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An experimental investigation on the unsteady heat transfer process over an ice accreting airfoil surface

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ABSTRACT

In the present study, an experimental investigation was performed in an Icing Research Tunnel available at Iowa State University (i.e., ISU-IRT) to quantify the unsteady heat transfer and dynamic ice accretion process over an airfoil/wing surface under different icing conditions (i.e., dry rime ice accretion vs. wet glaze ice accretion). A theoretic model was developed at first to evaluate the unsteady heat transfer process over the ice accreting airfoil/wing surface in the term of convective heat transfer coefficient. During the experiments, a high-speed infrared (IR) thermal imaging system was used to achieve temporally-resolved measurements of the surface temperature distribution over the ice accreting airfoil/wing surface. The transient behaviors of droplets impingement, surface water runback and dynamic phase changing processes over the airfoil/wing surface were characterized quantitatively based on the quantitative surface temperature measurements. Based on the time evolution of the measured surface temperature distributions over the airfoil/wing surface for the rime ice accretion case, the water collection efficiency distribution around the airfoil surface was determined quantitatively, which was then imported into the theoretic heat transfer model to estimate the convective heat transfer coefficients over the ice accreting airfoil/wing surface. The convective heat transfer coefficient was found to reach its maximum value at the airfoil stagnation point, and decrease gradually at the downstream locations. The formation of the ice roughness near the airfoil leading edge was found to be able to enhance the convective heat transfer process over the airfoil surface, which would further promote the ice formation and accretion over the roughed airfoil surface.

1. Introduction

Aircraft icing is widely recognized as a significant aviation hazard to aircraft operation in cold weather. While the most familiar and frequently observed aircraft icing events are the ice buildup over airframe surfaces with airplanes being exposed to frozen precipitation at airports, such icing hazard can be easily overcome by applying de-/anti-icing fluids over the airframe surfaces prior to takeoff [1]. In-flight aircraft icing occurs when small, super-cooled, airborne water droplets, which make up clouds and fog, freeze upon impacting onto airframe surfaces. Since the airborne water droplets are in a super-cooled state, they can either freeze immediately or become mixtures of liquid water and ice upon impinging onto airframe surfaces, depending on the ambient conditions [2]. Ice accretion over in-flight aircraft surfaces was found not only to result in a significant decrease in lift and a rapid rise in drag, but also to induce unstable control conditions when ice accumulates asymmetrically on aircraft control surfaces [3]. The importance of proper in-flight aircraft icing control was highlighted by many aircraft crashes in recent years like the deadly accident occurred at Clarence Center, New York on 02/12/2009 with fifty fatalities in the accident of a Bombardier DHC-8-400 aircraft operated as Continental Flight 3407 [4].

It is well known that ice accretion process over the surface of an in-flight airplane can be either wet (glaze) or dry (rime), depending on ambient conditions [5]. When an airplane encounters clouds with low liquid water content (LWC) and small-sized super-cooled water droplets at relatively low ambient temperature (i.e., typically below −8 °C), rime ice would usually form as the super-cooled water droplets freeze immediately upon impact. In rime icing conditions, the released latent heat of fusion due to phase change of the impinged super-cooled water droplets would be removed efficiently through heat transfer, and no surface water flow would exist over the airframe surfaces [2]. The amount and rate of ice accretion over the airframe surfaces would be solely determined by the impingement behavior of the super-cooled water droplets [2]. Glaze icing process was found to be associated

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with warmer ambient temperatures (i.e., usually above −8 °C), higher liquid water contents in clouds, and larger super-cooled water droplets. In glaze icing conditions, while the heat transfer is insufficient to remove all the released latent heat of fusion of the impinged super-cooled water droplets, only a portion of the impinged super-cooled water droplets would freeze upon impact, and the remaining would remain in liquid as unfrozen water and run back over the airframe surfaces, as driven by the boundary layer airflow over the aircraft surface [2,6,7]. As a result, the amount and rate of glaze ice accretion over the airframe surfaces are mainly determined by the heat transfer capacity to remove the latent heat of fusion of the impinged supper-cooled water droplets over the ice accreting surface [3,8–10].

A number of engineering software tools (e.g., TURBICE and LEWICE) have been developed in recent years to predict the ice accretion process for various aircraft icing mitigation applications [11–15]. Such packages utilize airflow speed, temperature, accretion time, liquid water content and droplet size as input data to predict the shape and amount of resulting ice accretion on airfoil/wing surfaces. It was found that, due to the very complex interactions among multiphase flows (i.e., the boundary layer airflow, super-cooled water droplets and surface water runback flows, and ice accreting process over airframe surface) and the unsteady mass and heat transfer processes associated with the dynamic impingement of the super-cooled water droplets, transient surface water transport and the dynamic solidification (i.e., phase changing) process, the accurate prediction of ice accretion over airframe surfaces, especially for the glaze ice accretion case, was still very challenging [16]. While the ice accretion tools usually include classical models and correlations for various multiphase components which are assumed to contribute to the ice formation and accretion processes, many important details of the complex coupled multiphase micro-physical processes associated with the dynamic ice accretion process were usually ignored [6,17,18]. Such simplistic evaluation of the transient behavior of surface water transport and unsteady heat transfer process is considered to be a significant contributing factor in the poor agreement between the predictions of the theoretical models and the experimental results about glaze ice accretion process [14,19–21].

