An Experimental Investigation on the Unsteady Heat Transfer Process over Ice Accreting Surfaces of Aero-engine Spinner Models

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The heat transfer process in an aero-engine icing event is highly dependent on the oncoming flow conditions and local impingement status. In the present study, an experimental study was conducted to investigate the transient heat transfer during the ice accretion process over three typical types of rotating aero-engine spinners (i.e., conical, conicalonal, and elliptical). The experiment study was performed in the Iowa State University Icing Research Tunnel (ISU-IRT) with a scaled aero-engine fan model operated under various icing conditions. The details in the unsteady heat transfer process were resolved using an infrared thermal imaging system. The time-evolutions of the surface temperature at different monitoring points were recorded and illustrated. Based on a simplified heat balance model, the dynamic processes of the latent heat release during liquid-solid phase change and its competing effects with convective/conductive heat transfer were evaluated in accordance with the surface temperature variation. The experiments demonstrated the effects of the spinner profiles on the unsteady local heat transfer process. It was found that the conical-shaped spinner would have more uniform ice accretion as indicated by the equivalent temperature distribution, while the conical and elliptical spinners displayed obvious temperature gradient along the surface during the icing processes. The dynamic heat transfer stages of the different icing processes (i.e., glaze and rime) are also elucidated in details.

Nomenclature

\( AT \) = temperature variation, \(^{\circ}{\text{C}}\)

\( A_{\text{volume}} \) = control volume surface area, \( m^2 \)

\( D_s \) = spinner diameter, \( mm \)

\( h_{cv} \) = convective heat transfer coefficient, \( W/(m^2 \cdot K) \)

\( h_{cd} \) = conductive heat transfer coefficient, \( W/(m^2 \cdot K) \)

\( L_s \) = solidification latent heat, \( J/(kg \cdot K) \)

\( LWC \) = liquid water content, \( g/m^3 \)

\( MVD \) = mean volume diameter, \( \mu m \)

\( m_{\text{freeze}} \) = freezing water mass of unit time, \( kg/s \)

\( Q_{\text{adi}} \) = adiabatic heating, \( W \)

\( Q_{\text{eva/sub}} \) = evaporation and sublimation heat, \( W \)

\( Q_{\text{in}} \) = input heat, \( W \)

\( Q_{\text{kin}} \) = kinetic heating, \( W \)

\( Q_{\text{latent}} \) = latent heat of fusion, \( W \)

\( Q_{\text{out}} \) = output heat, \( W \)

\( Q_{\text{rad}} \) = radiation, \( W \)

\( R_o \) = rotation speed, \( rpm \)

\( t \) = time, \( s \)

\( T_o \) = freestream temperature, \( ^{\circ}{\text{C}} \)

\( T_w \) = water/ice surface temperature, \( ^{\circ}{\text{C}} \)

\( T_{\text{spinner}} \) = spinner surface temperature, \( ^{\circ}{\text{C}} \)

\( U_o \) = freestream velocity, \( m/s \)

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I. Introduction

Aero-engine icing is a common safety hazard for aircraft operation in cold weather. When aircraft flies in a cold and humid cloud, the super-cooled water droplets suspending in the cloud would impinge and freeze on the exposed surfaces of aero-engines, such as inlet lips, spinners and fan rotor blades. Even the ice shedding from these surfaces could be sucked into the core engine and cause power-loss events, i.e., stall, flameout or roll back [1]. A statistic indicates that there have been over 240 icing related events listed since 1990s [2]. Ice accretion on the inlet lips, spinners and fan rotor blades of aero-engines can not only degrade the aerodynamic efficiency of aero-engines, but also cause imbalance of the rotor rotation, which may result in serious mechanical vibrations that can damage the components of aero-engines. Although some anti-/de-icing measures have been developed to ensure safer operations of aero-engines in hazardous conditions [3-5], it should be noted that the extra consumption of hot air/liquid from the compressor or electricity power to heat up the icing/iced surfaces could cause significant engine-performance penalties. Moreover, according to the airworthiness certification standard, each engine with an icing protection system must satisfy the strict icing operational requirements stated in CFR Part 33 Section 33.68 and 33.77 [6,7]. Advancing the technology for safer and more efficient operations of aero-engines in atmospheric icing conditions requires a deeper understanding of the dynamic ice accretion process to develop more innovative, effective anti-/de-icing strategies tailored for aero-engine icing mitigation and protection.

