Superhydrophobic Surface Application of Runback Icing Elimination and Anti-icing Power Reduction and Icing Wind Tunnel Test

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Abstract: In order to prevent the formation of runback ice and achieve dry anti-icing effect while reducing energy consumption, a low-energy consumption dry anti-icing technology is developed. Based on the principle of thermal anti-icing, the idea of water shedding is introduced to keep the impact water liquid at a lower surface temperature. Superhydrophobic materials are used to promote water shedding as the main protection method to increase water shedding and reduce heat exchange time. The runback of liquid water on the surface and the energy consumption of surface heat exchange are reduced. The formation of runback ice is suppressed to achieve anti-ice effect and reduce energy consumption. The test results show that the low-energy dry anti-icing technology can significantly inhibit the formation of leading edge ice and runback ice, and reduce the required power compared with traditional thermal protection methods.

Key words: icing; anti-icing; superhydrophobic surface; low-energy consumption

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0 Introduction

Icing at key positions of aircraft, such as wings, empennage and engines, will pose a threat to flight safety[1]. In order to prevent icing hazards, aircraft generally use anti-icing and de-icing systems. The thermal anti-icing system is a widely used protection method. The engine bleed air or electric heating system provides heat energy for the protective surface to achieve anti-icing effect[2]. The thermal protection method with the best protection effect is the dry anti-icing method, which provides sufficient high temperature so that the supercooled water droplets immediately evaporate when they hit the protection area, and to maintain the aircraft surface in the dry state, completely eliminating the risk of icing[3]. If the bleed air anti-icing system adopts the dry protection mode, it will consume more engine bleed air and affect the engine power. And affected by the design of fully electric or multi-electric aircraft, bleed air anti-icing technology will be gradually replaced by other anti-icing methods. Electric heating anti-icing technology has been widely used in helicopter blades, windshields, instruments and equipment, etc., and just starts in the icing protection of large-area components such as wings and empennages. If the electric heating system adopts the dry protection mode, it will consume more electric energy and is not practical in engineering. Therefore, periodic de-icing or wet anti-icing mode is preferred[4]. Wet anti-icing means that heating cannot ensure the complete evaporation of the impacted water droplets, and part of the supercooled water impacted on the surface remains liquid and is blown away from the surface by the airflow. This method requires relatively low-energy consumption, but

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there is a certain risk that the liquid water flowing backward may not be able to completely fly off the surface, and it will freeze after the temperature drops below the freezing point behind the protected area, forming runback ice[5]. This is also the main reason for the ATR72 crash in Roselawn[6]. The traditional thermal protection method has relatively excellent protection effect, but the energy consumption demand is relatively large. The energy-saving effect that can be achieved by optimizing the structure and heating efficiency is close to the bottleneck, and the reduction of energy consumption often leads to a greater risk of runback ice, which increases the risk of flight safety[7]. In recent years, more research hotspots have focused on anti-icing technology with low-energy consumption and good effect.

Superhydrophobic material is a new type of material that has been developed rapidly in recent years[8]. With its special surface wettability and low surface energy, the contact angle of water droplets on its surface is greater than 150°, and the rolling angle is less than 10°[9]. Water droplets can converge on the surface and roll down quickly, and the shedding phenomenon is more obvious on the surface of the aircraft due to the shear force of the airflow. It has great application potential in the field of aircraft anti-icing[10]. Many studies have focused on the wettability and preparation methods of superhydrophobic surfaces, but few studies have been carried out in the field of aircraft anti-icing. Kim et al.[11] studied the freezing process of a single water droplet on a superhydrophobic surface through experiments, and found that the static contact angle change would delay the freezing process of liquid water droplets. Kimura et al.[12] tested the ice adhesion of seven superhydrophobic surfaces in the laboratory and found that the improved anti-icing coating was more likely to let the ice fall off than the polyurethane coating. Somlo et al.[13] applied hydrophobic materials to the aluminum surface, and believed that hydrophobic materials can reduce the ice binding force. Yin et al.[14] compared the hydrophilic surface and the hydrophobic surface at the initial moment of icing, revealing the application potential of superhydrophobic materials in aircraft anti-icing field. Fortin et al.[15] tried to use superhydrophobic materials combined with electric heating systems for anti-icing, saving 13% energy in the rime ice condition and 33% energy in the glaze ice condition. Zhong's team of Tsinghua University designed a new type of superhydrophobic material with three-scale micro-nano structure. This new type of material has good resistance to high-humidity environments, its surface ice adhesion strength can be as low as 1.7 kPa, and has good anti-icing durability[16].

