 mm, and the surface roughness *Ra* is 0.79 μm.

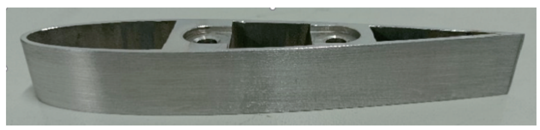

Fig.1 Experimental blade

1.2 Icing wind tunnel experimental system

In this paper, the schematic diagram of the reflux icing wind tunnel experimental system is shown in Fig.2. The icing wind tunnel experimental system consists of refrigeration, spray, and air duct systems. The cross profile of the test section is 250 mm × 250 mm. The spray is placed on the central position of the stable section cross profile. The experimental blade is fixed on the support of the text section. The blockage ratio of the experimental blade and support is about 1.8%. More details about the icing wind tunnel experimental system can be obtained in Ref.[16].

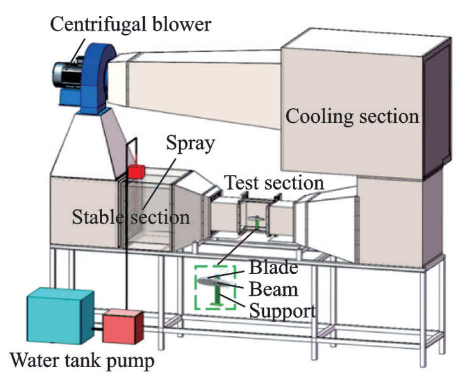

Fig.2 Icing wind tunnel experimental system

1.3 Ice adhesion measure system

In this paper, an ice adhesion measure system is designed and built, which consists of the freezer, the measuring device, and the data acquisition system. The operating temperature range of the freezer is −30—0 ℃ with an adjustment accuracy of 1 ℃ (China, XINGX, BD/BC-217JE). The schematic diagram of the measuring device is shown in Fig.3. The measuring device is placed in the freezer. In the measuring, the iced blade is taken down from the test section of the icing wind tunnel experimental system and fixed on the slider of the measuring device. The slider is driven by pressure sensors and slides along the parallel rails. The pressure sensors are fixed on the sensor fixture, which is driven by the hydraulic thruster. The movement speed of the iced blade is 5 mm/s. The data acquisition system consists of pressure sensors, a digital transmitter, and a computer. The working temperature range of the pressure sensor is −20—70 ℃, and the measuring range is 0—500 N with an error of 3 ‰ (China, Bengbu Jinnuo Sensor, JLBM-1). When the iced blade passes the de-icing hole, the ice layer separates from the blade's surface under a tangential force. The pressure sensors measure the tangential force in real-time and transmit the data to the computer. In this paper, the maximal tangential force in real-time is taken as the adhesion force of impact ice on the blade's surface.

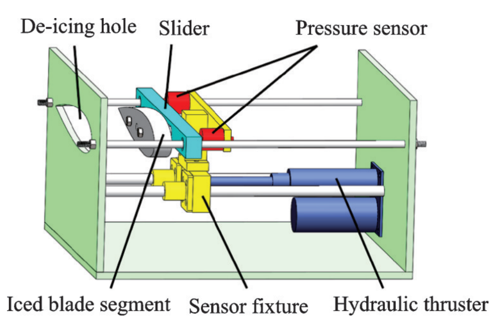

Fig.3 Measuring device of ice adhesion

1.4 Experimental scheme and procedure

The present study shows that ambient temperature is an important factor in ice adhesion strength. In order to research the effect of ambient temperature on ice adhesion strength, five ambient temperatures are selected, −5, −8, −10, −12, and −15 ℃. To study the effect of wind speed on ice adhesion strength, five wind speeds are selected, 5, 8, 10, 12, and 15 m/s. In addition, for studying the effect of icing time on ice adhesion strength, five icing time are selected, 2, 4, 6, 8, and 10 min. The liquid water content (LWC) is 0.1—5.0 g/m^3, and the median volumetric diameter (MVD) is 20 —100 μm.

The experiments are carried out in the winter in Harbin. In the experiment, the laboratory temperature is below 0 ℃, which avoids the effect of the laboratory temperature on experimental results. The adhesion force of ice is measured 10 to 15 times for the blade under each experimental condition. The main steps of the experimental procedure are as follows:

(1) Set the experimental parameters and run the icing wind tunnel experimental system.

(2) Fix the clean blade on the support in the test section of the icing wind tunnel experimental system and cool the blade.