During the ice accretion process, one essential part is to understand the heat balance. Many heat transfer models of the airfoil icing have been widely developed. Messinger [8] first analyzed the temperature change of an unheated surface like airfoils under different icing conditions. Based on Messinger’s model, Myers [9] developed a one-dimensional mathematical model to describe the icing event on the solid substrate impinged by super-cooled water droplets. This model is extended to two and three dimensions’ application, which improved the capability of ice modeling for both rime ice and glaze ice accretion. Fortin et al. [10] built up a thermodynamic model used in the numerical simulation of ice accretion over a NACA0012 airfoil surface, which can be used to evaluated the water mass rate, ice roughness height and convective heat transfer coefficient. These studies have provided a good insight into the heat transfer process during ice accretion over airfoil surface, but few studies addressed the heat transfer process on the rotating aero-engine fan.

Compared with other aero-engine components, the spinner is more sensitive to ice accretion due to its relatively lower spinning velocity and larger impinging area for the super-cooled water droplets. Some studies were conducted to investigate the heat and mass transfer process during icing processes on aero-engine spinners. Dong et al. [11] introduced a model of heat and mass balance to study the water run back on the rotating cone by numerical simulation. It correlates the mass transfer and heat transfer processes in order to calculate the accreted ice height and predict ice shape. Dong and Zhu et al. [12,13] conducted both numerical and experimental studies to evaluate a newly-developed hot-air anti-icing system applied to a full-scale nonrotating cone model. The surface temperature distribution under different icing conditions were measured by thermocouples and simulated by a conjugate heat transfer computation. However, few dynamic heat transfer details were discussed in these studies.

In the present study, a comprehensive experimental investigation was conducted to characterize the unsteady heat transfer process over three kinds of typical aero-engine spinner models with elliptical, conical and conical shapes. The experimental study was performed in an icing research tunnel available at Iowa State University (i.e., ISU-IRT in short) with a scaled aero-engine fan model operating under different controlled icing conditions (i.e., from glaze ice to rime ice). An infrared (IR) thermal imaging system was used to map the temperature distributions over the ice accreting surfaces of the aero-engine spinner models. A simplified heat balance model was introduced to characterize the unsteady heat transfer processes. Based on the acquired time-resolved IR thermal image sequences during the icing events, the influence of spinner shapes on heat transfer process was evaluated and discussed in details. These results could provide experimental information for aero-engine ice modelling and optimization design of anti-/de-icing systems of aero-engines.

II. Heat Transfer Process of Ice Accretion

Based on a previous study [14], a heat balance process in a control volume during ice accretion is shown in Fig.1. In this control volume, it is assumed that the energy added into the control volume is equal to the energy loss from the control volume. The input energy includes the latent heat of fusion, adiabatic heating and kinetic heating. The output energy includes convection heat, conduction heat, energy radiation and evaporation/sublimation [9,10]. The definition of this input and output energy balance is shown in Eq. (1) and Eq. (2):

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Fig. 1 Schematic of heat balance process in a control volume

Given that the latent heat of fusion released during liquid-solid phase change plays an important role in the input energy group; and given that the aerodynamic induced adiabatic heating and the kinetic energy caused by droplet impact are relatively weak in the heat balance process, the input heat to the control volume can be simplified to one term, which can be written in the form of:

\[ Q_{\text{in}} \approx Q_{\text{latent}} \]  

(3)

