Experimental study of superhydrophobic coating effects on dynamic ice accretion ice accretion process along S-1223 airfoil

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Abstract— **Ice accretion on can be considered as a major threat for the operation of UAVs in the ice prone region, leading to loss of control and catastrophic failures. Active ice mitigation techniques are not suitable for UAV's due to availability of limited power. Superhydrophobic coatings can be considered as a promising passive ice mitigation technique for UAVs featuring exceptional capability to repel water, low power consumption, and lightweight properties. The effect of superhydrophobic coating on the ice accretion behaviour of a UAV wing with high lift airfoil S1223 is studied. High speed images of the ice accretion and force measurements were done to study the dynamic ice accretion process. For airfoils with high camber the application of superhydrophobic coatings can lead to rough ice structures close to the leading edge and can lead to more aerodynamic penalties.**

Keywords— ***UAV, ice accretion, superhydrophobic coating, S-1223, icing wind tunnel.***

I. INTRODUCTION

This Atmospheric Icing can be considered as a significant threat on the performance of UAVs. Ice can accumulate on the body, wing and propeller of UAV [1]. Atmospheric icing occurs when super cooled water droplets impinge on the surface of the aircraft and then freezes. Ice accretion on the aircraft can alter its weight, which in turn changes center of gravity and thus causing a deterioration of the performance and stability of aircraft [2-4]. The ice mitigation methods can be classified in two categories: active and passive methods. When the 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 without additional power input. Most of the active systems developed for icing mitigation are thermal systems that remove ice buildup by applying heat to wings. It should be noted that, this massive heating for operation would not be applicable to UAS due to the limited payload and excess power**.** In 2023 Müller developed an electro thermal ice protection system for UAV propeller and was tested at -5^oC and -15^oC icing condition. The amount of power required for anti-icing increased from 90 W to 200 W, when the temperature is lowered from 5^oC to -15^oC. Such high-power requirements can drain the battery in seconds and leading to the failure of mission. Therefore, passive methods are more appropriate for UAV deicing considering the power constrains. Superhydrophobic coatings can be considered as a promising passive ice mitigation technique for UAVs featuring exceptional capability to repel water, low power consumption, and lightweight properties [5].

The self-cleaning property of the lotus leaf and duck feathers inspired the development of super hydrophobic coatings, 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. These coatings reduce the ice adhesion strength on the surface and thus preventing the ice accumulation. The various methodologies adopted for the fabrication of superhydrophobic coatings are discussed in detail by Zhang et.al [6] and Chauhan [7]. Numerous studies related to different types of superhydrophobic coatings and the applicability of the same as an aircraft anti-icing material is done by Bhushan et al. [8-11]and Farzaneh et al. [12-17].

Wang in 2010 [18] studied the ice accretion on aluminum surface with super hydrophobic coatings by conducting experiments in a climatic chamber with a working temperature of -6^oC. The studies are done with a focus of anti-icing on transmission line, but the insights of such studies are useful in proposing ice mitigation techniques for UAVs. The experiments were conducted on 3 different aluminum surfaces: a hydrophilic surface, a hydrophobic surface and a superhydrophobic surface. During the initial spraying of super cooled water only few areas of the superhydrophobic sample were covered by water droplets, whereas the hydrophobic surface is partially, and hydrophilic surface is fully covered with water droplets. With increase in spraying time the water droplets transformed into ice and is observed that no new ice crystals appeared for the superhydrophobic surfaces with time, the ice start accumulating only on the surfaces initially covered by droplets. Ice started accumulating on more surfaces of hydrophobic surface with time and ice covers the entire hydrophilic surface within a comparatively shorter time.

The use of superhydrophobic coatings as an anti-icing technique for UAVs were also studied by few researchers. Liu in 2017 [19] conducted experimental investigations to understand the effect of surface wettability on the dynamic ice accretion over a UAV propeller. The experiments were conducted for glaze ice conditions at the Iowa State University Icing Research Tunnel (ISU-IRT) for a hydrophilic and superhydrophobic surfaces. The ice accretion on the superhydrophobic surfaces is observed to be much less than the same on hydrophilic surfaces, but still considerable icicle structures were observed along the leading edge of the superhydrophobic propeller. This can be attributed to the fact of low or no shear stress near the stagnation line and thus not able to overcome the capillary forces. Further accumulation of ice occurs over the initial ice surface as it is no longer hydrophobic. It could be interesting to note the capability of superhydrophobic coating to prevent any ice accretion on the surface of propeller due to water runback. The performance degradation of propeller due to ice accretion is also measured during this study. The performance penalties were observed to be less for superhydrophobic surfaces, reduction of the thrust loss (~70% less) and a reduction in power consumption (~75% less) is observed.