Aiming at the application of superhydrophobic materials, this paper proposes a dry anti-icing method with low-energy consumption. Based on the design idea of heat exchange and the idea of promoting water shedding, the surface water shedding in the protected area is realized. The complete anti-icing of the protection area is achieved, while the dry anti-icing without runback water behind the protection area is realized, and the energy consumption of anti-icing is effectively reduced.

1 Principle Analysis

The traditional wet anti-icing design method is a limited protection method. A fixed anti-icing power is designed in a given protection area, and the surface water is heated and evaporated by contact heat exchange. Areas of greater water collection near the stagnation point at the leading edge of the skin allow the flow of liquid water, which slowly evaporates as it flows gradually backwards within the protected area. This design method usually has good protection ability in light or moderate icing conditions, and has a certain energy saving effect, but it will bring potential runback ice generation risk under severe icing weather conditions (Fig.1). The traditional dry anti-icing method is to completely evaporate the water collected on the airfoil surface by increasing the heat exchange. This method can avoid the flow of liquid water on the icing surface, suppress the formation of runback ice, and have the best anti-icing effect, but the energy consumption demand is huge. Superhydrophobic materials can make water droplets converge on the surface and fall off quickly. A large

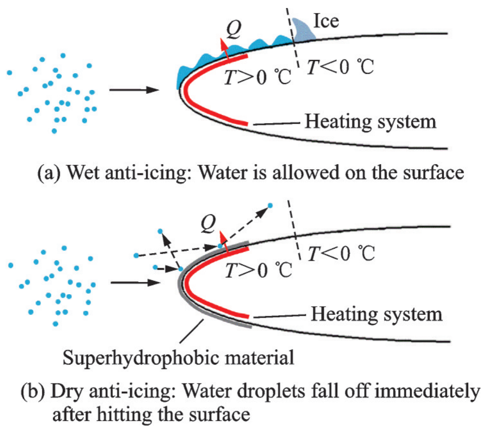


Fig.1 Principle of dry anti-icing method

amount of surface water shedding saves anti-icing energy. This new anti-icing design method using superhydrophobic surface to induce water shedding is expected to achieve dry anti-icing effect with extremely low-energy consumption.

When the supercooled water droplets hit the metal surface, it will form a water film on the surface and flow backwards. When water droplets hit the superhydrophobic surface, some water droplets splash off the superhydrophobic surface, and a small part of the remaining liquid water on the superhydrophobic surface no longer forms a water film similar to the hydrophilic surface, but flows backward in the form of water droplets, and its rolling speed is greater than that of the water film on the hydrophilic surface, as shown in Fig.2. The energy required to be provided by the internal heating of the anti-icing system is positively related to the quality and maintenance time of the surface liquid water. The superhydrophobic surface has less residual water, fast separation speed from the surface, and short residual time on the surface. Therefore, the superhydrophobic surface water needs less energy to maintain the liquid state, and can achieve low-energy consumption under the same condition.

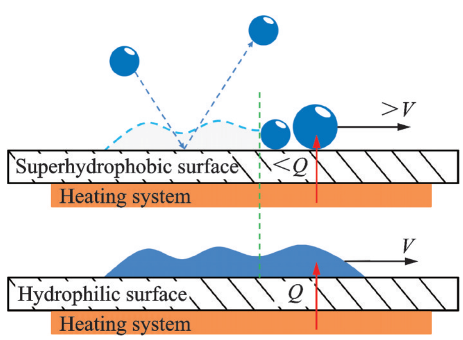


Fig.2 Principle of low-energy consumption

The low-energy consumption dry anti-icing system based on superhydrophobic materials is to supplement superhydrophobic materials on the basis of traditional thermal protection systems. Through the design of the range of material arrangement, the shedding of water on the surface is promoted, and energy consumption is reduced at the same time.