The heat loss from the control volume is mostly due to the heat convection caused by air flow passing the spinner surface; and partially due to the heat conduction of the spinner substrate. In this instant heat balance process, the heat loss from evaporation and sublimation is relatively small, which can be ignored. Also, there is no obvious radiation source or absorber around the test section during the tests. The heat loss caused by radiation can be assumed to be very small in the present study. Therefore, the output heat from the control volume can be simplified to two terms, which can be written in the form of:

\[ Q_{\text{out}} \approx Q_{\text{cv}} + Q_{\text{cd}} \]  

(4)

Since the latent heat of fusion is released when the super-cooled water changes from liquid to solid state after impacting upon the surface, the amount of released latent heat is defined by the product of the mass of frozen super-cooled water during the time step and solidification latent heat, which is shown in Eq. (5):

\[ Q_{\text{latent}} = m_{\text{freeze}} \cdot L_s \]  

(5)

The convection heat transfer can be expressed as the product of the convective heat transfer coefficient and the temperature difference between the oncoming flow and the water/ice surfaces, which is shown in Eq. (6):

\[ Q_{\text{cv}} = h_{\text{cv}} \cdot (T_\infty - T_s) \cdot A_{\text{volume}} \]  

(6)

Similarly, the conduction heat transfer can be expressed as a function of the conduction heat transfer coefficient and the temperature difference between the spinner surface and the water/ice layer on the spinner, which is shown in Eq. (7):

\[ Q_{\text{cd}} = h_{\text{cd}} \cdot (T_{\text{spinner}} - T_s) \cdot A_{\text{volume}} \]  

(7)

Substituting Eq. (5) to (7) in Eq. (4), so the instant heat balance of the control volume can be written in the form of:

\[ m_{\text{freeze}} \cdot L_s = h_{\text{cv}} \cdot (T_\infty - T_s) \cdot A_{\text{volume}} + h_{\text{cd}} \cdot (T_{\text{spinner}} - T_s) \cdot A_{\text{volume}} \]  

(8)

As the spinner model is put into the test section in advance before spraying water, the surface temperature can be cooled down to the same level as the oncoming flow temperature, i.e., \( T_{\text{spinner}} = T_\infty \). Using \( \Delta T \) to represent the
temperature difference in the convection and conduction terms of Eq. (8), the temperature difference can be expressed as:

$$\Delta T = \frac{m_{lq} \cdot L_s}{h_v \cdot A_{volume} + h_d \cdot A_{volume}}$$ (9)

In the present study, the time resolve temperature distribution over three different kinds of spinners were measured by the infrared camera. Based on the simplified heat balance model shown in Eq. (9), the amount of the latent heat release and the convective/conduction heat transfer variation will be investigated.

III. Experimental Methodology

A. Aero-engine Fan Model

The aero-engine fan model used in the present study is same as our previous study [15], which is designed based on Boeing 18-inch fan rig [16]. Figure 2 shows the schematically of the three kinds of engine spinners investigated in the present study. The test models are made of a hard plastic material by using a rapid prototyping machine, i.e., the 3D printer. Moreover, the upper surface was processed with fine sandpaper (i.e., up to 2000 grit) to achieve a very smooth finish and painted with black paint (Rustoleum, Flat Protective Enamel, Black) to achieve a higher emissivity for the infrared testing.

![Fig. 2 Diagrams of three kinds of spinners studied in the present study](image)

B. Experimental Setup and Instruments

The experimental study was conducted in an Icing Research Tunnel located in the Aerospace Engineering Department of Iowa State University. The ISU-IRT, which was originally donated by UTC Aerospace System (formerly Goodrich Corporation) to Iowa State University, is a newly refurbished research-grade multifunctional icing research tunnel. Detailed specifications of the ISU-IRT can be found in Ref. 15.