Han [20] in 2022 conducted experimental studies on UAV propeller to compare the effectiveness of three different anti-icing coatings: superhydrophobic coating (SHS), Slippery Liquid-Infused Porous Surfaces coating (SLIPS) coating and Stress Localized anti-icing Coating (SLS). SLS and SLIPS attempt to diminish the ice's adhesion force; hence, the ice sheds more quickly. SHS prevents the droplet from adhering to the surface, causing it to fall away. The experimental results demonstrate that both low-adhesion coatings are significantly successful at preventing icing, while the superhydrophobic surface's anti-icing performance is quite subpar. The various challenges related to the durability of superhydrophobic coatings as an ice mitigation technique for UAV is discussed in [6].

The studies related to use of superhydrophobic coatings in UAVs were focused on the rotary wing UAVs. Ice mitigation in such cases happens mainly due to the repulsion of droplets from the surface due to centrifugal forces due to propeller rotation. In case of manned aircraft, the droplets are transported away from the surface by the action of shear force. In case of fixed wing UAVs, the centrifugal effects are absent, and the shear forces are smaller due to low operating velocities. Thus, it is interesting to study the capability of super hydrophobic coatings as an anti-icing technique for small and medium scaled fixed wing UAVs. Most high lift airfoils are characterized by high camber, such high cambers can affect the water transport behaviour on the airfoil surface. Thus, the study focuses on the effectiveness of superhydrophobic coatings as a anti icing technique for UAVs operating at low Reynolds number with highly cambered airfoils.

II. Experimental Methodology

This experimental study was performed in an Icing Research Tunnel available at Aerospace Engineering Department of Iowa State University (ISU-IRT). A schematic of the ISU-IRT icing tunnel is shown in Fig. 1. The ISU-IRT has a test section of 2.0 m in length × 0.4m in width × 0.4m in height with four optically transparent side walls. It has the capacity to generate a maximum wind speed of 60 m/s and an airflow temperature down to −25 ◦C. An array of 8 pneumatic atomizer/spray nozzles are installed at the entrance of the contraction section of ISU-IRT to inject micro-sized water droplets (10 ∼100 μm in size), which can be sufficiently cooled down to the air temperature during the flight along with the airflow before impacting on the model. By manipulating the water flow rate through the spray nozzles, the liquid water content (LWC) in ISU-IRT could be adjusted in the range from LWC=0.1 g/m^3 to 5.0 1 g/m^3. In summary, ISU-IRT can be used to simulate atmospheric icing phenomena over a range of icing conditions (i.e., from dry rime to extremely wet glaze ice conditions). Further information about ISU-IRT is available in Waldman and Hu [21]. The operating conditions for the experimental studies were selected according to the FAR 25 Appendix C icing envelope and it listed in

TABLE 1.

The experiments were performed on a UAV wing with s1223 airfoil having a chord length of 20 cm and wingspan of 40 cm. Uncoated (clean) and coated models are tested in these experiments. The wing model is made of a hard plastic material (VeroWhitePlus, RGD835 by Stratasys, Inc.), and was manufactured using a rapid prototyping machine (3D printer). The surface of the wing model was coated with several layers of spray-on sandable primer. The primed surfaces were then wet-sanded using a series of progressively finer sandpapers (up to 2000 grit) to achieve a very smooth, glossy finish with a characteristic roughness over the propeller surface being about 25μm. Then, a readily available all-weather protective spray-on enamel (Rustoleum, Flat Protective Enamel, white) was coated onto the primed surface. The sanded primer layers would provide a strong adhesion of the enamel onto the propeller surface. Then the surface of the wing was treated with a spray-on superhydrophobic coating (Rust-Oleum™ NeverWet™).

III. Results and Discussion

The experiments were initially performed on the clean wing without any super hydrophobic coating at glaze ice conditions. The ice accretion process is captured using a high-speed camera as a function of time. The lift and drag forces were also measured as a function of time. The wing is coated with the superhydrophobic coating, and the icing tunnel experiments are performed for the same experimental conditions as of clean wings to understand the effect of super hydrophobic coatings on ice accretion.

