REVIEW OF EXPLORATION OF AIRCRAFT DE/ANTI-ICING MECHANISM AND AIRBORNE APPLICATION OF SUPERHYDROPHOBIC MATERIALS

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Abstract

The aircraft surface icing changes the flight dynamics characteristics of the aircraft and seriously threatens flight safety. Therefore, aircraft de/anti-icing technologies are of great significance for safe flight. The basic principle, type, and influence of aircraft icing are analyzed and the existing de/anti-icing technology methods and their advantages and disadvantages are compared. Literature review of superhydrophobic materials was comprehensively conducted, and its specific conditions (superhydrophobic property failure) were analyzed, especially the existing problems and challenges. A hybrid de/anti-icing system was proposed for the defects of a single de/anti-icing system, and several hybrid de/anti-icing systems were introduced and compared with the single de/anti-icing system. In addition, aiming at the possible problems in the application of superhydrophobic materials, an aircraft de/anti-icing system combining loop heat pipe and superhydrophobic materials is presented. Benefiting from the efficient heat transfer mode of the loop heat pipe system and the superhydrophobic effect of the superhydrophobic material, this method can not only reduce the energy consumption of the aircraft's de/anti-icing system, but also reduce the formation of secondary *icing. Finally, the issues of superhydrophobic coating and hybrid de/anti-icing systems are analyzed and prospected.*

Key words: icing mechanism, icing detection, superhydrophobic surface, loop heat pipe, hybrid de/anti-icing system

1. Instructions

Aircraft surface icing has always been one of the main factors threatening flight safety. When flying at a Critical Mach Number, components such as wings, windshields, and engine inlets collide with supercooled water droplets in the atmosphere, resulting in icing [1-2]. Aircraft icing seriously affects flight safety, which destroys the aerodynamic shape of the aircraft surface, increases flight resistance, and reduces the lift coefficient of the aircraft. As we know that aircraft inevitably fly in icing weather, obtaining efficient de/anti-icing technology is urgent and significant to aircraft's flight safety [3]. Aircraft de/anti-icing technology is mainly divided into active de/anti-icing system, passive de/anti-icing system and hybrid de/anti-icing system [4-6]. The traditional de/anti-icing method requires a large amount of external energy, which affects the aerodynamic shape of the aircraft or increases the structural weight to reduce the effective payload. The technology of improving the external surface structure of aircraft seems an effective method for passive de/anti-icing. At present, the use of active and passive hybrid (surface structure material [7] + active de/anti-icing) aircraft de/anti-icing systems is one of the new directions to effectively solve the problem of aircraft icing.

In the actual flight process, according to the different physical processes of icing, the ice types formed on the aircraft skin are not the same, which also causes various degrees of hazards to the aircraft. The aircraft's aerodynamic shape will be destroyed by icing, and the lift and the maximum stall angle of attack are significantly reduced. It will also affect the operability and stability of the aircraft [8]. The icing on the wing skin causes a 34 % increase in stall velocity [9] (the maximum lift can be reduced by 45 %), causing severe flight safety hazards. There are two mechanisms for the formation of ice nucleation[10] at the solid-liquid contact surface: homogeneous nucleation and heterogeneous nucleation. Since the presence of foreign particles usually reduces the free energy barrier of the water-solid matrix interface (or surface), thereby reducing the difficulty of nucleation [11], the presence of foreign particles on the container wall will promote nucleation. Therefore, nucleation that occurs near or on foreign particles is called heterogeneous nucleation. Fig. 1(a) [12] shows the shapes of rime, glaze, and mixed ice.The area of ice nucleation in water droplets and its potential effects are shown in Fig. 1(b) [12].

Aiming at the problems of high energy consumption of de/anti-icing system, the poor effect of inhibiting backflow ice, and limited application of passive anti-icing technology in the field of aircraft de/anti-icing, this paper summarizes and combs various methods and technologies of active aircraft de/anti-icing, and makes a detailed review of the popular superhydrohobic surface anti-icing technology in passive de/anti-icing technology. The novelty of this paper is to propose an active and passive hybrid de/anti-icing system based on the existing de/anti-icing technology to compare and evaluate the advantages and disadvantages of different de/anti-icing technologies, as well as to explore and analyze the applicability of the hybrid de/anti-icing system, which provides a new idea for the development of aircraft de/anti-icing technologies.

