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An experimental investigation on the dynamic ice accretion and unsteady heat transfer over an airfoil surface with embedded initial ice roughness

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ABSTRACT

In the present study, a comprehensive experimental study was conducted to evaluate the effects of initial ice roughness formed around the leading-edge of an airfoil model on the dynamic ice accretion and unsteady heat transfer processes over the airfoil surface. The experimental study was performed in the Icing Research Tunnel at Iowa State University, Two airfoil models with the same airfoil shape were manufactured by using a rapid protype machine for a comparative study, i.e., one test model was designed to have embedded initial ice roughness around the airfoil leading-edge and the other model having smooth airfoil leading-edge as the comparison baseline. During the experiments, while a high-speed imaging system was used to record the early-stage icing morphologies over the airfoil surfaces with and without the initial leading-edge roughness, an infrared (IR) thermal imaging system was also utilized to map the corresponding surface temperature distributions over the airfoil surfaces to quantify the unsteady heat transfer and dynamic icing, i.e., phase changing, processes under different test conditions. It was found that, the initial ice roughness formed around the airfoil leading-edge would affect the characteristics of local airflow, impingement of supercooled water droplets, collection and transport of impacted water mass, unsteady heat transfer and subsequent ice accretion processes dramatically. The initial ice roughness formed around the airfoil leading-edge would redistribute the impacted water mass, with more impacted water mass being captured and frozen over the roughness region. In addition, the initial ice roughness was also found to produce span-wise-alternating low- and high-momentum pathways (LMPs and HMPs, respectively), which can significantly affect the convective heat transfer and subsequent ice accretion processes over the airfoil surface.

1. Introduction

Aircraft icing has been recognized as a big threat to flight safety for several decades [1]. The flight performance of an aircraft encountering icing clouds can be significantly contaminated by the ice layers accumulated on critical surfaces [2]. Ice accretions could negatively affect the aerodynamic performance of aircraft by reducing stall margin, increasing drag, and decreasing lift [3]. It is documented that more than 1200 accidents and incidents occurred in the US in the past a few decades [4,5]. Considerable amounts of the accidents/incidents were related to in-flight ice accretion on wings, fuselage or control surfaces of aircraft. While many anti-/de-icing techniques have been developed to mitigate ice accretion on aircraft [6–9], the in-flight icing is still a severe weather hazard to flight safety. The in-flight ice accretion is highly dependent on weather conditions, e.g., cloud liquid water content (LWC), atmosphere temperature, and cloud droplet median volumetric diameter (MVD). Various ice shapes have been observed under different icing cloud conditions [10,11]. In the past years, many efforts have been made to characterize the effects of LWC, air temperature and velocity, and droplet size on ice shape formations [2,3,12]. While clouds with low LWC and small droplets at cold temperatures (typically below −10 °C) tend to produce ice shapes with rough, milky white appearance conforming to aircraft surfaces, i.e., rime ice, some irregular ice horns with clear, smooth, and dense appearance, i.e., glaze ice, may form and extend into the oncoming flows under other cloud conditions with high LWC and large droplets at temperatures just below the freezing point [13].

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Heat transfer is one of the most essential mechanisms that control the ice accretion on aircraft [14]. Ice forms when the latent heat of fusion in the impinged water mass is removed by heat transfer. If the heat transfer is sufficiently fast to remove all of the latent heat of fusion in the impinged water droplets, they would freeze immediately upon impacting on the aircraft surfaces. If not, however, only a portion of the impinged water mass would be frozen upon impact, with the remaining being transported downstream and frozen over a larger area. Many experimental studies, either in-flight or ground wind tunnel test, have been conducted to evaluate the heat transfer in aircraft icing [15,16]. It has been revealed that the heat transfer during icing processes is significantly affected by the roughness elements formed in the initial stage of ice accretion. Further studies showed that the initial ice roughness is significant because it couples the fluid flow, droplet impingement, and heat transfer processes [17,18]. The initial ice roughness essentially induces higher turbulence in the airflow, and accelerate the convective heat transfer from the surfaces to freestream [19]. There are multiple heat transfer mechanisms occurring on the airfoil/ice surfaces during ice accretion [20,21], among which, convective heat transfer is considered to be predominant in aircraft icing [16,22]. Since the initial ice roughness is closely coupled with the local flow field and convective heat transfer, even a slight change in roughness characteristics (element size, element spacing, etc.) could essentially impact the convective heat transfer, and hence, change the amount and rate of ice accretion [23].