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A. High Speed Images

The high-speed images for ice accretion on a clean wing at different time instants is shown in Fig. 3. It can be observed from the images that the thickness of ice along the leading edge increases with time. It could be interesting to note that the extent of ice accretion on the wing surface remains same with time and no considerable runback is observed. As the time increases more droplets of water are impinging on the airfoil surface and ice keeps on accumulating on the top of already accumulated ice. Thus, the leading edge of the airfoil is contaminated with more rough ice structures with time. Fig. 4 shows the ice accretion on the wings coated with superhydrophobic coatings. The behaviour of ice formation with time is similar to what is observed for clean wings, but the extend of ice on the airfoil surface is considerably less in this case. The formation of ice is limited to areas very close to the leading edge and the runback is considerably reduced. Because the water droplets are not spreading on the wing surface, the droplets start freezing on the portion very close to leading edge and thus creating more rough structures close to the leading edge. The effect of this change in ice accumulation behaviour on the coated and non-coated models are reflected on the aerodynamic forces. The effect of ice accretion on the aerodynamic forces on the clean and coated models is discussed below. Further a comparison is also made between the variation of forces in the clean and coated cases.

TABLE 1. TEST MATRIX

No	Airfoil	T_{∞}^{oC}	LWC (g/m^3)	MVD (µm)	V_{∞} (m/s)	AOA	Time (S)	Ice Type
1	Clean S1223	-5	2	20	20	0	463	Glaze
2	Coated S1223	-5	2	20	20	0	463	Glaze

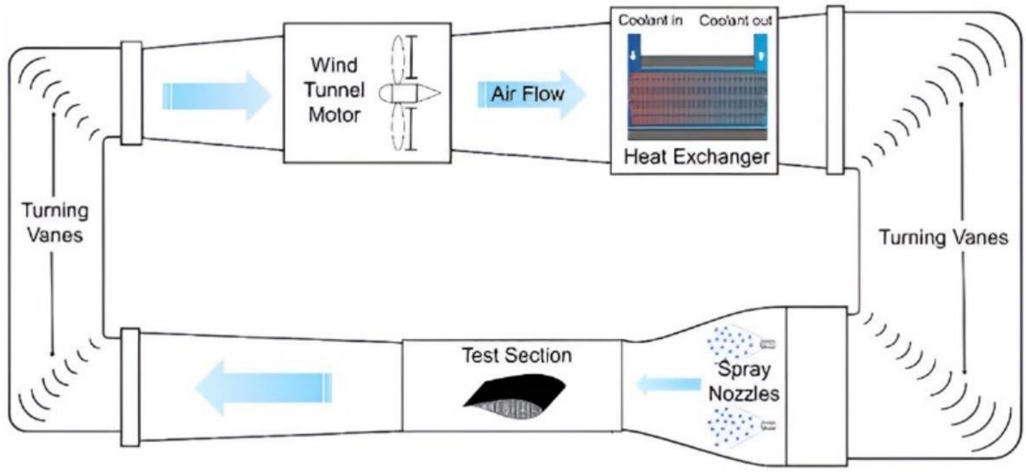

Fig. 1: Schematic of Icing Research Tunnel available at Aerospace Engineering Department of Iowa State University (ISU-IRT)