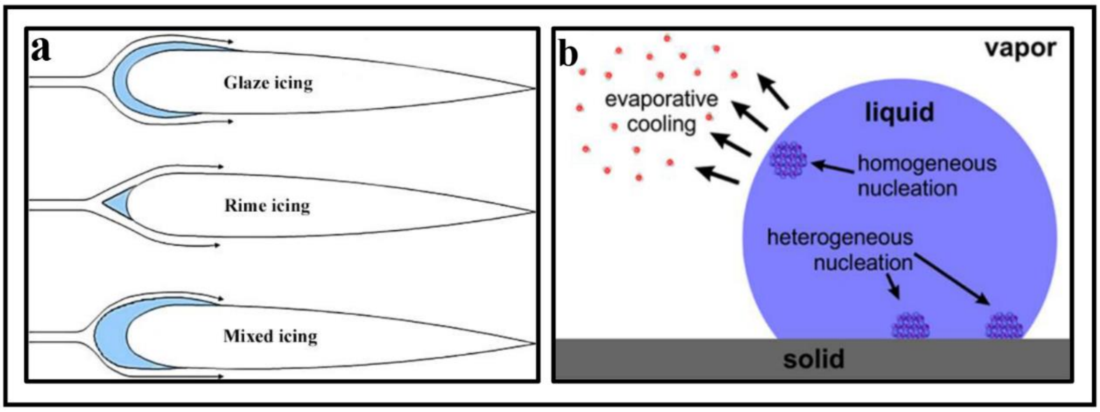


Fig. 1 (a) Three ice shapes on the airfoil [8]; (b) Schematic depicting the regions within a water droplet, where ice can nucleate and potential influences [12].

2. Aircraft surface icing detection

The icing phenomenon has a severe impact on the flight safety of the aircraft. The icing detection technology can help accurately detect the degree of icing, cooperate with airborne de/anti-icing systems, and improve flight safety. Therefore, icing detection technology should be taken into consideration. The icing detector identifies whether it is frozen after data processing of detected icing parameters (meteorological conditions, icing area, icing amount).

Ice detection technologies based on fundamental principles such as optics, thermals, electricity, machinery, and waveguides have been developed based on different technical principles.

2.1. Optical icing detection

Optical icing detection is divided into visual, photographic, infrared energy reflection, and optical fiber methods. The visual method is the most primitive, directly observed and judged by the pilot. Compared with other methods, the optical fiber method is more advanced. The light signal is transmitted from the optical fiber to the aircraft's surface. The light enters the receiving optical fiber after reflection, scattering, and transmission in the ice layer. A series of signal processors at the end of the optical fiber is used to analyze the difference in the reflected light signal, which can detect the ice type and thickness.

Ge[13] proposed and evaluated an ice-type identification and thickness measurement method based on optical fiber sensors. They established finite element models of different structures for several typical ice types and found a cascade model of machine learning algorithms based on icing data to achieve real-time ice shape recognition and thickness measurement. Ikiades[14] proposed using optical fiber arrays to detect the optical diffusion of light in ice to obtain the characteristic light intensity distribution map, which was used as a function to detect the type and thickness of the ice. Zou[15] developed a composite fiber optic sensor consisting of two source and signal fiber bundles. All bundles had inclined fiber end faces, which were not perpendicular to the fiber axis. Optical fiber sensor does not require unique sensitive materials and has the advantages of low energy consumption, lightweight, high detection accuracy, and strong anti-interference ability.

2.2. Electrical icing detection

The icing detectors developed by electrical icing detection technology include capacitance, conductance, and admittance icing sensors. Roy[16] introduced a micro-machined diaphragm as a sensitive element and a portable. capacitance detection circuit for the icing detection system and conducted a series of experiments. They have proved the system's feasibility and could accurately measure the ice layer from 0.5-1.5 mm. Owusu[17] tested an ice sensor based on the principle that ice would cause changes in the capacitance and resistance of the sensing probe. The results showed that the ice type and icing severity can be distinguished according to the resistance. They have established a correlation between capacitance, resistance, wind velocity, and icing rate to add multiple functions to the icing sensor.

2.3. Mechanical icing detection

Mechanical icing detection includes obstacles, pressure difference, and resonance methods. Claffey [18] introduced three kinds of ice detectors manufactured by Rosemount and evaluated the methods of collecting and processing data through these ice detectors. They found that as the ice detector aged, the vibration frequency of the sensor would decrease. As the influence of the increase of the diaphragm stiffness caused by icing was more significant than that of the rise of the diaphragm mass, the resonance frequency in diaphragm would increase.

The flat diaphragm sensor is used to determine whether the aircraft surface is iced and the ice thickness by measuring the resonant frequency of the diaphragm. Thomas[19] made a metal plate compound integrated with a piezoelectric ceramic module. They combined MFC (macro fiber composite) M8528 P1 with a thickness of 0.3 mm in the adhesive layer, which could reduce the influence of external factors on the piezoelectric module. The experiment successfully realized the integrated icing detection and de-icing of materials. Magnetostrictive ice detectors should be extended out of the fuselage surface, which would destroy the aerodynamic shape of the aircraft. However, the flat diaphragm sensor is installed in an embedded way, which does not affect the aerodynamic shape of the aircraft.