(3) When the temperature and wind speed reach the set value, the spray system is operated to start the icing experiments. The high-speed camera acquires the ice layer distribution on the blade surface (America, Phantom v5.1, 1 024 pixel×1 024 pixel). When the icing time reaches the set value, the spray system stops spraying and cools the iced blade.

(4) The iced blade is taken out of the icing wind tunnel experimental system and fixed on the slider of the measuring device of ice adhesion. The ice adhesion measure system runs, and the data of tangential force are recorded. After measuring the ice adhesion, record the residual ice layer on the blade surface.

(5) The blade is cleaned and prepared for the next experiment.

2 Evaluation Method

In this paper, the adhesion strength τ is selected to carry out quantificational analysis for the adhesive property of ice on the blade surface. τ is expressed as

$$\tau = \frac{F}{S} \tag{1}$$

where τ is the adhesion strength; F the adhesion force; and S the adhesive area of ice removed from the blade surface, and it is expressed as

$$S = L_1 \times L_2 \tag{2}$$

The schematic diagram of S, L_1 and L_2 is given in Fig.4.

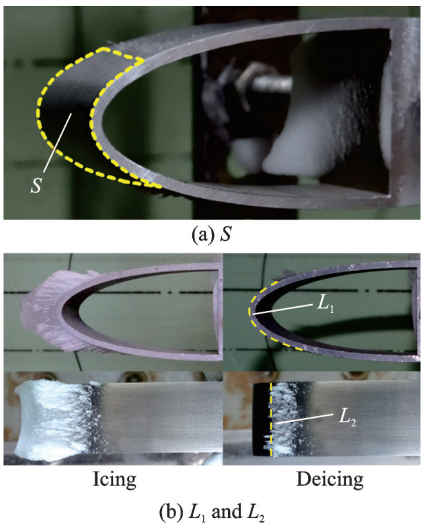

Fig.4 Schematic diagram of S, L_1, and L_2

3 Results and Discussion

3.1 Distribution of ice on leading edge

The distribution of ice on the blade surface is shown in Fig. 5. The ice layer mainly accumulates on the blade leading edge under different conditions.

The ice layer is thinner in the initial stage of the icing experiment, as shown in Fig.5(a). The ice accumulates layer by layer as the icing time increases. When the icing time is 10 min, the icicle appears on the lower surface of the leading edge. The causes of the above experimental phenomena are analyzed as follows. The thermal conductivity of ice is 2.2 W/(m·K), and that of aluminum is 167 W/(m·K). The conduction velocity of energy in ice is slower than that of aluminum. Therefore, as the thickness of the ice layer increases, the energy exchange time between the supercooled droplet and the ice layer increases after the supercooled droplet impacts the blade surface. Under the action of airflow and gravity, the unfrozen droplet flows and accumulates on the lower surface of the leading edge, and the icicle appears.