Figure 3 shows the diagram of the experimental setup of present study. Similar to the previous study in Ref. 15, the engine fan model with blades and spinner was installed in the center of the test section with the support of an aluminum tube, and the rotor disk of the fan was set to be normal to the freestream of the oncoming airflow. An infrared transmission window (FLIR IR Window-IRW-4C) with a diameter of 4 inches was installed on the top panel of the test section. The infrared camera (FLIR A655) was mounted above the IR window, with a distance of 250 mm from the spinner model. The spectral range of the camera was 7.5 - 14 μm and the resolution was 640 x 480 pixels with a temperature measurement range from -40 °C to 150 °C. The dynamic range was able to achieve 16-bit temperature linear output at 50 Hz, allowing a high accuracy (i.e., ±0.2 °C) and time resolved measurement. In addition, in the present study, a direct current power supply (BK PRECISION, 1692) was used to power a brush-less motor (Scorpion, SII-4020-420KV) to drive the fan model, and an ESC (Scorpion, Commander 15V 60A) was used to control the rotation speed of the fan by means of changing the duty cycle of PWM control signal. During the experiment, the rotation speed of fan was measured by a tachometer (MONARCH, PLT200) to achieve a constant rotation speed feedback control based on LabView platform.
C. Infrared Measurement Parameters

In the infrared measurements, the measuring objects include spinner surface, water and ice. The emissivity of these objects are listed in Table 1 respectively [14]. Also the IR camera was mounted above the test section at a distance of 250 mm. The transmission coefficient of the IR window is 0.82. All these parameters were used to preset the IR camera before measuring.

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Paint</td>
<td>0.98</td>
</tr>
<tr>
<td>Water</td>
<td>0.95-0.963</td>
</tr>
<tr>
<td>Ice (Smooth – Rough)</td>
<td>0.966-0.985</td>
</tr>
</tbody>
</table>

D. Icing Test Conditions

According to the CFR Title 14 CFR FAA Part 25 and Part 33, aircraft and aero-engines with ice protection system must demonstrate the capability to operate safely under the ice conditions shown in Appendix C and Appendix O. Traditionally, continuous maximum conditions are used to guide airframe ice protection system design and intermittent maximum conditions are used to guide aero-engine ice protection system design [17]. In order to simulate a natural icing environment on the atmosphere (i.e., glaze ice, mixed ice and rime ice), the icing conditions and test parameters used for present study are selected based on the intermittent maximum envelope [6], which are listed in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>T∞, °C</th>
<th>LWC, g/m³</th>
<th>Ro, rpm</th>
<th>U∞, m/s</th>
<th>MVD, µm</th>
<th>Ice style</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5°C</td>
<td>2.4</td>
<td>2500</td>
<td></td>
<td></td>
<td>Glaze</td>
</tr>
<tr>
<td>2</td>
<td>-10°C</td>
<td>2.2</td>
<td>2500</td>
<td>15</td>
<td>10~50</td>
<td>Mixed</td>
</tr>
<tr>
<td>3</td>
<td>-15°C</td>
<td>1.1</td>
<td>2500</td>
<td></td>
<td></td>
<td>Rime</td>
</tr>
</tbody>
</table>
IV. Measurement Results