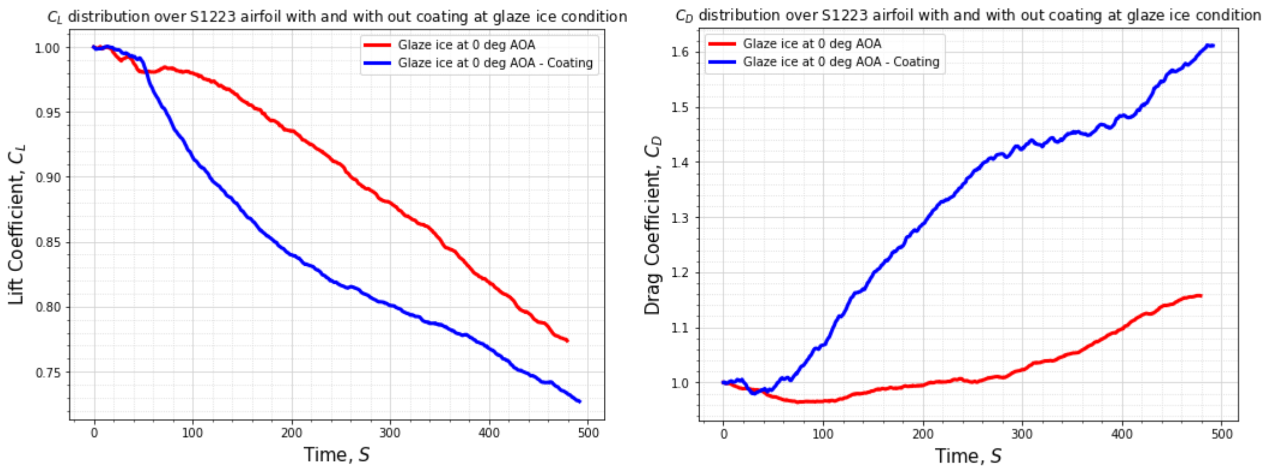

Fig. 2: C_L(left) and C_D (right) distribution over clean and coated S1223 airfoil wing at rime ice condition.

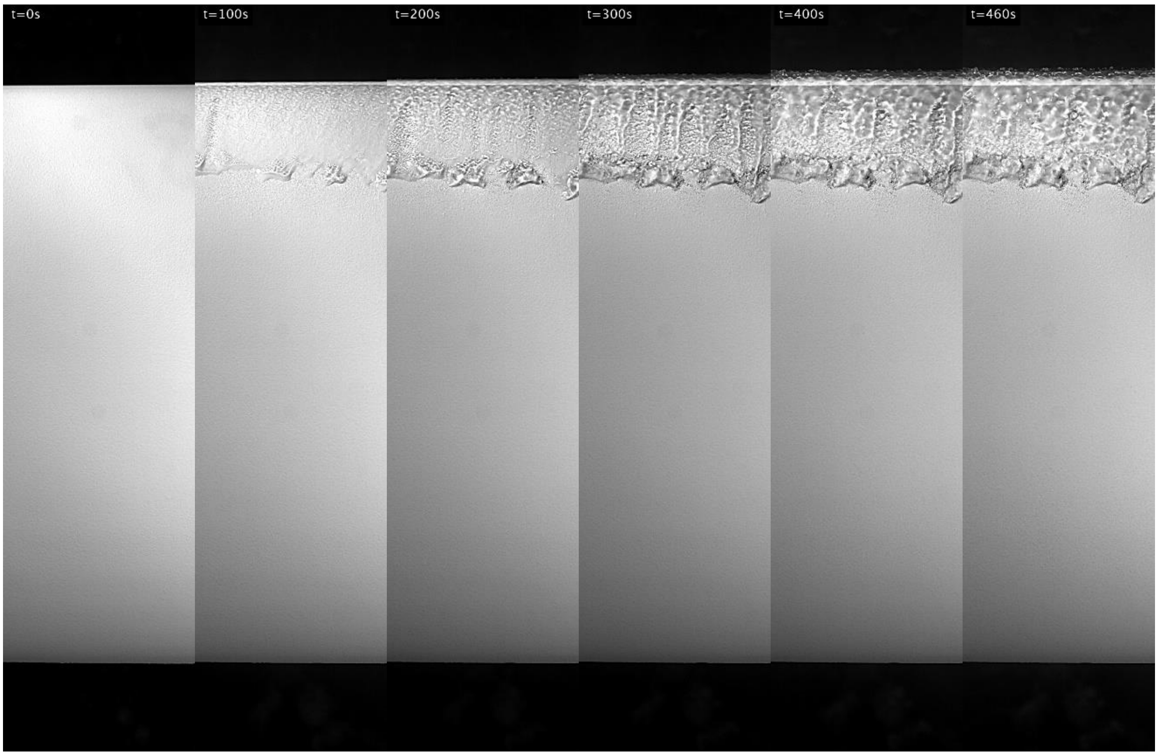

Fig. 3: Ice accretion on the surface of clean UAV wing at glaze ice condition (0,100,200,300,400,460 seconds).