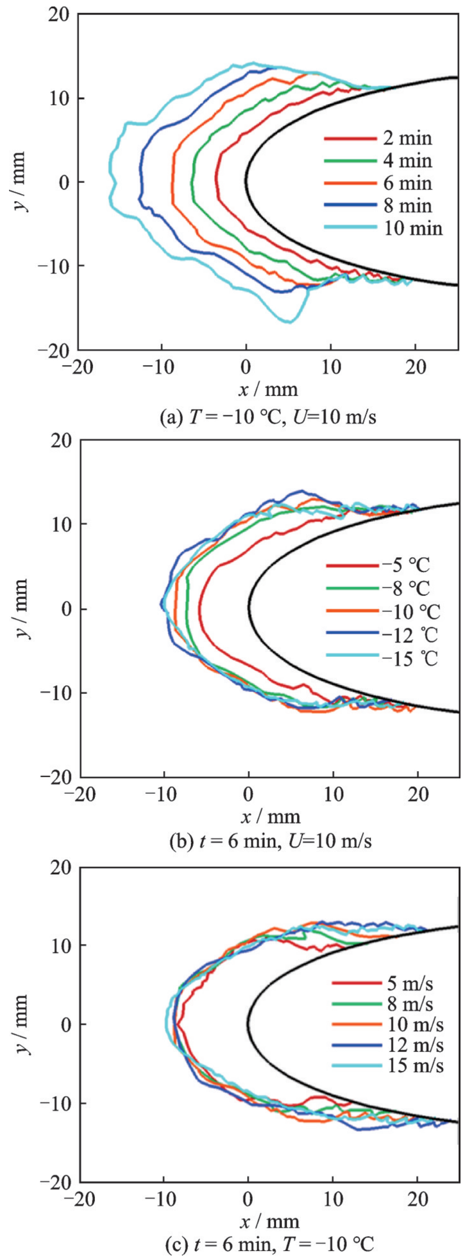

Fig.5 Distribution of ice on leading edge

When the ambient temperature is −5 ℃, the ice layer is thinner on the leading edge, as shown in Fig.5(b). As the ambient temperature decreases, the thickness of ice on the leading edge increases. When the ambient temperature is below −8 ℃, the effect of ambient temperature on the ice thickness is insignificant. The reasons for the above experimental phenomena are analyzed as follows. The ambient temperature is an important factor in the energy exchange duration between supercooled droplet, environment and blade surface. When the ambient temperature is relatively high, the energy exchange time is relatively long, and the freezing rate of the supercooled droplet is relatively slow. When the force of airflow on the unfrozen droplet is greater than that of adhesion force, the unfrozen droplet will separate from the blade surface. Therefore, the thickness of the ice layer is thinner on the leading edge when the ambient temperature is −5 ℃. As the ambient temperature decreases, the freezing speed of supercooled droplets increases, and the ice thickness at the leading edge increases. However, the ice thickness changing with ambient temperature is not linear because the LWC is constant. Therefore, the effect of ambient temperature on ice thickness is insignificant when the ambient temperature is below −8 ℃.

When the wind speed is 5 m/s, the ice layer accumulates on the leading edge, as shown in Fig.5(c). As the wind speed increases, the ice layer accumulates from the direction of the leading edge to the trailing edge. The causes of the above experimental phenomena are analyzed as follows. When the wind speed is relatively low, the effect of airflow on the supercooled droplet is getting smaller after the supercooled droplet impacts the blade surface. Therefore, the ice layer accumulates on the leading edge when the wind speed is 5 m/s. As the wind speed increases, the effect of airflow on the supercooled droplet increases. Under the action of airflow, the unfrozen droplet flows on the blade surface from the direction of the leading edge to the trailing edge. Hence, the ice layer accumulates from the leading edge to the trailing edge.

3.2 Effect of icing time on adhesion strength

In the present study, five kinds of icing time are selected to study the effect of icing time on adhesion strength, 2, 4, 6, 8, and 10 min. The ambient temperature is −10 ℃, the wind speed is 10 m/s, and the experimental results are shown in Fig.6.

As shown in Fig.6, the thickness of the ice layer on the leading edge increases with the icing time increases. The effect of the ice thickness on the adhesion strength is insignificant. Under different icing time, the mean adhesion strength is about

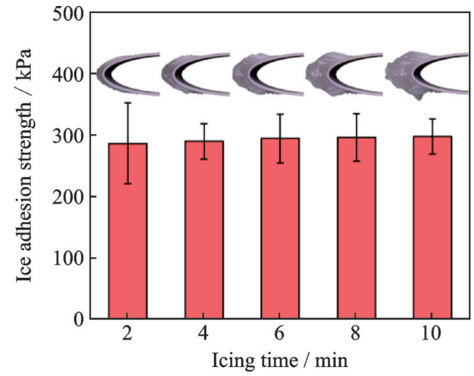

Fig.6 Effect of icing time on ice adhesion strength

293.97 kPa on the iced blade surface. When the icing time is 2 min, the discreteness of the experimental result is significantly higher than that in other conditions, which may be related to a thinner ice layer.

3.3 Effect of ambient temperature on adhesion strength

The effect of ambient temperature on adhesion strength is shown in Fig.7. In this study, five kinds of ambient temperatures are selected, −5, −8, −10, −12, and −15 ℃. The wind speed is 10 m/s, and the icing time is 6 min.