A. Time Resolved Temperature Distribution over the Icing Spinners

First, a typical glaze ice accretion trail was tested, i.e., $T_\infty = -5 \, ^\circ C$, $LWC = 2.4 \, g/m^3$. From the images shown in Fig. 4 (a), for the conical spinner (left side), it can be found that at the very beginning of the icing process, i.e., $t = t_0 + 1s$, the water droplets impact upon the tip area first causing a temperature change. After 1s ($t = t_0 + 2s$), the water droplets impacted upon the whole surface and the temperature change area became larger. At the same time, more water was being collected at the tip area that cause the local temperature increase higher due to ice accretion. As time progresses, from $t = t_0 + 3s$ to $t = t_0 + 5s$, the temperature on the surface showed a uniform distribution as there was no obvious temperature difference between the front area and downstream area. Figure 4 (b) presents the dynamic heat transfer process over the conical spinner (middle). In comparison to the conical spinner, the water droplets similarly impacted on the tip area at $t = t_0 + 1s$, but in contrast, after one second ($t = t_0 + 2s$), only the frontal area showed temperature change. The surface temperature of the downstream area was still close to the temperature of the oncoming flow. Figure 4 (c) shows the dynamic heat transfer process over the elliptical spinner (right), which showed a similar temperature change and distribution to the conical spinner.
Compared with these images sequence, it was found that the temperature distribution showed significant difference between various spinner shapes. As the super-cooled water droplets can directly impinge upon all the surface of conical spinner to form ice evenly, the temperature change on its surface showed a uniform distribution during this icing process. However, for the coniopital and elliptical spinners, as the super-cooled water droplets can only impinge upon the front area of spinners, there was only partial surface temperature changed that shown in the first two images. Moreover, under this glaze ice condition, the water collected on the surface cannot be frozen immediately and a water film formed on the surface. In that case, the water runback transferred the water downstream to an area without direct water impingement, where these water was freezing continually and the latent heat release increased the object’s temperature. From \( t=t_0+2s \) to \( t=t_0+5s \), for the conical and elliptical spinners, it was found that the boundary of the temperature change area moved downstream continually and formed a temperature gradient along the oncoming flow direction on the surface.

![Fig. 5 Time evolution of temperature distribution over icing spinners](image)

After the glaze ice condition, a mixed ice condition with high liquid water content and moderate cold temperature, i.e., \( T_\infty = -10^\circ C \), \( LWC = 2.2 \text{ g/m}^3 \), was investigated as well. Figure 5 demonstrates the dynamic temperature change process over these three kinds of spinners under this mixed ice condition. Figure 5 (a) presents the unsteady temperature change process over the conical spinner (left). Similar to the glaze ice condition, at the beginning...
(t=t₀+1s), the water only impinged upon the very small tip area, then, the water/ice covered the whole spinner surface quickly. After two seconds (t= t₀+3s), the temperature distribution of the whole surface became uniform. Figure 5 (b) and 5 (c) shows the dynamic temperature change over the conical spinner (middle) and elliptical spinner (right) under this mixed ice condition. Compared with the conical spinner, it was very easy to distinguish ice and no ice area on the spinners surface; the temperature gradient along the oncoming flow direction became more obvious than conical spinner as times going on.

Compared with the glaze ice condition, since the temperature of the oncoming flow is lower, a greater portion of the super-cooled water droplet can freeze after the impact on the surface. Only a small part of the water formed the water film on surface, and this water was frozen soon before it reaches further downstream area. From t=t₀+3s to t=t₀+5s, it was hard to observe the temperature change area boundary growing along the oncoming flow direction like glaze ice condition. In addition, for conical and elliptical spinners, as more water was collected near the tip area to form ice, there was a significant temperature concentration increase in this area, which was caused by mass latent heat release from water solidification.

Fig. 6 Time evolution of temperature distribution over icing spinners
(U∞=15 m/s, T∞= -15 °C, LWC=1.0 g/m³, Re=2500 rpm)
Figure 6 shows the time evolution of temperature distribution over the spinners surface under the rime ice condition, i.e., $T_0 = -15^\circ C$, LWC=1.0 g/m$^3$. Figure 6 (a) shows the dynamic temperature change over the conical spinner (left) under this rime ice condition. Similar to the previous conditions, after the super-cooled water droplets impinge upon the tip area, the water continually impinged upon the rest area in a short time and formed a uniform temperature distribution as well. But the amplitude of temperature rise was relatively less. The temperature change process over the conical spinner (middle) and elliptical spinner (right) under the rime ice condition are shown in Fig. 6 (b) and Fig. 6 (c). Similar to the previous icing conditions, there was still a clear separation boundary between iced and no-ice region. However, the temperature gradient was not as strong as the glaze and mixed ice conditions. Although there was still a temperature increase near the tip region, the area of this temperature concentration increasing became smaller.