During the past years, some ice accretion prediction codes have been developed to simulate icing process from water droplet trajectory calculations to ice growth on aircraft surfaces. However, these codes are limited in their capabilities in predicting ice accretion especially in glaze conditions. An important reason for that is the use of simplified ice roughness models. For example, in the LEWICE code [1], the ice roughness height is estimated based on the sand-grain equivalent model. Convective heat transfer is then determined by coupling with the ice roughness height estimation [24]. This simplification could essentially affect the ice accretion shape and size because the sand-grain roughness is different from the actual ice roughness formed in in-flight icing conditions [25]. Based on the comparison of the ice shapes generated in the icing experiments and that from the LEWICE simulation, it was found that the predicted ice shapes did not match well with the experimental results. The comparison, consequently, presented a poor agreement of the convective heat transfer coefficients [26].

Many experimental studies have been conducted to evaluate the effects of the roughness elements on the local convective heat transfer and boundary layer development. However, due to the difficulties in characterizing the initial ice roughness, most of these studies have focused on the effects of the non-realistic ice roughness, or simplistically distributed roughness [27–29]. Although these simulated roughness elements can be easily generated and manufactured, they may not reflect the irregularity and broad range of topographical scales of practical roughness [30]. The unique ice surface features formed in actual in-flight icing conditions would not be captured by the ordered arrays of discrete roughness elements. The use of these non-realistic ice roughness has created biases in convective heat transfer coefficients in comparison to those with the realistic distributions of roughness elements [31]. Thus, assessing the impact of realistic ice roughness on the heat transfer and further ice accretion is of great importance to improve our understanding of the nonlinear icing processes on aircraft.

Over the years, several techniques have been developed to create realistic ice roughness distributions [32]. One recent example is the Lagrangian droplet simulator, which can be used to generate realistic ice roughness distributions [23,32]. The generated roughness is a bead distribution with random spreading and diameters. This approach enables the characterization of boundary layer development and convective heat transfer from surfaces exhibiting such kind of roughness distributions [23]. Since the actual ice roughness generated in real icing conditions could be of various shapes and sizes, another approach employing cast surfaces of real icing models was developed [22] in order to characterize the boundary layer flow and local heat transfer in these situations. While the three-dimensional ice roughness features can be captured using the mold and casting method, this approach is time consuming in operation, and the cost can be significant [33]. In recent years, laser-based and other optical scanning methods have been developed to accomplish three-dimension, i.e., 3D, digitization of ice accretion [34,35], which are capable to accurately record and reproduce the details of ice roughness features. The advancement of the 3D scanning techniques enables the acquisition of realistic ice roughness data during the early stage of aircraft icing. With such realistic ice roughness data, a series of icing experiments were conducted in the present study to reveal the impacts of these initial ice roughness on the dynamic ice accretion and unsteady heat transfer processes over aircraft wing surfaces. To the best knowledge of the authors, this is the first effort of its kind to quantitatively evaluate the effects of initial ice roughness (with realistic shapes and distributions) in aircraft icing phenomena.

In the present study, two airfoil models with the same airfoil shape, i.e., one model with embedded initial ice roughness around the airfoil leading-edge and the other model with smooth airfoil leading-edge as the comparison baseline, were manufactured by using a rapid protype machine, i.e., 3D printed. The experimental study was performed in the Icing Research Tunnel at Iowa State University, i.e., ISU-IRT. While a high-speed imaging system was used to record the dynamic ice accretion over the airfoil surfaces with and without the initial ice roughness, an infrared (IR) thermal imaging system was also utilized to map the corresponding surface temperature distributions over the airfoil surfaces simultaneously to quantify the unsteady heat transfer and phase changing processes. Such measurements provide insight into the droplet collection distribution and unsteady heat transfer processes with and without the presence of initial ice roughness during the different icing conditions.

2. Test model used in the present study

The two airfoil models used in the present study were designed to have the same NACA 23012 airfoil shape, and were made of a hard-plastic material and manufactured by using a rapid prototyping machine, i.e., 3-D printing, that builds 3-D models layer-by-layer with a resolution of about 25 μm. While one test model was designed to have smooth leading-edge as the comparison baseline, the second model was designed to have embedded realistic initial ice roughness around the airfoil leading-edge. The initial ice roughness was formed under a typical in-flight icing condition, i.e., wind speed of $U_\infty = 102.9$ m/s; LWC = 0.75 g/m^3; MVD = 15 μm, and airflow temperature of $T_\infty = -2.2$ °C, with a icing duration of 30 s, by performing an icing experiment in the Icing Research Tunnel (IRT) at NASA's Glenn Research Center [33]. The iced airfoil model was then 3-D scanned using a 3D laser scanning system. The point cloud data file generated by using the 3-D laser scanning system was used as the input file for designing the airfoil model with realistic ice roughness used in the present study. The construction of the solid airfoil model from the point cloud data is a typical reverse engineering project. The point cloud file was imported into a 3D CAD software (CATIA-V5-R20 in this study) as shown in Fig. 1(a). The imported point cloud was then manipulated, i.e., points filter, local and global points activate