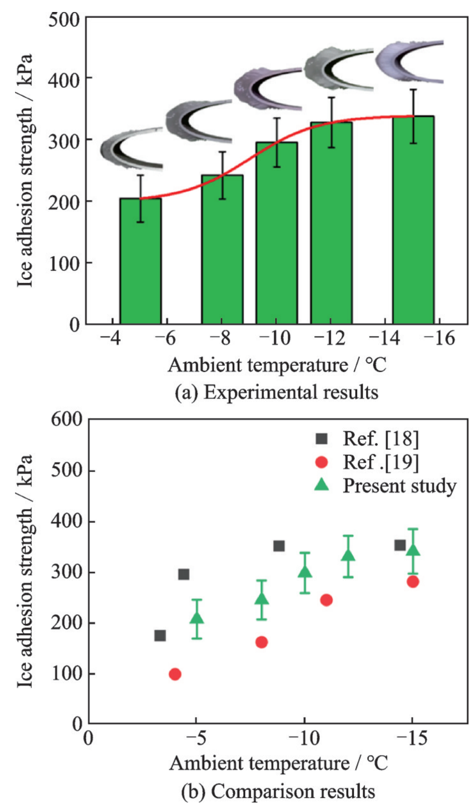

Fig.7 Effect of ambient temperature on ice adhesion strength

As shown in Fig.7(a), the type of ice on the blade surface changes from glaze ice to rime ice as the ambient temperature decreases. The experimental phenomenon coincides with the current research results[17]. The adhesion strength of ice on the blade surface increases as the ambient temperature decreases, but the growth rate of adhesion strength decreases. The reasons for the increase of adhesion strength are analyzed as follows. On the micrometer scale, the surface structure of the smooth blade is similar to the terrain. The mountains and valleys with different shapes and sizes randomly distribute on the blade surface. When the supercooled droplet impacts the blade surface, the broken droplet will fill the space around mountains and valleys. At this time, the droplet exchanges energy with the low-temperature blade and begins the phase transition. In the phase transition, the droplet releases the latent heat, which causes the increase of the blade temperature. When the latent heat release ends, the droplets completely freeze, and the temperature of the blade stops increasing. Under the convective heat transfer of the low-temperature flow field, the temperature of the ice layer and blade decreases and finally approaches the ambient temperature. In the cooling, the ice and the blade volume shrink. The volume expansion coefficient of ice is greater than that of aluminum. Therefore, the volume shrinkage of ice is more significant than the mountains and valleys on the blade surface. The ice and the surface mountain squeeze against each other and form an interlocked state. When the ambient temperature decreases, the volume shrinkage of the ice and surface mountain increases, which leads to an increase in compressive stress between ice and surface mountain. The adhesion increases between the ice layer and the surface mountain. Therefore, the adhesion strength of ice increases as the ambient temperature decreases. However, the increasing trend of adhesion strength is not linear. Ice is the brittle material, and aluminum is the rigid material. The compression stress between ice and surface mountain is not illimitably increasing as the ambient temperature decreases. When the compression stress is beyond the limit of the ice, the ice will fragment. In that case, the surface defect appears on the adhesion interface between ice and blade. Therefore, as the ambient temperature decreases, the growth rate of ice adhesion strength decreases.

As shown in Fig.7(a), the relationship between adhesion strength and ambient temperature is expressed as Eq.(3), which is available to the ambient temperature range of −5—−15 ℃.

$$\tau = -199.08 + \frac{140.18}{1 + e^{\frac{T+9.01}{1.25}}} \tag{3}$$

where T is the ambient temperature.

The measuring results of ice adhesion strength are compared with the previous research, which is shown in Fig.7(b). As shown in Fig.7(b), in the present study, the adhesion strength of ice is 204.45—313.77 kPa under the ambient temperature of −5—−15 ℃. In Ref.[18], the adhesion strength of ice is 90—350 kPa under the ambient temperature of −3.3—−14.4 ℃. In Ref.[19] the adhesion strength of ice is 84—280 kPa under the ambient temperature of −4— −15 ℃. The present study results are approximate to the previous works in comparison. There are minor differences between the present result and previous ones. The reason for the differences in the results is the discrepancies in the experimental conditions. In the icing experiment, there exist some key conditions, such as the profile of icing sample, surface characteristics and environmental conditions, affecting ice adhesion. For comparison, the experimental condition for each research is listed in Table 1.

Table 1 Comparison of experimental conditions

Paper	Geometrical shape	Surface roughness Ra/μm	Ambient temperature T /℃	Wind speed U/ (m·s^{-1})	LWC/ (g·m^{-3})	MVD/μm
Ref.[18]	Column		−3.3—−14.4	58.1	20.0	1.3
Ref.[19]	Column	3.19	−4.0—−15.0		1.0	22.0
Present study	Airfoil	0.79	−5.0—−15.0	10.0	0.1—5.0	20.0—100.0

As listed in Table 1, the experimental samples in Ref.[18] and Ref.[19] are both columns. However, the experimental sample in the present study is an airfoil blade segment. For the column sample, the curvature is constant at any point of the column surface. However, the one for airfoil profile changes continually. Therefore, the difference in curvature between samples is one of the reasons for the experimental differences.

In addition, it is found in Ref.[19] that the adhesion strength of ice increased along with the surface roughness, and first increased and then decreased slowly with the increase in MVD. In Ref.[19], the surface roughness was 3.19 μm, and MVD was 22 μm. Compared with Ref.[19], in the present study, surface roughness is 0.79 μm, and MVD is in the range of 20—100 μm. Furthermore, in the present study the wind speed affects the adhesion strength of ice and the wind speed is 10 m/s, which is also one of the reasons resulting in the difference between the present study and Ref.[19].