3. De/anti-icing of external aircraft surface The main parts of the aircraft that need de/anti-icing include wings, tails, windshields, and engine intakes. According to the operating methods of the de/anti-icing system, aircraft de/anti-icing technology can be divided into mechanical de-icing technology, liquid de/anti-icing technology, and thermal de/anti-icing technology.

3.1. Engine air bleed de/anti-icing

Engine bleed air de/anti-icing is the most widely used and reliable de/anti-icing method[20]. This technology achieves the purpose of de/anti-icing by heating the aircraft skin with high-temperature air (mainly from the low-pressure section or high-pressure section of the engine compressor). Cavity thermal impact heat conduction de/anti-icing technology is widely used. In the air bleed de/anti-icing process, after entering the engine compressor, the air is injected into the inner surface skin through the pipe after adjusting the temperature and pressure. The heat conduction between the air in the pipe and the external surface skin increases the temperature of the external surface skin to achieve the purpose of de/anti-icing. This technology is mainly used in wings, engine inlets, and other parts.

3.2. Electro-pulse De-icing

The fundamental principle of the electromagnetic pulse is to discharge the capacitor bank
to the coil. After the coil is energized, a strong magnetic field is generated, which causes the aircraft components (such as the skin) to generate a high amplitude and short-duration electromagnetic force. After the skin is stressed, it vibrates rapidly, causing the ice layer to fall off or break from the skin [21].

3.3. Dielectric Barrier Discharges plasma de/anti-icing

Dielectric barrier discharge (DBD) is a typical plasma active flow control method. According to the waveform of excitation voltage, it is divided into AC-DBD, NS-DBD, RF-DBD and so on [22]. When a high AC voltage is applied to the electrode, the air on the packaged electrode will be ionized, and a plasma flow will be generated. The plasma will heat the ambient air on the packaged electrode during this process. Therefore, the DBD de/anti-icing system can heat the gas layer on the wing surface to achieve de/anti-icing. Liu [23] compared the DBD plasma de/anti-icing method with the electric heating de/anti-icing method, and found that under the same power input, the effect of DBD plasma on wing de/anti-icing was comparable to that of traditional electro-thermal under extreme conditions. Therefore, DBD plasma has excellent potential in de/anti-icing applications. How to optimize the DBD plasma actuator and further enhance the de/anti-icing effect needs to be further studied[24].

3.4. Electro-thermal de/anti-icing technology

Electric heating de/anti-icing technology is a technology that converts electrical energy into thermal energy[25]. The electro-thermal de/anti-icing system comprises a power supply, selection switch, overheating protection device, and heating element. The heating methods of electro-thermal de/anti-icing technology include continuous heating and periodic heating. If the de/anti-icing system on the aircraft applies continuous de/anti-icing technology, it will consume a lot of electric energy. Therefore, periodic intermittent heating technology is generally applied. The system periodically provides electrical power to make the ice on the outer surface of the wing melt, break and then taken away by the airflow. The composite film heater has the advantages of sensitive electro-thermal response, low energy consumption, and being lightweight. It has become a research hotspot in the electro-thermal de/anti-icing field.

3.5. Loop heat pipe de/anti-icing technology

Loop heat pipe de/anti-icing system (LHP) is an integrated thermal management technology[26]. It uses the vapor-liquid phase change of the working fluid to transfer heat and the pore core's capillary force to circulate the working fluid without additional power consumption. Compared with the traditional de/anti-icing system, it has significant energy-saving efficiency. Due to its high heat transfer capacity, long transmission distance, flexible design, and installation, it has been widely used in the thermal management of space equipment.

3.6. Comparison of advantages and disadvantages of de/anti-icing systems

The advantages, disadvantages, and applications of the above aircraft de/anti-icing systems are compared in Tab. 1 [27-34]:

Tab. 1 Advantages and disadvantages of de/anti-icing systems

de/anti-icing technologies	Advantages	Disadvantages	Applications
Engine bleed air [27]	easy-maintenance, reliable operation	large thermal inertia, reduced engine thrust, excessive bleed air may cause serious flight accidents	wings, engine inlet
Electro-pulse [28]	lightweight, low energy consumption	vulnerable to electromagnetic interference, materials easily fatigued	helicopters, transport aircraft, UAV
Dielectric Barrier Discharges plasma [29]	fast response, lightweight, be used in high G-Load	electric magnetic radiation, high voltage power supply, heavyweight	no application
Ultrasonic [30]	lightweight, low energy consumption	materials aging	no application
Electro-thermal [31]	good efficiency	higher energy consumption, not suiTab. for materials with poor thermal conductivity	Boeing 787
The loop heat pipe [32]	can use aircraft waste heat, low energy consumption	need to choose the appropriate fluid, and for high G-Load, the reliability of capillary force needs to be verified.	Global hawk, satellites
Liquid [33]	good efficiency	large consumption of antifreeze, environmental pollution	mainly used for ground aircraft de-icing before takeoff.