Under this icing condition, since the temperature of the oncoming flow was much lower and the LWC was smaller, when the water impacted on the surface, it was frozen immediately. In other words, no water film formed on the surface during this icing process. Compared with the previous icing conditions, the iced region became smaller due to the ice accretion depended only on direct water impingement. As the super-cooled water droplets cannot impinge upon the downstream surface, there was no ice accretion there. Therefore, there is no latent heat release to increase the local temperature. Furthermore, as time go on, there was still an apparent temperature concentration increasing at the tip region of these spinners because of greater water collection than other places. However, the amplitude of these temperature concentration increasing varied between different spinners, the elliptical spinner showed the largest temperature concentration increasing, and the conical and conical spinners showed the smallest and smaller temperature concentration increasing respectively. It is because the round head of elliptical spinner has larger area to collect more water and release more latent heat during ice accretion, but the local area of the sharp head of conical and conical spinner is relatively smaller so that less water is collected to form ice near the tip.

**B. Temperature Variation History and Heat Transfer Evolution along the Axis Direction**

In order to compare the heat transfer evolution over these three kinds of spinners during different icing processes, three monitoring points were selected at different positions along the symmetric axis to demonstrate the temperature variation history, which are shown in Fig. 7. Point A was set at the tip region of the spinner, i.e., $X_A=1.0$ Ds. And the spacing between these three points were equal to 30% spinner length, i.e., $X_B=0.7$ Ds and $X_C=0.4$ Ds.

From the temperature distribution images shown above, it is known that, there is a continued water collection and phase change process on the spinner surface, accompanied with latent heat release. If all of the latent heat released from the first collected water can be taken away by the heat transfer processes like convection or conduction, the amount of latent heat released can be demonstrated by the temperature difference between the ice/water surface and the oncoming flow [14]. If the temperature difference become stable, it indicates that the amount of heat input and output of the control volume reaches a steady state. In the following section, the temperature variation history of these discrete points under three icing conditions will be discussed in details.

![Fig. 7 Three monitoring points along the symmetric axis of spinner](image)

Figure 8 presents the temperature variation history of these points under the glaze ice condition, i.e., $T_0 = -5^\circ C$, LWC=2.4 g/m$^3$. As shown in Fig. 8 (a), for all the spinners, when water droplets impinged upon the spinners surface, the temperature difference increased dramatically in a very short time and then reached a steady state synchronously.
It is because the initial collection of super-cooled water releases much latent heat during icing, after that the strong convection near the stagnation point can remove these latent heat quickly. In that case, the plots kept constant after the initial rise. In other words, local heat transfer process reaches an equilibrium state. Point B experienced a similar process which is shown in Fig. 8 (b). The temperature difference of these three spinners at this area also rose sharply at the beginning stage, but the plot of elliptical spinner experienced a smoother rise and a less hysteresis than conical and conical spinners. As times progress, both plots reached a steady state and the local heat transfer became stable. Fig. 8 (c) shows the temperature variation of point C, which indicates a significant difference between the spinners. For the conical spinner, as the super-cooled water droplets can directly impinge on point C region, the latent heat release from this phase change raised the object’s temperature dramatically like point B and point A. However, for the conical and elliptical spinners, there was a remarkable hysteresis of temperature increase at point C. On one hand, there was less or no direct water impacted on point C region, the surface temperature increase was mainly caused by the latent heat release from water runback on the surface. On the other hand, as the amount of water which deposited into this downstream area was less than upstream area, the amount of the latent heat release was relatively lower, resulting in a lower temperature rise when they reached steady state for the conical and elliptical spinners.