The range of traditional heating protection systems needs to cover impact limit of supercooled water droplets in icing environments. The layout range of superhydrophobic materials designed in this paper includes the following three forms, as shown in Fig.3:

(1) The superhydrophobic materials have the same scope as thermal protection systems;

(2) The superhydrophobic materials are arranged behind the thermal protection system;

(3) The layout of superhydrophobic materials covers the thermal protection system and the rear area.

Among them, the design idea of Form 1 is that the water droplet will fall off when it hits the superhydrophobic surface, and the runback area will not

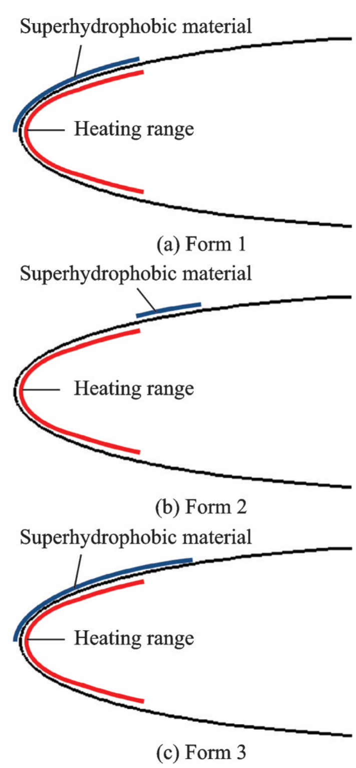


Fig.3 Layout of superhydrophobic materials

exceed the range of the protection system. The design idea of Form 2 is to use superhydrophobic materials to promote shedding in the runback area of liquid water, so that the liquid water flowing through the protection range is shed. The design idea of Form 3 is to achieve the goal of further reducing energy consumption by increasing the use of superhydrophobic materials and reducing the internal heating power.

In this paper, different surface layouts of superhydrophobic materials are designed to verify which of the above three forms is more suitable for low-energy consumption dry anti-icing system.

2 Experimental Method

2.1 Experimental equipment

This phase of experiment was completed in the FL-61 wind tunnel of AVIC Aerodynamics Research Institute[17]. The wind tunnel is a subsonic, transonic and supersonic continuous wind tunnel. The cross sectional size of the test section is 0.6 m×0.6 m, and the total length of the test section is 2.7 m. The structure of the FL-61 wind tunnel is shown in Fig.4.

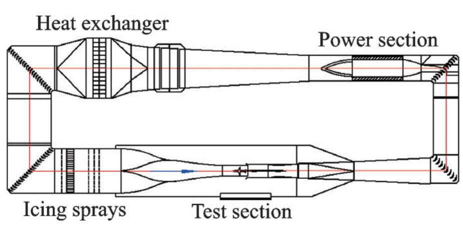


Fig.4 Structural diagram of FL-61 wind tunnel

2.2 Experimental model

The model used in the study is the NACA0012 swept airfoil model[18]. The airfoil chord length is 500 mm. The sweep angle is 15°, and the spanwise length is 600 mm. Thermocouple temperature sensors are designed inside the model, and three temperature measurement sections are selected in the middle section and the sections on both sides 150 mm away from the middle section in the spanwise direction, as shown in Fig.5. In this paper, only the temperature acquisition data of thermocouples in the middle section are given.

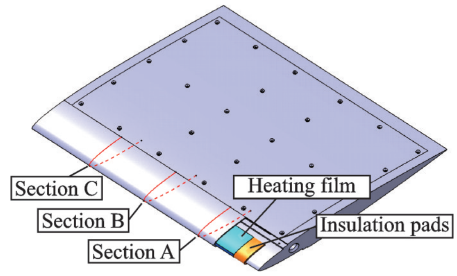


Fig.5 Experimental model and sensor sections

The internal heating system designed for this model is shown in Fig.6. The electric heating strip is used as the heating system, which is arranged in five areas along the chord direction. The three ranges A, B, and C cover the water droplet impact limit under the design state. The ranges D and E are reserved heating areas. The heating strip is arranged in the same position along the spanwise direction.