Expansion boot [34]	a mature technology	influence the aerodynamic shape, need regular maintenance	medium passenger aircraft

4. Aircraft outer surface structure with superhydrophobic materials

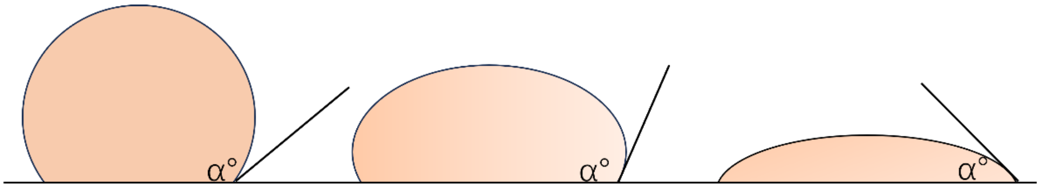
In nature, lotus leaves and Nepenthes show strong hydrophobicity. W. Barthlott [35] demonstrated for the first time that surface roughness, minor particle adhesion, and hydrophobicity are the key to surface self-cleaning. The classical wetting models of superhydrophobic coatings are Young's equation, the Wenzel model, and the Cassie-Baxter model, respectively.

4.1. Wetting model

When the liquid contacts the solid surface, the liquid will expand outward along the solid surface. The solid-liquid interface will replace the original solid-gas interface and liquid-gas interface, which is called wetting [36]. The angle formed between the liquid and the solid surface is the contact angle, which is one of the essential characteristic parameters to indicate the wettability of the solid surface. According to the size of the contact angle θ, the surface wettability can be divided into hydrophilicity（$\theta < 90°$）, hydrophobicity（$\theta > 90°$）, and superhydrophobicity（$\theta > 150°$）[37]. The diagram is shown in Fig. 2.

Young [38] proposed Young’s equation by studying the wetting model. Young’s equation reveals the relationship between contact angle and surface tension. Eq. (1) is the relationship between contact angle and surface tension:

Young’s equation is an ideal equation only applicable to inelastic, smooth, and chemically uniform surfaces. It cannot explain the wetting mechanism under current conditions. The model represented by Young’s equation is shown in Fig. 3 [39] (c).



(a) super-hydrophobicity (b) hydrophobicity (c) hydrophobicity

Fig. 2 Schematic diagram of surface wettability

$$\gamma_{LA} \cdot cos\theta_Y = \gamma_{SA} - \gamma_{SL} \tag{1}$$

In the Eq. (1): $\gamma_{SA}$is the surface tension of the solid-gas interface(mN/m), γ_{SL} is the surface tension of the solid-liquid interface(mN-m), γ_{LA} is the surface tension of the liquid-gas interface(mN/m), $\theta_Y$is the droplet contact angle in the equilibrium state.

Wenzel [40] improved Young’s equation by proposing the concept of surface roughness, explaining the relationship between surface roughness and droplet contact angle. The Eq. (2) has been expressed as follows.

$$cos\theta_w = \gamma \frac{\gamma_{SA}-\gamma_{SL}}{\gamma_{LA}} = \gamma \cos\theta_Y \quad (2)$$

In the Eq. (2): $\theta_W$is the Wenzel contact angle(°), $\theta_Y$is the droplet contact angle in the equilibrium state(°), γ is the surface roughness factor(mN-m).