![Fig. 8 Relative temperature variation history at three discrete points on the spinners](image-url)

Figure 9 presents the relative temperature variation history of these monitoring points under mixed ice condition, i.e., $T_\infty = -10 \, ^\circ C$, $LWC=2.2 \, g/m^3$. As the temperature was relatively colder and $LWC$ was still higher in this situation, the surface temperature increased larger than previous glaze ice condition, which means more latent heat were released from ice accretion since more water was frozen after the impingement. In Fig. 9 (a), when water droplets impinged upon these three kinds of spinners’ tip area, the temperature difference increased considerably in a very short time as well. But temperature rise of conical spinner was smaller than the others, it was because the sharp tip collected less water droplets and released less latent heat during icing process. It is worth noting that, after the initial jump of the
temperature, the temperature variation of coniptical and elliptical experienced a slight fall which is caused by the strong convection heat transfer near this region. Fig. 9 (b) shows the temperature change at point B of these three spinners. Both plots experienced a slighter temperature increase and reached similar temperature level after the initial stage, but the coniptical one reached the steady state faster, followed by the conical one and elliptical one. Fig. 9 (c) shows the temperature variation of point C, which also demonstrates a significant difference between the spinners. It was known that for the conical spinner, there was a lot of water deposit into point C region through direct water impingement. The temperature variation history experienced a quicker rise and reached the same temperature constant level like point A and point B. Different from conical spinner, as no direct water impingement on point C region of coniptical and elliptical spinners, little ice formed there and the temperature variation increased much slower and lower. In other words, it took longer time for the local heat transfer to reach equilibrium state for coniptical and elliptical spinners.

![Fig. 9 Relative temperature variation history at three discrete points on the spinners](U_{∞}=15 m/s, T_{∞}=-10 °C, LWC=2.2 g/m^3, Re=2500 rpm)

Figure 10 shows the relative temperature variation history of these discrete points under the rime ice condition, i.e., T_{∞}=-15 °C, LWC=1.1 g/m^3. Under this rime ice condition, all the collected water droplets froze immediately upon impact, the latent heat release was strong. As shown in Fig. 10 (a), there was a considerable temperature difference increase at the tip region of both spinners. The plot of conical spinner reached steady state which means the local heat transfer can remove all the latent heat release during icing. However, the plots of coniptical and elliptical grew gradually during the forty seconds icing process and cannot reach a constant temperature level. Similarly, at point B, after the initial impingement of super-cooled water droplets, the temperature variation for both spinners climbed steadily during the icing process, which is shown in Fig. 10 (b). During this icing process, the temperature rise at this point of coniptical spinner was relatively higher, followed by conical spinner’s temperature change. The
elliptical spinner’s change was the lowest, which indicated that less water was collected at point B area of elliptical spinner. Fig. 10 (c) presents the temperature variation history of point C. For the conical spinner, as the water can continually impinged upon this area, the temperature variation experienced a similar trend as point B, which was growing gradually and cannot reach steady state during this icing process. For the conical and elliptical spinners, as point C was out of the direct water impingement area in this situation, the temperature change cannot be caused by the latent heat release from water freezing. Since the point C of conical was very close to the ice accretion area, the heat conduction through the spinner substrate raised the local surface temperature gradually. But for the point C of elliptical spinner, as it was far from the iced area, the temperature varied little near zero and no heat transfer information was illustrated here.

![Graph](graph.png)

**Fig. 10** Relative temperature variation history at three discrete points on the spinners

\((U_{\infty}=15 \text{ m/s}, T_{\infty}= -15^\circ \text{C}, \text{LWC}=1.1 \text{ g/m}^3, \text{R}_{0}=2500 \text{ rpm})\)

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V. Discussion

As described previously, the dynamic heat transfer over the spinner models are highly dependent on the icing conditions. Moreover, the temperature variation experiences two different stages during the icing process, which can be separated into the initial impingement stage (1\textsuperscript{st} stage) and the continued collection stage (2\textsuperscript{nd} stage). The heat transfer modes for the glaze ice and rime ice behind these stages are discussed in this section.