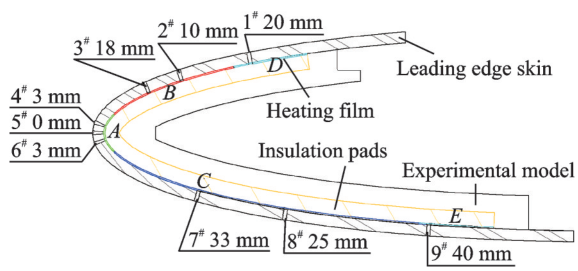


Fig.6 Electric heating and thermocouple distribution

The geometric zero point of the airfoil is taken as the reference point, thus the total arc length of the heating strip A is 12 mm, and the arc length of the upper and lower airfoils is 6 mm; the arc length of the heating strip B is 35 mm; the arc length of the heating strip C is 85 mm; the arc length of the heating strip D is 20 mm; and the arc length of the heating sheet E is 20 mm.

Nine thermocouples are arranged along the chord direction of the airfoil in each section. The thermocouples are arranged as follows: $1^{\#}$ thermocouple is located in the D heating strip; $2^{\#}$ and $3^{\#}$ thermocouples are located in the B heating strip; $4^{\#}$, $5^{\#}$, and $6^{\#}$ thermocouples are located in the A heating strip; $7^{\#}$ and $8^{\#}$ thermocouples are located in the C heating strip; and $9^{\#}$ thermocouple is located in the E heating strip.

The thermocouple hole is a hole with a diameter of 1.1 mm. The hole is drilled from the inside to the outer surface. The outer surface is covered with aluminum skin. The diameter of the thermocouple probe is 0.64 mm. After inserting into the thermocouple hole, the gap is filled with aluminum powder. After the thermocouple is installed and calibrated in the early stage, the measurement temperature fluctuation range is about ±0.5 ℃.

2.3 Superhydrophobic surface

The superhydrophobic material used in this study was prepared by Zhong's team at the Laser Materials Processing Research Center of the School of Materials Science and Engineering, Tsinghua University. The material was prepared by ultrafast laser on the surface of 0.3 mm thick 6061 aviation aluminum alloy material, and the superhydrophobic surface was formed after chemical modification, as shown in Fig.7.

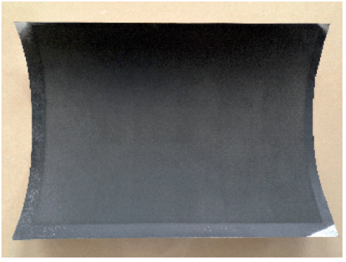


Fig.7 Superhydrophobic material

Two samples were selected for performance test. According to the calculation of the test instrument, the average contact angle on the surface of test sample Ⅰ was 150.14°, and the average rolling angle was 6.63°; the average contact angle on the surface of test sample Ⅱ was 150.48°, and the average rolling angle was 6.97°. The superhydrophobic material was pasted on the surface of the model with 3M9495LE double-sided adhesive.

2.4 Experimental content

In this paper, the effect comparison experiment of the low-energy consumption dry anti-icing method and the traditional thermal protection method under different icing environments was carried out. One of the typical conditions were selected to carry out the test of the superhydrophobic material layout range and internal heating range, and the experiment contents are shown in Table 1. Among them, the power density of 5 kW/m^2 is selected, which, according to previous tests, is the lowest energy consumption for low-energy dry anti-icing systems that can achieve anti-icing effects.

Table 1 Experiment schedule

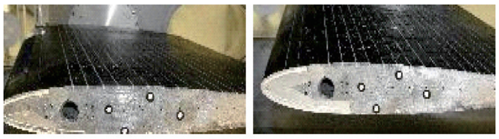
Case	Velocity/(m·s^{-1})	MVD/μm	LWC/(g·m^{-3})	Heating range	Power density/(kW·m^{-2})	Superhydrophobic range
1	90	20	1	*A*, *B*, and *C* strips	5	*A*, *B*, and *C* / None
2	80	15	0.7	*A*, *B*, and *C* strips	5	*A*, *B*, and *C* / None
3	90	40	1.3	*A*, *B*, and *C* strips	5	*A*, *B*, and *C* / None
4	90	20	1	*A*, *B*, and *C* strips	10	None
5	90	20	1	*A* strip	20	*A*, *B*, and *C*
6	90	20	1	*A*, *B*, *C*, *D*, and *E* strips	Adjustment	*A*, *B*, *C*, *D*, and *E*
7	90	20	1	*A*, *B*, *C*, *D*, and *E* strips	10	*D* and *E*