3.4 Effect of wind speed on adhesion strength

The effect of wind speed on adhesion strength is shown in Fig.8. In the present study, five kinds of wind speeds are selected, 5, 8, 10, 12, and 15 m/s. The ambient temperature is −10 ℃, and the icing time is 6 min.

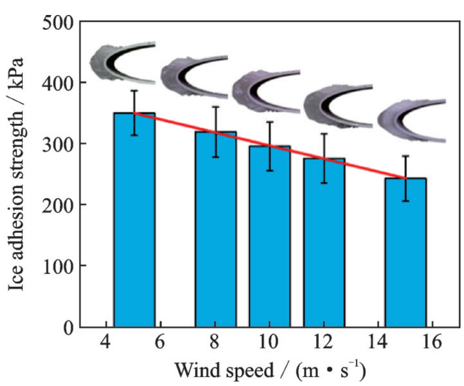

Fig.8 Effect of wind speed on ice adhesion strength

As shown in Fig.8, the adhesion strength of ice on the blade surface decreases with the increase in wind speed. The reasons for the decrease in adhesion strength are analyzed as follows. When the supercooled droplet impacts the blade surface, the supercooled droplet exchanges energy with the blade and the low-temperature flow field. With the wind speed increasing, the convective heat transfer between the blade and the low-temperature flow field increases. In the droplet phase transition, the energy carried away by the low-temperature flow field increases. Therefore, when the droplets completely freeze, the temperature rise on the blade surface will decrease. During the cooling process, the volume shrinkage of the ice layer and surface mountains decreases, resulting in a decrease in compressive stress. Therefore, as the wind speed increases, the adhesion strength of ice on the blade surface decreases. As shown in Fig. 8, the relationship between adhesion strength and wind speed is expressed as Eq.(4), which is available to the wind speed range of 5—15 m/s.

$$\tau = 403.22 - 10.67U \tag{4}$$

where U is the wind speed.

4 Conclusions

The adhesion strength of ice on airfoil blade surface is studied and analyzed by experimental method, and some conclusions are drawn as follows:

(1) A measurement system of ice adhesion for airfoil blade is designed and built. An evaluation method of ice adhesion strength is proposed. The distribution and adhesion strength of ice, covering the aluminum blade with the NACA0018 airfoil, are recorded and measured under different conditions, including icing time, ambient temperature and wind speed.

(2) The experimental results show that the ice thickness on the blade surface increase along with icing time. The effect of ice thickness on adhesion strength is insignificant. The factor of icing time has little effect on the adhesion strength of ice covering the blade surface. When the ambient temperature is −5 ℃, the ice type on the blade surface is glaze ice. As the ambient temperature decreases, the ice type changes from glaze ice to rime ice, and the adhesion strength of ice covering the blade surface increases, but the growth rate decreases. When the wind speed

is 5 m/s, the ice layer only accumulates on the leading edge of blade. As the wind speed increases, ice accumulates along the blade surface from the leading edge to the trailing edge, and the ice adhesion strength decreases. Within the range of 5 m/s to 15 m/s, there is a linear relationship between the ice adhesion strength and the wind speed. The research findings provide a reference for deeply studying the adhesion mechanism of ice on blade airfoil.

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Acknowledgement This work was funded by the National Natural Science Foundation of China (No.51976029).

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Author contributions Mr. **SHEN He** contributed to data, conducted the analysis, interpreted the results and wrote the manuscript. Prof. **LI Yan** designed the study, and contrib-

uted to data analysis. Dr. **GUO Wenfeng** contributed to data and the discussion. Prof. **KOTARO Tagawa** contributed to background of the study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing inrests.

(Production Editor: SUN Jing)

对称翼型前缘积冰粘结强度试验研究

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摘要：当飞机在寒冷潮湿的环境中飞行时，机翼前缘有时会出现结冰现象威胁飞行安全。为了发展防冰和除冰技术，有必要对叶片翼型表面覆冰的粘结特性进行研究。本文设计并搭建了叶片翼型覆冰粘结力测量系统，提出了叶片翼型覆冰粘结强度的评估方法，记录和测量了不同条件下NACA0018翼型叶片段上的结冰分布和粘结强度。试验结果表明，结冰时间对冰粘结强度的影响较小。随着环境温度降低，叶片翼型表面冰粘结强度增加，但增长速率减小。此外，随着风速增加，叶片翼型表面冰粘结强度降低。本研究结果为深入探索叶片翼型覆冰粘结机理提供了参考。

关键词：飞机；冰；粘结；评估方法；风洞试验