The Wenzel equation characterizes the ratio of the actual solid-liquid contact area to the solid-liquid projected contact area, and the model represented is shown in Fig.3(b)[40]. According to the Wenzel equation, the object's surface will be more hydrophobic as the roughness (surface roughness factor) increases. However, on the hydrophilic surface, the opposite effect will be shown (the surface will be more hydrophilic and the contact angle will be smaller). On this basis, Cassie and Baxter [41] further developed the Cassie-Baxter equation in 1944:

$$cos\theta_{CB} = f_1 cos\theta_1 + f_2 cos\theta_2 \quad (3)$$

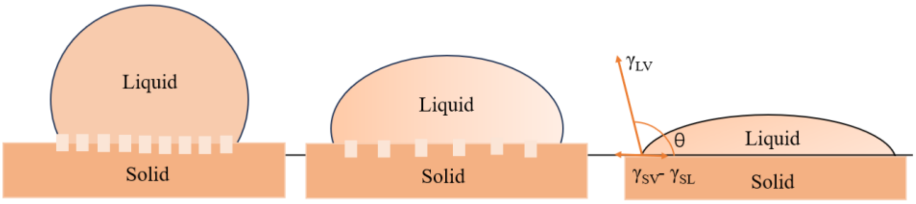
In the Eq. (3): θ_{CB} characterized the apparent contact angle in the Cassie-Baxter state(°). $\theta_1$and θ_2 are the contact angles of droplets on the first and second interface, respectively. F_1、$f_2$are the proportion of the solid-liquid interface and gas-liquid interface to the apparent contact area, and $f_1 + f_2 = 1$.

The Cassie-Baxter model is shown in Fig. 3(a) [41]. The Eq. (3) can be used to characterize the non-uniform wetting model. The smaller the f_1, the larger the apparent contact angle and the better the surface hydrophobicity.

Static hydrophobicity and dynamic hydrophobicity are the keys to accurately describing superhydrophobic surfaces. Generally speaking, the static contact angle is the main feature of static hydrophobicity, and rolling angle and contact angle hysteresis are the main characteristics of dynamic hydrophobicity. The rolling angle (α) refers to the minimum inclination angle when the droplet rolls off the solid surface. If the solid surface is tilted at a rolling angle α, the water droplets will slide down. $\theta_\alpha$is defined as an advanced contact angle, θ_γ is defined as a receding contact angle, and the difference between θ_α and $\theta_\gamma$is defined as contact angle hysteresis [42]. In 1962, Furmidge [43] proposed the relationship between rolling angle and contact angle hysteresis：

$$\mathrm{mg}\sin \mathrm{a} = \omega\gamma^{1\alpha}(\cos\theta_\gamma - \cos\theta_\alpha) \quad (4)$$

In the formula **Error! Reference source not found.**: m is the quality of the droplets(kg). g is the acceleration of gravity(N/kg). ω is the width of the wet area(m). $\gamma^{1\alpha}$is the tension or free energy of the liquid-gas interface(mN/m). θ_α is defined as an advanced contact angle(°). θ_γ is defined as a receding contact angle(°). It can be seen from this formula that the smaller the contact angle hysteresis, the smaller the corresponding rolling angle.



(a) Cassie-Baxter Model (b) Wenzel Model (c) Young's Model

Fig. 3 Schematic illustration of theoretical wetting models

In summary, Young's equation is ideal to only apply to inelastic, smooth, and chemically uniform surfaces. The Wenzel model is suiTab. for the uniform area where there is no air at the interface between the solid surface and droplets and cannot be applied to the uneven wetting state.

4.2. Anti-icing mechanism of superhydrophobic materials

Superhydrophobic materials are considered as a prospective of anti-icing technology. It does not require energy consumption, and the superhydrophobic coating can be manufactured in artificiality [44]. The superhydrophobic material retains air in the nano-surface (texture), which minimizes the contact area between solid and liquid. This nano-surface (texture) has some crucial anti-icing properties, which can effectively reduce the heat transfer coefficient and the heterogeneous nucleation sites [45]. This surface can effectively form a thermal barrier (the thermal conductivity of air is less than that of water droplets) to reduce the heat transfer in the icing stage. Similarly, the heterogeneous nucleation sites of ice can be reduced by applying this surface to lower the possibility of heterogeneous nucleation. If the droplet only contacts part of the surface, the adhesion between the ice and the surface will be impaired. This condition is similar to the Cassie-Baxter model of water droplets on rough surfaces [46]. If the solid-air composite surface is wholly wetted, the surface state changes from the Cassie-Baxter state to the Wenzel state, and the superhydrophobicity is invalidity.

During the flight, supercooled water droplets impact the aircraft's surface at high velocity and easily penetrate the interface of the superhydrophobic material (from the Cassie-Baster state to the Wenzel state), resulting in the superhydrophobic material being completely wet. In the Wenzel state, supercooled water droplets penetrate the texture of the superhydrophobic material, and it is easy to freeze after contact with the surface due to the increased thermal conductivity. Increased ice adhesion strength [47] leads to the difficulty of removing ice deposits on the surface. In summary, the superhydrophobic material may even enhance the icing phenomenon when the supercooled water droplets impact the wing surface at high velocity in the flight icing area. Therefore, many researchers have started to study composite superhydrophobic materials with specific characteristics (such as the photothermal effect) or coupling superhydrophobic passive anti-icing with active de/anti-icing systems.