Note: Other parameters remain unchanged, that is, the angle of attack is 0°, the static temperature is −7 ℃, and the anti-icing time is 3 min. MVD denotes the mean volumetric diameter and LWC the liquid water content.

3 Results and Analysis

3.1 Analysis of dry anti-icing effect

The anti-icing effects of the low-energy dry anti-icing method and the traditional thermal protection method were compared and tested under different combinations of MVD and LWC in the three states of Cases 1, 2, and 3. The comparison results are shown in Fig.8. The results show that under the same protection power, the traditional thermal protection system can only achieve anti-icing effect at the leading edge, but cannot inhibit the emergence of runback ice. In contrast, the new anti-icing method based on superhydrophobic materials can significantly inhibit the emergence of runback ice and achieve the dry anti-icing effect.


(a) Case 1


(b) Case 2

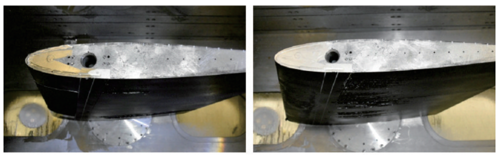
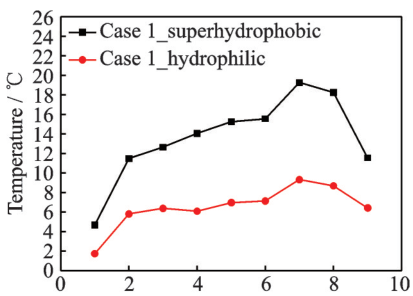
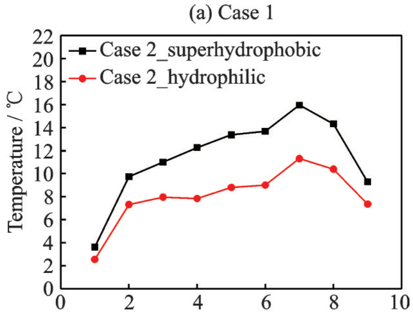

(c) Case 3

Fig.8 Comparison of protection effects

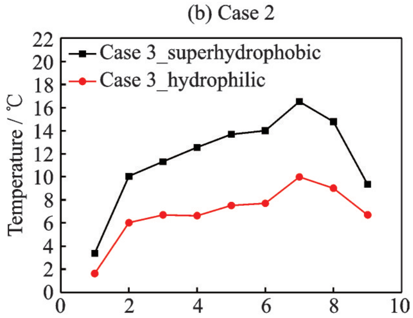
According to the surface temperature results under the three states shown in Fig.9, under the same heating power, the surface temperature of the



(a) Case 1



(b) Case 2



(c) Case 3

Fig.9 Surface temperature comparison of the low-energy dry anti-icing method and the traditional thermal protection method

anti-icing method with superhydrophobic materials is higher, indicating that the energy demand for maintaining the surface water in a liquid state is lower, which is consistent with the analysis of the aforementioned low-energy consumption realization principle.

3.2 Analysis of energy consumption reduction effect

The protection power of the traditional thermal protection method is doubled in Case 4, and the power density reaches 10 kW/m^2, which is used to quantitatively analyze the energy consumption reduction effect of low-energy dry anti-icing technology. The experiment results show that after increasing the protection power, it still cannot suppress the emergence of runback ice, as shown in Fig.10. When the superhydrophobic material is pasted in the corresponding Case 1 state, only power density of 5 kW/m^2 power is needed to achieve the effect of suppressing runback ice, and it can be seen that the required power density is significantly reduced.

