Aerospace Science and Technology 73 (2018) 164–172

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

An experimental study of surface wettability effects on dynamic ice accretion process over an UAS propeller model

Yang Liu, Linkai Li, Haixing Li, Hui Hu *

Department of Aerospace Engineering, Iowa State University, 2271 Howe Hall, Room 1200, Ames, IA 50011, USA

ARTICLE INFO

Article history:
Received 25 September 2017
Received in revised form 1 December 2017
Accepted 2 December 2017
Available online 6 December 2017

Keywords:
Ice accretion
Surface water transport
Surface wettability
Latent heat release
Unmanned Aerial System

ABSTRACT

An experimental study was conducted to evaluate the effects of surface wettability on the dynamic ice accretion process over the surface of a rotating Unmanned-Aerial-System (UAS) propeller model and the resultant aerodynamic performance degradation due to the ice accretion. A propeller model was installed in an Icing Research Tunnel at Iowa State University (i.e., ISU-IRT) with its surface wettability changed significantly (i.e., hydrophilic surface *versus* superhydrophobic surface). In addition to acquiring "phase-locked" images to reveal the dynamic ice accretion process over the rotating propeller surface, the thrust generation and the required power input to drive the propeller model to operate at a constant rotation speed were also measured during the ice accretion process. The dynamic ice accretion process over the rotating propeller surface was found to vary remarkably with changes to the propeller surface wettability. By making the propeller surface superhydrophobic, the detrimental effects of the ice accretion on the aerodynamic performance of the propeller model were found to be mitigated greatly with much less ice accretion over the propeller surface, significant reduction of the thrust loss and less demand for extra power consumption due to the ice accretion, in comparison with the case with the propeller surface being hydrophilic.

1. Introduction

Inflight icing has been found to pose significant safety and performance concerns for both unmanned and manned aircraft in a cold climate [1]. With the rapid development of Unmanned Aerial Systems (i.e., UAS in short) in recent years, UAS icing has become an urgent-to-solve problem in order to ensure safe and efficient operation of UAS in cold weather [2]. In comparison with conventional, large-sized manned aircraft, a lightweight UAS is more susceptible to inflight icing problems due to the lower cruising altitude with relatively higher liquid water content (*LWC*) levels and warmer air temperatures, smaller excess power margin to offset the increased drag caused by ice accretion [3], lower flight velocity resulting in longer exposure to icing conditions, and more damage to important sensors onboard [4]. The potential damage of inflight icing to UAS renders their operation unfeasible in cold weather. As described in Botura and Fahrner [5], 25% of UAS flights had encountered ice during a specific military action that have negatively impacted the success of the mission. The common icing avoidance strategies for UAS in nowadays are keeping UAS on the ground [6] or modifying path planning [7]. This would greatly reduce the operation capability of UAS in cold climate. This is particularly troubling for military UAS applications, in which icing conditions can lead to aborted missions and the loss of crucial tactical capabilities.

To mitigate the detrimental effects of ice accretion on the operational performance of aircraft (for both unmanned and manned), various anti-/de-icing techniques have been developed and employed to prevent or reduce ice accretion on the aircraft. While anti-icing refers to the prevention of any buildup of ice on a surface, de-icing denotes the case where ice has already formed on a surface, which is subsequently removed. Most of the anti-/de-icing methods currently used for UAS icing mitigation can be classified in two categories: active and passive methods. While active methods rely on an external system, passive methods take advantage of the physical properties of wing or/and propeller surfaces to eliminate or prevent ice formation and accretion. Most of the active systems developed for UAS icing mitigation are thermal systems that remove ice buildup by applying heat to iced wings [8–12]. It should be noted that, massive heating for de-icing operation would not be applicable to UAS due to the limited payload and scant excess power. Furthermore, caution must be taken in the design of thermal systems since runback water can re-freeze after passing the heated area. In the present study, we pay special attention to

---

* Corresponding author.
E-mail address: huhui@iastate.edu (H. Hu).

https://doi.org/10.1016/j.ast.2017.12.003
1270-9638/

passive methods which take advantage of surface properties (e.g., wettability) of UAS airframes to prevent or eliminate ice formation and accretion without additional power input.