Figure 11 shows the dynamic heat transfer process at point A under glaze ice condition. According to Eq. (9), the temperature difference indicates the amount of latent heat release and heat convection/conduction influence. At the 1\textsuperscript{st} stage, when the first part of the super-cooled water droplets impinges upon the clean spinner surface, the solidification of the water happens quickly, which releases a lot of the latent heat inside the ice layer instead of transferring to the surroundings [18]. Consequently, there is a dramatic increase of temperature variation of the measured object. After that, as more water is collected, just a small part of the super-cooled water freezes and a water runback forms on the top of the initial iced layer. At the same time, the latent heat released from ice solidification is removed by heat...
convection with freestream flow and heat conduction to the substrate and water film. In that case, local heat transfer arrives a steady state quickly and the temperature variation remains stable during the 2nd stage.

Figure 11 shows the dynamic heat transfer process at point A under glaze ice condition. As the temperature is very low and LWC is small, a large portion of super-cooled water droplets freezes immediately after impacting with the surface. At the 1st stage, when the first part of the super-cooled water droplets impinges upon the clean spinner surface, the solidification of the water also happens quickly, the dramatic rise of temperature variation in the first two seconds indicates a strong latent heat release in the ice [18]. After that, as more water is continually collected, most of the super-cooled water freezes immediately resulting in ice thickness growing on the spinner surface [15], which means latent heat release remains strong. Since the heat convection with freestream flow and the heat conduction to the substrate cannot remove all released latent heat of fusion, the temperature of the object increases gradually at the 2nd stage.

Figure 12 shows the dynamic heat transfer process at point A under rime ice condition. (U∞=15 m/s, T∞= -5 °C, LWC=2.4 g/m², Ro=2500 rpm)

1st Stage

2nd Stage

Fig. 11 Dynamic heat transfer modes of point A under glaze ice condition (U∞=15 m/s, T∞= -5 °C, LWC=2.4 g/m², Ro=2500 rpm)

Fig. 12 Dynamic heat transfer modes of point A under rime ice condition (U∞=15 m/s, T∞= -15 °C, LWC=1.1 g/m², Ro=2500 rpm)
VI. Conclusion

In the present study, a simplified heat transfer model was constructed based on the previous studies to characterize the relationship between the surface temperature variation and latent heat release. After which, a comprehensive experimental study was performed to investigate the dynamic heat transfer process during ice accretion over the spinner models of a rotating aero-engine fan. The experiments were conducted in ISU-IRT with a scaled aero-engine fan model operated under a variety of icing conditions (i.e., ranged from glaze to rime ice conditions). A high-speed IR camera was used to record the time resolved temperature map on three typical spinner profiles (i.e., conical, coniptical, and elliptical). Based on the temperature variation history along the spinners, the influence of spinners’ geometric shape on heat transfer process was examined in detail and the dynamic heat transfer modes were discussed.

The time resolved temperature image sequences of the icing processes demonstrate that the geometric shape highly affects the dynamic temperature change process on the spinners. It is found that under glaze ice conditions, an ice/water film forms on the surface of spinners. The impingement water covers the whole conical spinner surface and shows a uniform temperature distribution. But, the water runback transfers part of the water to the downstream area without direct impingement on the conical and elliptical spinners. This water also releases latent heat through ice formation and causes a surface temperature increase. After the initial impingement stage, the convective/conduction heat transfer is sufficient to remove all the latent heat from water solidification and the surface temperature reaches steady state soon. Under the mixed ice condition, as more super-cooled water is freezing at the initial impingement, more latent heat released from the solidification results in greater temperature increase during icing process. Also, since less water film forms on the surface, it takes a longer time for heat convection and conduction to remove all latent heat released and reach the steady state. Under the rime ice condition, there is only ice accretion at the direct water impingement area and the latent heat release is relatively stronger than the heat convection and conduction at the 2nd stage. With more water impact and ice accretion, the temperature variation on the surface grows gradually and does not reach equilibrium during the test duration. But for area without impingement, the heat conduction does not demonstrate significant influence and the surface temperature varies a little.

The unsteady heat transfer process over ice accreting surfaces of aero-engine spinners is very complex, and it is related to various affecting factors and icing conditions. Moreover, compared with 2D airfoils’ issues, the rotation effect on the ice accretion and mass/heat transfer process is still not very clear, which is a potential research topic for the future study.

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