5. Hybrid de/anti-icing technology

The results of icing experiments in the wind tunnel technology show [48] that it is difficult to ensure the reliability of the de/anti-icing of aircraft in flight only using superhydrophobic surfaces under the high-velocity impact of supercooled water droplets. When the droplets are immersed in the surface texture, the liquid icing increases the ice adhesion force on the superhydrophobic surface. Adhesion emerges between the ice layer and the superhydrophobic surface, leading to the challenge of removing the icing. Therefore, the active de/anti-icing method is still needed to ensure the de/anti-icing reliability of the aircraft in flight. Based on the new active de/anti-icing method, bio-inspired anti-icing surfaces to achieve anti-icing and energy saving have become a significant development trend of bio-inspired anti-icing surfaces for flight environments [49].

5.1. Superhydrophobic surface + electro-thermal de/anti-icing system

The anti-icing effect of the superhydrophobic surface is not ideal under certain conditions.

During the flight, many supercooled water droplets impact the aircraft's surface and condense in the pores of the superhydrophobic material. The supercooled water droplets nucleate, grow in relatively large rough pores, and increase the adhesion force. Once the supercooled droplets freeze on the superhydrophobic surface, it will be difficult to remove the ice. Therefore, it is better to add some active de/anti-icing techniques to assist when using superhydrophobic coatings in de/anti-icing.

The active electro-thermal de/anti-icing system is a de/anti-icing technology that converts electric energy into heat energy. Compared with the engine bleed air system, it shows a shorter response time and a higher efficiency. However, its high energy consumption causes a giant load on the aircraft.

Superhydrophobic surface+electro-thermal de/anti-icing system can effectively reduce aircraft energy consumption. The adhesion between the liquid and the superhydrophobic surface is low, and most liquid water/ice rolls off the surface after heating with the electro-thermal de/anti-icing system. C. Antonini [50] conducted experiments in an open-loop icing wind tunnel (IWT) using NACA0021 standard airfoil under two icing conditions: freezing rain and supercooled droplets with a diameter of 50μm. The experimental results showed that if the whole wing was not iced (Run-back Ice is not allowed), the thermal power required for the wing with the superhydrophobic coating was 33 W. The thermal energy required for the wing without superhydrophobic coating was 171 W. It was concluded that coupling systems in this experiment could save about 80 % of the thermal power. Many research experiments showed that the combination of active de/anti-icing technology and a passive de/anti-icing method could improve the de/anti-icing effect and reduce the energy consumption of de/anti-icing. The de/anti-icing technology not only enhanced the stability of the de/anti-icing system but also replaced the traditional electro-thermal resistance with a material with a large conductivity, which reduces the weight of the de/anti-icing system and increases the aircraft's payload.

5.2. Engine bleed air + de-icing fluid system

The engine bleeds air de/anti-icing system has an excellent effect but consumes more energy than mechanical de-icing systems. If the engine glass volume is too large, it often causes the aircraft engine to be underpowered, and the droplets flow to the wing after de-icing to form glazed ice again. The glazed ice accumulates behind the wing surface to create an ice ridge. The large angularity of the ice ridge will increase the surface roughness of the wing. The influence of the ice ridge on the aerodynamic characteristics is often more significant than that of the rime ice [51].

The fluid de-icing system has little effect on the aerodynamic performance of the wing surface [52] and does not cause the engine power to be insufficient. However, the load of de-icing fluid is limited, and the load of de-icing fluid reduces the effective load of the aircraft. The hybrid system consumes less energy than single de/anti-icing systems. It ensures that no ice ridge is formed behind the wing surface, increasing the de/anti-icing system's stability in the icing environment.

5.3. Electro-thermal + electric pulse de/anti-icing system

Electro-thermal + electric pulse de/anti-icing technology is a sTab. and efficient method that combines electro-thermal de-icing technology with electric pulse technology. The electric heater and electromagnetic pulse exciter are installed on the wing surface with a small gap between the pulse exciter and the skin. When the wing freezes, the electro-thermal system opens and melts the ice layer in contact with the wing skin. After reducing the adhesion force between the ice layer and the wing skin, the electric pulse de-icing system is opened to remove the thin ice of the wing skin by vibration. Compared with the electro-thermal system and the electric pulse de/anti-icing technology, this hybrid technology can effectively reduce the energy consumption of the aircraft during the de-icing process and reduce the fatigue damage caused by excessive excitation of the aircraft surface [53].