Inspired by the outstanding self-cleaning capability of lotus leaves and duck feathers, a number of studies have been conducted in recent years to develop coatings to make superhydrophobic surfaces [13–15], on which water droplets bead up with a very large contact angle (i.e., >150°) and drip off rapidly when the surface is slightly inclined (i.e., very small contact angle hysteresis). Such superhydrophobic surfaces have been demonstrated to have the capability of repelling water drops on the surface [9,16–19], delaying the crystallization of water drops that contact the surface [20–22], and reducing the adhesion of aqueous media in both liquid and crystalline states to the surfaces [23–26]. However, the direct correlation between superhydrophobicity and icephobicity has been under debate for several years [27–30]. As described in Hejazi et al. [28], the parallelism between the hydrophobicity and icephobicity suggests a reasonable anti-icing performance of superhydrophobic surfaces (i.e., low adhesion strength and delayed ice crystallization and droplets bouncing). Yet a multifaceted evaluation of freezing delay and liquid-shedding ability and their competing effects were suggested to be taken into account when choosing a superhydrophobic coating as anti-icing surface [27]. It should also be noted that, while most of previous studies on superhydrophobic coatings were accomplished with only simple and static tests (i.e., by spraying water droplets or pouring water onto substrates and then freezing the test samples in refrigerators) to demonstrate their water- and ice-phobic characteristics [31,32], very little can be found in the literature to evaluate their capabilities to suppress "*impact icing*", which is the process pertinent to UAS in-flight icing phenomena. Here, "*impact icing*" is defined as ice formed due to the dynamic collision of super-cooled water droplets onto a surface at a high impact velocity. The structure of impact ice accretion can vary considerably depending upon the conditions in which the ice is formed. Air temperature, air speed, water droplet size, liquid water content, and airframe geometry would all affect the accreted ice structures. Very recently, Waldman et al. [33] conducted an experimental study to demonstrate the feasibility to use a superhydrophobic coating to mitigate impact icing over an airfoil/wing model with the speed of the incoming airflow along with the impinging supper-cooled water droplets being as high as 50 m/s. The aerodynamic stresses from the airflow over the wing surface were found to sweep away impinged water droplets/films from most of the superhydrophobic wing surface to prevent impact ice accretion. However, ice was still found to form near the leading edge of the super-hydrophobic wing in the vicinity of the stagnation line, which highlights one of the major challenges facing hydro- and ice-phobic coating strategies, i.e. when a water droplet impacts a superhydrophobic surface at extremely high velocity, it can penetrate into the surface texture and adopts the Wenzel state, which leads to increased contact area between water and solid surface [34–36] and consequently leads to higher ice adhesion strength. It also illustrates that superhydrophobic coatings that are effectively ice-phobic at nominal conditions may not perform well under impact icing conditions pertinent to inflight icing phenomena.

Unlike most large manned aircraft using turbofan or turbojet engines for propulsion, almost all the UAS are powered by propellers. Since ice may accumulate on every exposed frontal surfaces of UAS, not only on wings, but also on the surfaces of rotating propellers, which can significantly degrade the aerodynamic performance of the propellers. In moderate to severe conditions, the propellers can become so iced up that continued flight would become impossible. In comparison to ice accretion on stationary surfaces, the ice accretion process over rotating propeller surfaces is even more complicated, due to the combined effects of aerodynamics shear forces exerted by the incoming airflow and the centrifugal forces induced by rotation. Furthermore, as revealed in the recent experimental study of Liu et al. [3], ice structures accreted over the rotating propeller blades would be shed off when the centrifugal forces acting on the accreted ice overcome the interfacial adhesion forces between the accreted ice layer and the blade surfaces. By applying a superhydrophobic coating onto propeller blades, the adhesion strength between the accreted ice layers and the blade surfaces can be potentially reduced, as suggested by Wang et al. [37]. Thus, an improved anti-/de-icing performance of the superhydrophobic surface coatings would be expected when applied onto rotating UAS propellers, in comparison with the case over the fixed wing models.

With this in mind, we conducted an experimental study to evaluate the effects of surface wettability on the dynamic ice accretion process over the surface of a rotating UAS propeller model and the resultant performance degradation due to the ice accretion. The experimental study was performed in an Icing Research Tunnel available at Iowa State University (ISU-IRT) with a scaled UAS propeller model operated under a typical glaze icing condition. During the experiment, the surface of the UAS propeller model was treated to change its surface wettability (i.e., hydrophilic surface case *versus* superhydrophobic surface case). The "phase-locked" images were acquired using a high-speed imaging system to reveal the time-evolution of the dynamic ice accretion processes over the surfaces of the rotating propeller with significant changes in surface wettability (i.e., hydrophilic case *vs.* superhydrophobic case). In addition, the aerodynamic performance degradations (i.e., thrust loss and extra power consumption) of the UAS propeller model due to the ice accretion were also assessed to provide more insights into the potential benefits of using superhydrophobic surfaces for UAS inflight icing mitigation.

2. Experimental setup and test model

2.1. Tested propeller model

Fig. 1 shows the schematic of the UAS propeller model used in the present study, which is a three-blade propeller with a coniptical spinner of 33 mm in diameter in the center of the propeller. As shown schematically in Fig. 1, with their radius being 100 mm (i.e., $R = 100$ mm), the rotor blades of the propeller model have typical airfoil cross sections and platform profiles commonly used in modern UAS propellers. Two airfoil profiles (i.e., ARA-D 13% and ARA-D 20%) were used at different spanwise locations along the rotor blades: while an ARA-D 20% airfoil profile was used between $0.10R$ and $0.30R$, an ARA-D 13% airfoil was used from $0.30R$ through the blade tip. With the prescribed blade platform profiles and twist angles (i.e., optimized based on the freestream airflow velocity and rotational speed of the propeller), a spline function was used to interpolate the prescribed cross section profiles to generate the three-dimensional geometry of the propeller blade using SolidWorks software. While the primary design parameters of the UAS propeller model are listed in Table 1, further details about the dimensions and design of the UAS propeller model can be found in Liu et al. [3].

The propeller model is made of a hard plastic material (i.e., VeroWhitePlus, RGD835 by Stratasys, Inc.), and was manufactured using a rapid prototyping machine (i.e., 3D printer). During the experiments, an aluminum tube with a streamlined cross section was used to support the propeller model when installed in ISU-IRT.

2.2. Surface treatment

In the present study, the surface of the propeller model was treated to be in significantly different wettability (i.e., hydrophilic