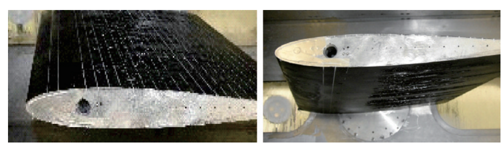


Fig.10 Protection effects of Case 4

From the comparison of the surface temperature between the two cases shown in Fig.11, the increase of the power in the Case 4 leads to an increase of the surface temperature, but it cannot prevent the emergence of runback ice, indicating that the influence of temperature is not the most important factor of low-energy dry anti-icing. The method

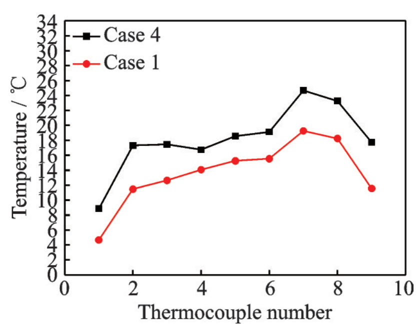


Fig.11 Surface temperature comparison between Case 1 and Case 4

proposed in this paper can promote the surface water to fall off at a lower temperature and achieve better protection effect.

3.3 Analysis of influence of superhydrophobic material protection range on anti-icing effect

It is of great significance to the anti-icing of the aircraft. In the case of the excellent anti-icing effect in Case 1, the total power is reduced by reducing the internal heating range as far as possible. In Case 5, while keeping the arrangement of the superhydrophobic material on the outer surface unchanged in the A, B, and C ranges, the internal heating range is reduced, and only the A heating strip is turned on for heating, the power is greatly increased to 150 W (power density 20 kW/m^2), which is still less than the total power of three heating strips, A, B, and C, at 5 kW/m^2 power density. The results show that this method cannot achieve the same anti-icing effect, and even the anti-icing of the leading edge cannot be guaranteed, as shown in Fig.12.

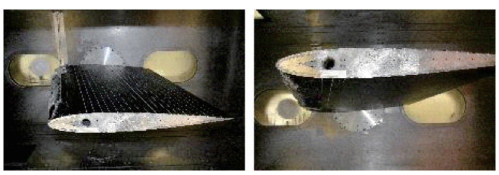


Fig.12 Anti-icing failure in Case 5

Fig.13 shows the temperature comparison between the two heating methods. In terms of temperature, the high power input to the leading edge of Case 5 causes the temperature of the leading edge to be approximately close to the temperature of Case 1, but the temperature at the rear of the leading

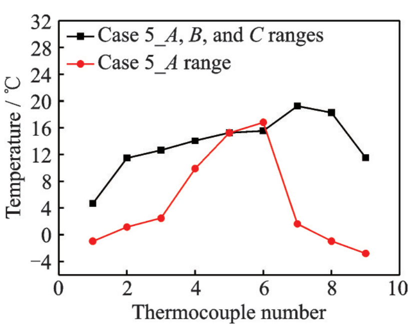


Fig.13 Surface temperature comparison between A, B, and C heating ranges and A heating range

edge decays rapidly, and the temperature of the superhydrophobic surface approaches the freezing point rapidly, and icing occurs. The results showed that the same anti-icing effect could not be achieved by reducing the internal heating area.

In order to test whether the increase of the layout range of superhydrophobic materials is helpful to reduce the total power of internal heating, Case 6 is set up for a power adjustment experiment. The range of superhydrophobic materials is increased to A, B, C, D, and E heating strips and internal heating is provided within the A, B, C, D, and E ranges, and the power is adjusted from high to low, as shown in Table 2. The surface temperature comparison of Case 6 is shown in Fig.14.

Table 2 Anti-icing power adjustment

P_A/W	P_B/W	P_C/W	P_D/W	P_E/W	P_{total}/W	Power density/(kW·m^{-2})	Effect
36	105	255	60	60	516	5	Good
33	95	230	54	54	466	4.5	Good
29	84	204	48	48	413	4	Failure