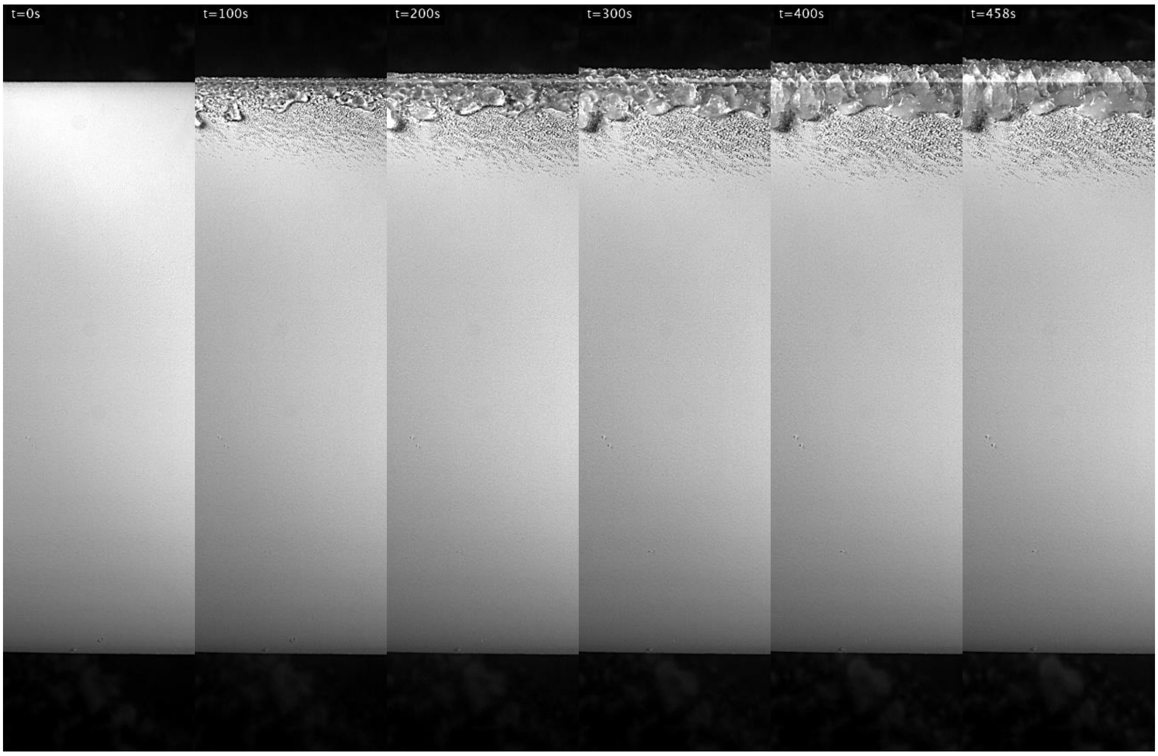

Fig. 4: Ice accretion on the surface of coated UAV wing at glaze ice condition (0,100,200,300,400,460 seconds).

B. Force Measurements|

Aerodynamic force measurements were made for both the coated and uncoated cases, the coefficient of lift (C_L) and coefficient of drag (C_D) are measured as a function of time. The coefficients are normalized by their value at no ice condition. For glaze ice condition, the lift decreases and drag increases with time for both the coated and uncoated cases as shown in Fig. 2. On comparing the lift coefficient of coated and uncoated case, it can be observed that the rate of decrease of lift is more for the coated case than the uncoated case. Also, the drag increases suddenly for the coated wing case as compared to the uncoated case. These observations are not expected as the purpose of applying superhydrophobic coating is to reduce the intensity of icing. But this can be explained with the help of high-speed images. It can be observed from the high-speed images that the accumulation of ice near the leading edge leads to the formation of large rough ice structures near the leading edge and this can lead to flow separation which can lead to increase in drag and decrease of lift.

IV. CONCLUSION

The influence of superhydrophobic coating on the ice accretion behaviour of a high camber UAV airfoil is studied. At glaze ice conditions the coated airfoils lead to agglomeration of water droplets near the leading edge of the airfoil and thus leading to the formation of rough ice structures close to the leading-edge area. Thus, the lift decreases and drag increases at a higher rate than the non-coated ones. Thus, for airfoils with high camber the application of superhydrophobic coatings can lead to rough ice structures close to the leading edge and can lead to more aerodynamic penalties at glaze ice conditions.

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