Advancing the technology for safe and efficient operation of aircraft in atmospheric icing conditions requires the development of innovative, effective anti-/de-icing strategies for aircraft icing mitigation and protection. Doing so requires a keen understanding of the underlying physics of complicated thermal flow processes pertinent to aircraft icing phenomena, both for the icing itself as well as for the unsteady heat transfer and dynamic water runback along ice accreting airframe surfaces. While a number of previous studies have been carried out to simulate ice formation and accretion on airfoil/wing models through icing wind tunnel testing [8,22,23] or using "artificial" iced profiles with various types and amounts of ice accretion to investigate the aerodynamic performance degradation for iced airfoils/wings [24–26], very few fundamental studies can be found in literature to elucidate the underlying physics of the dynamic ice accreting process. Many important micro-physical processes associated with aircraft icing phenomena, such as characteristics of the unsteady heat transfer and dynamic phase changing processes over ice accreting airfoil/wing surfaces, are still not fully explored.

In the present study, we reported an experimental investigation to quantify the unsteady heat transfer and dynamic phase changing processes as super-cooled water droplets impacting onto the surface of an airfoil/wing model under different icing conditions (i.e., both dry rime and wet glaze icing conditions) to elucidate the underlying icing physics pertinent to aircraft icing phenomena. In the context that follows, a theoretic model was developed at first to evaluate the unsteady convective heat transfer process over an ice accreting airfoil/wing surface. By leveraging the unique Icing Research Tunnel available at Iowa State University (i.e., ISU-IRT), a comprehensive experimental campaign was conducted to investigate the unsteady heat transfer and dynamic phase changing processes over an ice accreting airfoil/wing surfaces under both rime and glaze conditions. During the experiments, an infrared (IR) thermal imaging system was used to achieve spatially-and-temporally-resolved temperature distribution measurements over the airfoil/wing surface during the dynamic ice accretion process. The characteristics of the unsteady heat transfer and transient behaviors of the surface water runback process over the ice accreting airfoil/wing surface were examined quantitatively in the course of the dynamic ice accretion process. Based on the spatially-and-temporally-resolved temperature measurements around the leading edge of the airfoil/wing model, the distribution of water collection efficiency around the airfoil leading edge was derived quantitatively, which was then imported into the convective heat transfer model to further evaluate the unsteady heat transfer characteristics over the ice accreting airfoil/wing surface.

2. Theoretical analysis of unsteady heat transfer over an ice accreting airfoil surface

In the present study, the energy conservation law was applied to an arbitrarily-chosen control volume over an ice accreting airfoil/wing surface in order to evaluate the unsteady heat transfer process over the airfoil/wing surface. As shown schematically in Fig. 1, the rate at which the thermal and/or mechanical energies enter into the control volume, minus the rate at which the thermal and mechanical energies leave from the control volume would be balanced by the rate of net energy increase stored within the control volume [27], which can be expressed as:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{st}}{dt} \equiv \dot{E}_{st} \qquad (1)$$

where $\dot{E}_{in}$ is the rate of energy enters the control volume, $\dot{E}_{out}$ is the rate of energy leaves the control volume, and $\dot{E}_{st}$ is rate of the net energy increase stored inside the control volume.

The energy enters the control volume includes adiabatic heating and kinetic heating energy. The energy leaves the control volume includes the evaporation and sublimation, convection heat, energy radiation, conduction heat, and sensible heat that is produced by the temperature changes of the water and ice over the surfaces of the control volume [6,18]. The net energy increase stored inside the control volume are due to the changes in the internal, kinetic, and/or potential energies of its contents [27], which is given as following:

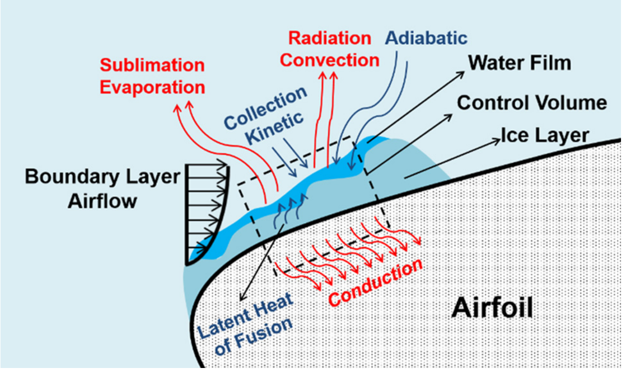

Fig. 1. A schematic of energy balance in an arbitrarily-chosen control volume over an ice accreting airfoil/wing surface.