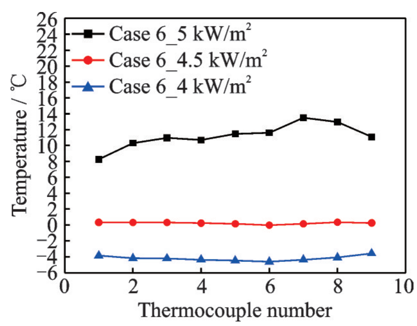


Fig.14 Surface temperature comparison of Case 6

The power adjustment results show that, with the same icing environment as Case 1, compared with turning on the A, B, and C three strip protection, with the increase of the internal heating range, the power density can be reduced on the premise of ensuring the anti-icing effect (from 5 kW/m^2 to 4.5 kW/m^2), but the total power increases, increasing the superhydrophobic range and internal heating range cannot achieve the effect of reducing energy consumption. Therefore, it can be seen that under the premise of ensuring that the protection range covers the impact range of water droplets, the total power cannot be reduced by increasing the superhydrophobic material position and the heating range, and reducing the single strip heating power.

In Case 7, the superhydrophobic material is only arranged in the D and E areas after the water dropets reach the limit position (the A, B and C areas are covered with aluminum strips to ensure no step difference), and a high power density of 10 kW/m^2 is provided to ensure that the water droplets in the protection area are in a liquid state. It is used to test whether the water impacting on the surface flies away when it flows through the superhydrophobic area. The test results are shown in Fig.15. The surface temperature comparison between Case 1 and Case 7 is shown in Fig.16. There is no ice in the protected area, but there is runback ice behind the protected area. The result shows that the water collected in the A, B, and C regions does not completely fly off the surface when passing through the D and E regions. Compared with the results of Case 1, when the superhydrophobic material is arranged in the A, B, and C areas, the complete liquid water completely flies out, and there is no runback ice. The comparison of the two test results shows that the arrangement of superhydrophobic materials in the D and E areas has no effect, and the promotion of water shedding by superhydrophobic materials mainly occurs within the impact limit of water droplets.

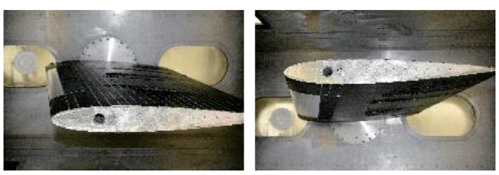


Fig.15 Runback ice in Case 7

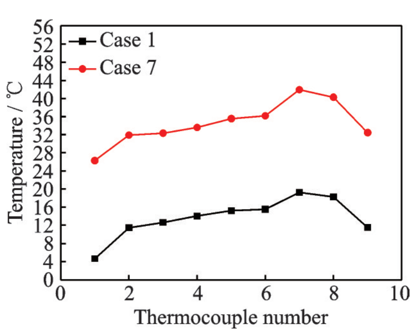


Fig.16 Surface temperature comparison between Case 1 and Case 7

A inspiration given by this result is that the increase of the arrangement range of superhydrophobic materials will not play a beneficial role, as long as it covers the impact limit of water droplets. In practical applications, in order to avoid the impact limit of the involved water droplets being too small, the arrangement range of superhydrophobic materials can be appropriately increased, and a certain safety margin can be reserved, but it is not necessary to increase it in a large scale.

4 Conclusions

A low-energy consumption dry anti-icing technology is developed. Through designing verification tests, the following conclusions are obtained:

(1) The low-energy consumption dry anti-icing technology based on superhydrophobic materials can significantly inhibit the formation of runback ice, and significantly reduce the required power compared with traditional thermal protection methods.

(2) The droplet shedding on the superhydrophobic surface mainly occurs within the range of the water droplet impact limit, and the superhydrophobic material beyond this range does not achieve the shedding effect of runback water.

(3) The layout range of superhydrophobic materials should cover the impact range of water droplet, and a certain safety margin can be properly reserved. It is not necessary to arrange superhydrophobic materials outside this range.

References

[1] THOMAS S K, CASSONI R P, MACARTHUR C D. Aircraft anti-icing and de-icing techniques and modeling[J]. Journal of Aircraft, 1996, 33(5): 841-854.

[2] PAPADAKIS M, WONG S H. Parametric investigation of a bleed air ice protection system AIAA: 2006-1013[R]. [S.l.]: AIAA, 2006.