5.4. Superhydrophobic surface + loop heat pipe de/anti-icing system

The loop heat pipe system utilizes the gas-liquid phase change of the working fluid to achieve efficient heat transfer and drives the circulating flow of the working liquid through the capillary action of the heat pipe core. By coupling the loop heat pipe technology with the aircraft thermal management system, the aircraft waste heat can be used as the heat source of the loop heat pipe system to reduce the system's energy consumption. Therefore, a superhydrophobic surface + loop heat pipe de/anti-icing system is proposed. Superhydrophobic surface + loop heat pipe de/anti-icing technology utilizes the superhydrophobic characteristics of the surface to make the supercooled droplets that hit the wing during flight roll-off so that the supercooled droplets are unable to form ice crystals on the wing surface. At the same time, combined with the efficient heat transfer of the loop heat pipe technology, the de/anti-icing effect can be maintained when the superhydrophobic surface fails. In this way, the waste heat of the aircraft is utilized efficiently, which solves the problem of enormous energy consumption of the aircraft's de/anti-icing systems.

5.5. Comparison of hybrid de/anti-icing systems

It can be seen from the above that the hybrid de/anti-icing system can effectively improve the de-icing effect and reduce energy consumption, and reduce the shortcomings of a single de/anti-icing system. The specific comparison is shown in Tab. 2.

The superhydrophobic surface + electro-thermal de/anti-icing system maintains the superhydrophobic surface above the freezing point by electric heating. The system utilizes the unique wetting characteristics of the superhydrophobic surface to roll down the supercooled water droplets that impact the wing during flight, saving evaporation energy consumption. In this way, the surface temperature of the wing was generally maintained at 5-10℃, and the energy consumption was reduced by 80 % compared with the general electric-thermal system[50]. Therefore, the system is suiTab. for power-constrained aircraft such as drones.

Tab. 2 Comparison between compound anti-icing technology and single technology

hybrid de/anti-icing technologies		Disadvantages	Advantages after composite
Superhydrophobic surface + electro-thermal	Superhydrophobic surface	If encountering high-speed supercooled large droplets, the surface pores will be frozen, resulting in superhydrophobic surface failure.	When the coating fails, the electro-thermal de/anti-icing system can be started to melt the ice so that the electro-thermal system can be closed for saving energy consumption after the coating effect is restored.
	electro-thermal	The electro-thermal de/anti-icing system has large quality and energy consumption.	
Engine bleed air + de-icing fluid	Engine bleed air	Excessive bleed air will cause the aircraft engine power shortage, resulting in aircraft stalls.	Equipped with de-icing fluid can effectively prevent the formation of ice ridges and reduce the engine bleed air.
	de-icing fluid	Reduce the effective load of the aircraft	
Electro-thermal + electric pulse	electro-thermal	The electro-thermal de/anti-icing system has large quality and energy consumption.	Too much use of an electric pulse de/anti-icing system will lead to material fatigue damage to the aircraft's skin. The system first uses electric heating to melt ice and then uses an
	electric pulse	Fatigue damage of aircraft skin	

			electric pulse system to stimulate de/anti-icing to improve the de/anti-icing effect.
Superhydrophobic surface + loop heat pipe	Superhydrophobic surface	If encountering high-speed supercooled large droplets, the surface pores will be frozen, resulting in superhydrophobic surface failure.	Using the surface superhydrophobic properties to bounce off the supercooled droplets that impact the wing to save energy ; combined with the loop heat pipe technology, the de/anti-icing effect can be maintained when the superhydrophobic surface fails.
	loop heat pipe	need to choose the appropriate fluid, and for high G-Load, the reliability of capillary force needs to be verified.	

The engine bleed air + de-icing fluid system uses engine bleed air to heat the aircraft skin to achieve a de/anti-icing effect, but insufficient engine bleeds air power will form run-back ice. Therefore, the de-icing liquid is supplemented to eliminate the run-back ice to improve the de-icing effect. This method is suiTab. for large aircraft such as transport aircraft.

The thermal-mechanical coupling de-icing of the Electro-thermal + electric pulse first uses electric heating to melt the underlying ice intermittently and then vibrates the aircraft skin by the electric pulse to break and separate the surface ice. This method is suiTab. for helicopters. During the electric heating process, part of the icing will fall off from the rotor due to aerodynamic and centrifugal forces, which will cause periodic oscillation of engine parameters [54]. Based on this, the electric pulse de-icing system is used to break the ice on the helicopter rotor and reduce the ice shedding due to aerodynamic and centrifugal forces.