[3] SANTOS L, DOMINGOS R, MARIA R, et al. Sensitivity analysis of a bleed air anti-ice thermal model to geometrical and operational parameters: AIAA 2008-0445[R]. [S.l.]: AIAA, 2008.

[4] CHANG Shinan, AI Suxiao, HUO Xiheng, et al. Im-

proved simulation of electrotheral de-icing system[J]. Journal of Aerospace Power, 2008, 23(10): 1753-1758. (in Chinese)

[5] ALÈGRE N, HAMMOND D. Experimental setup for the study of runback ice at full scale[J]. Journal of Aircraft, 2011, 48(6): 1978-1983.

[6] GENT R W, FORD J M, MILLER D R. SLD Research in the UK: SAE 2003-01-2128[R]. [S. l.]: SAE, 2003.

[7] POURBAGIAN M, HABASHI W. Power and design optimization of electro-thermal anti-icing systems via FENSAP-ICE: AIAA 2012-2677[R]. [S.l.]: AIAA, 2012.

[8] ZHANG Haixiang, ZHU Dongyu, ZHAO Huanyu, et al. Photothermal anti/de-icing performances of superhydrophobic surfaces with various micropatterns[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2023, 40(2): 137-147.

[9] WANG L, TIAN Z, JIANG G, et al. Spontaneous dewetting transitions of droplets during icing & melting cycle[J]. Nature Communications, 2022, 13(1): 378.

[10] MOGHTADERNEJAD S, TEMBELY M, JADIDI M, et al. Shear driven droplet shedding and coalescence on a superhydrophobic surface[J]. Physics of Fluids, 2015, 27(3): 032106.

[11] KIM M H, KIM H, LEE K S, et al. Frosting characteristics on hydrophobic and superhydrophobic surfaces: A review[J]. Energy Conversion and Management, 2017, 138: 1-11.

[12] KIMURA S, YAMAGISHI Y, SAKABE A, et al. A new surface coating for prevention of icing on airfoils: SAE Technical Paper[R]. [S.l.]: SAE, 2007.

[13] SOMLO B, GUPTA V. A hydrophobic self-assembled monolayer with improved adhesion to aluminum for deicing application[J]. Mechanics of Materials, 2001, 33(8): 471-480.

[14] YIN L, XIA Q, XUE J, et al. In situ investigation of ice formation on surfaces with representative wettability[J]. Applied Surface Science, 2010, 256(22): 6764-6769.

[15] FORTIN G, ADOMOU M, PERRON J. Experimental study of hybrid anti-icing systems combining thermoelectric and hydrophobic coatings: SAE International[R]. [S.l.]: SAE, 2011.

[16] PAN R, ZHANG H, ZHONG M. Triple-scale superhydrophobic surface with excellent anti-icing and icephobic performance via ultrafast laser hybrid fabrication[J]. ACS Applied Materials & Interfaces, 2020, 13(1): 1743-1753.

[17] ZHU Dongyu, PEI Runan, YANG Qiuming, et al. Experimental researches on a hot air anti-icing system in FL-61 icing wind tunnel[J]. Aerodynamic Research & Experiment, 2020, 32(1): 144-150. (in Chinese)

[18] PEI Runan, ZHU Dongyu, SHU Jun. Icing test of characteristic of runback ice accretions on horizontal tail[J]. Journal of Nanjing University of Aeronautics & Astronautics, 2022, 54(6): 1074-1082. (in Chinese)

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超疏水表面抑制溢流冰和降低防冰功率的应用与结冰风洞试验研究

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摘要：为防止溢流冰的生成，在降低能耗的同时实现干态防冰的效果，发展了一种低能耗干态防冰技术。在基于传热原理的防冰设计基础上引入促进水脱落的思想，使撞击在表面的过冷水维持在液态并保持较低的表面温度。利用超疏水表面促进水脱落作为主要防护手段，增大水脱落量的同时减小换热时间，能够降低液态水在防冰表面的溢流，减少表面换热能耗，抑制了溢流冰的生成，实现了良好的防冰效果。结冰风洞试验结果表明，与传统的热防护方法相比，低能耗干态防冰技术能够显著抑制前缘结冰和溢流冰生成，并降低防冰能耗。

关键词：结冰；防冰；超疏水表面；低能耗