The superhydrophobic surface + loop heat pipe de/anti-icing system heats the aircraft skin through the loop heat pipe to melt the ice. It rolls down the supercooled water droplets that hit the wing surface through the superhydrophobic surface characteristics. This system is suiTab. for future-oriented electric aircraft. The electric aircraft power system not only inevitably produces waste heat during operation but also needs to ensure that the superconducting motor is in a low-temperature environment. Therefore, an efficient thermal management system is needed to ensure the normal operation of the aircraft power system. Benefiting from the efficient heat transfer mode of the loop heat pipe system, a large amount of waste heat generated by the aircraft power system can be used for the de/anti-icing of the wing surface.

6. Conclusions

In this paper, the icing mechanism is analyzed first. On this basis, the mainstream de/anti-icing methods are compared. The analysis shows that hybrid anti-icing systems are one of the trends in aircraft anti-icing systems. Given the advantages of superhydrophobic surface anti-icing mechanism and hybrid system applicability, the conclusions are summarized as follows:

1. Most aircraft icing is heterogeneous nucleation caused by the significant reduction of nucleation barrier between microparticles and solid matrix, which is significantly affected by the distribution of microparticles on the surface, the contact area between the interface and water droplets, and the solid matrix.

2. From the perspective of influence on aerodynamic shape, the expansion boot de-icing technology inevitably has the most significant impact on the aerodynamic shape. From the flight safety perspective, compared with the electro-thermal system, the engine bleed air de/anti-icing system reduces the engine's available power and affects flight safety. From the energy point of view, the energy consumption of electric heating de/anti-icing is high, and the quality of de-icing liquid is large, which affects the effective load of aircraft and pollutes the environment by using a large amount of de-icing liquid. It may be unable to balance aircraft energy efficiency (electric energy, engine bleed air, fuel temperature) in extreme flight conditions with traditional de/anti-icing technology.

3. Most anti-icing theories for superhydrophobic surfaces are based on Gibbs's classical nucleation theory. Generally based on the following three directions: The superhydrophobic coating reduces the surface microparticles and makes them homogeneous nucleation to reduce the probability of icing. The low rolling angle and high contact angle of the superhydrophobic surface are used to remove the droplets before they freeze.

4. The efficient heat transfer of the loop heat pipe system [55] makes it possible to couple the aircraft thermal management system with the de/anti-icing system. In addition, the special wettability of the superhydrophobic surface can not only make the supercooled water droplets roll off the surface of the wing but also reduce the formation of run-back ice. Therefore, an aircraft de/anti-icing system with superhydrophobic material passive de/anti-icing and loop heat pipe active de/anti-icing is proposed. The superhydrophobic surface + loop heat pipe de/anti-icing system has strong adaptability in both current fuel aircraft and future electric aircraft.

Based on the airborne application of the hybrid de/anti-icing system, the following problems need to be solved:

1. Superhydrophobic surfaces are applied to the airborne de/anti-icing system. In high-velocity flight, the surface of the aircraft skin will be impacted by supercooled water droplets, the leading edge coating of the wing will be lost, and wettability will be destroyed. The specific performance is that the contact angle decreases, and the rolling angle increases significantly [56]. The loss factors of superhydrophobic coatings in typical flight icing conditions (high speed, low temperature, and high humidity) were investigated. The preparation methods and durability of superhydrophobic surfaces were evaluated, and superhydrophobic materials for airborne de/anti-icing applications were developed.

2. When the loop heat pipe, airborne application is usually due to high G-Load and direction changes, resulting in a decrease in the working fluid returning to the evaporator and may even dry the heat pipe core. Therefore, it is necessary to explore the ultimate performance of heat and mass transfer of the loop heat pipe (high G-Load, AOA angle) and use DCCLHP to enhance the environmental adaptability of the system further. In addition, a suiTab. and sTab. heat source based on the complete thermal management system of the aircraft should be studied to match the physical properties of the working liquid in the heat pipe.

3. Position arrangement and design optimization of hybrid de/anti-icing system. The combination of de/anti-icing technologies can significantly improve the de/anti-icing effect of the system. However, some problems the composite technology brings (economic durability, stability, compatibility between technologies, and matching with aircraft structure) need to be carefully studied and optimized.

4. Under typical flight icing conditions (high-velocity, low temperature, high humidity), the mismatch between the material structure size of the superhydrophobic surface and the ice crystal forming size may lead to the failure or opposite effect of the superhydrophobic surface. Therefore, the correlation between the material structure size of the superhydrophobic surface and the ice crystal forming size should be studied to determine the corresponding material structure size suiTab. for anti-icing.

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Data availability statement

The data that support the findings of this study are available from [third party]. Restrictions apply to the availability of these data, which were used under license for this study. Data are available [from the authors / at URL] with the permission of [third party].

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