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Investigation of ice shedding properties of superhydrophobic coatings on helicopter blades

Stefania Tarquini [a,1], Carlo Antonini [a,b], Alidad Amirfazli [c], Marco Marengo [a,*], Jose Palacios [d,*]

[a] Department of Engineering, University of Bergamo, Dalmine, BG, Italy
[b] Laboratory of Thermodynamics in Emerging Technologies, Mechanical and Process Engineering Department, ETH Zurich, 8092 Zurich, Switzerland
[c] Department of Mechanical Engineering, York University, Toronto, ON M3J13P, Canada
[d] Department of Aerospace Engineering, The Pennsylvania State University, University Park, PA 16802, United States

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ABSTRACT

The state-of-the-art of icing protection systems for helicopter rotor blades is based on active thermal de-icing systems that require large amounts of power. This work focused on assessing the potential icephobicity of superhydrophobic coatings as an alternative passive strategy. Ice shedding tests were conducted in a helicopter blade icing chamber, to simulate atmospheric icing conditions. Ice accretion and shedding were tested on four different materials, including two common metals and two superhydrophobic materials, with the objective of evaluating icephobic potential for anti-icing purposes. Coating test results showed a strong influence of temperature and surface roughness on the ice adhesion: the strength increased when temperature decreased and roughness increased. Ice regime was independent of the type of surface used, but superhydrophobic surfaces resulted in a thinner ice shape in comparison with common metals, which resulted in a shorter shedding time, especially in rime ice conditions. The relationship between ice regime and adhesion load showed that ice adhesion load substantially increases in rime ice conditions, demonstrating that ice regime is an important parameter in the ice adhesion process. Additional results showed that superhydrophobic surfaces were associated with a decrease in the adhesion load with respect to the baseline materials ranging from the 16% to the 70% in the best case; but this reduction may not be revealing for practical applications as ice reduction mechanisms need to be first understood.

1. Introduction

Flight into adverse weather conditions is a critical operational issue for helicopters. Icing environment leads to potentially dangerous ice accretion on helicopter blades, which causes a change in the airfoil shape and performance degradation due to decreased lift, increased drag, and increased torque and blade vibration. Furthermore, ice shedding from blades due to centrifugal force poses a ballistic danger to the helicopter and creates large vibrations due to imbalanced rotors (Palacios et al., 2011). Helicopter rotors are more susceptible to icing than fixed wing vehicles of similar gross weight, because their operations occur almost exclusively at low altitudes, between 1000 and 4000 m, where the atmosphere contains supercooled water droplets, leading to an increase in icing potential (Palacios et al., 2011).

The state-of-the-art for ice protection is based on electro-thermal systems that operate as de-icing systems: they activate intermittently to melt the ice layer in contact with the solid surface and to allow ice removal by centrifugal and aerodynamic forces. However, they present several drawbacks: first, electro-thermal systems operate cyclically (to limit power consumption) allowing ice to accrete up to 6–7 mm in thickness prior to removal; and second, these systems only cover the leading edge of the blade, where most ice accretes, leading to the potential formation of the so-called “runback ice”, caused by liquid water flowing in the aft direction. Moreover, they require high power inputs (~4 W/cm^2) (Brouwers et al., 2011) obtained with high weight devices, unsuitable for smaller helicopters (Coffman, 1987; Yaslik et al., 1992). Further, these systems usually rely on high thermal conductivity of leading edge materials, which is not adaptable to new generation erosion resistant polymer based leading edge materials (Palacios et al., 2011).

The need for alternative solutions drove researchers and industry to explore the use of different active and passive strategies to prevent or mitigate ice formation. On one hand, different active technologies such as piezoelectric actuators (Ramanathan et al., 2000), Electro-Impulsive De-Icing (EIDI), and ultrasonic anti-icing devices (Palacios et al., 2006, 2008) have been investigated. On the other hand, the surface coating approach has the advantage to be passive and therefore with the final goal of being a low power, low weight and reliable de-icing system.

In literature, two different coating strategies for icing mitigation can be found: the first one is based on the use of icephobicity, the property

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* Corresponding authors.
E-mail addresses: marco.marengo@unibg.it (M. Marengo), jlp324@psu.edu (J. Palacios).

[1] Present address: Telespazio VEGA Deutschland, Europaplatz 5, 64293 Darmstadt, Germany.

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of surfaces where ice adhesion is low. Literature has many authors who tested these surfaces obtaining benefits in terms of performances (Karmouch et al., 2009; Laforte and Laforte, 2002; Menini and Farzaneh, 2011; Meuler et al., 2010; Raraty and Tabor, 1958); however, in some cases these materials have erosion problems inherent to rotor blade operations (rain, sand particle impact), degrading or losing their icephobic properties after a few tests (Brouwers et al., 2011; Laforte and Laforte, 2002). The second strategy is based on superhydrophobicity, or rather on the use of superhydrophobic surfaces (SHS), which are characterized by low liquid water adhesion (Antonini et al., 2011). Some coatings may exhibit both superhydrophobicity and icephobicity, but the two properties are by definition different.

With respect to the second strategy based on superhydrophobicity, the idea is to take advantage of water repellency, to reduce or eliminate water accumulation on the surface before water freezes by letting droplets rebound off the aerodynamic surface. This approach was explored by Antonini et al. (2011), where it was shown, by means of Icing Wind Tunnel (IWT) tests on fixed wing configurations that a superhydrophobic coating helped to reduce heat power input from 20% to 80%, depending on icing conditions. As explained in Marengo et al. (2011) and Quéré (2005), SHS are effective because they allow water drop rebound and liquid water shedding due to reduced capillary adhesion.

By changing temperature, Liquid Water Content (LWC) and Mean Volumetric Diameter (MVD), ice regimes can be reproduced to simulate natural icing conditions. There are 3 main ice regimes: *glaze* ice is obtained for temperatures from 0 °C to around −14 °C and it is characterized by a transparent color with ice accretion shapes presenting horn formations. *Rime* ice is obtained from around −14 °C below to lower temperatures, it has a milky white color, the ice shape follows the aerodynamic shape of the airfoil and it is the most difficult type of ice to detach. *Mixed* ice is the mixed regime between glaze and rime ice. While literature includes studies about ice adhesion at various temperatures, LWC and MVD (Anderson, 2004) or studies about ice regimes and ice shape in varying temperatures, there are no studies that correlate ice regime and icing conditions.

In the present study, icephobic properties of superhydrophobic coatings were investigated with application to rotor blades. In particular, experiments were performed on superhydrophobic surfaces to understand if they are also icephobic. From this perspective, icing tests on rotor blades represent a valuable test case because of the presence of centrifugal forces and higher impact velocities: by studying ice accretion and shedding in an environment that simulates natural atmospheric icing conditions, it is possible to evaluate if a coating can be effective in reducing ice adhesion compared to common materials on a blade where a thermal system is not present. The final objective of the study is to analyze the importance of parameters like temperature, LWC, MVD, surface roughness, wettability on ice regime and ice shedding, with the aim of assessing the potential icephobic properties of superhydrophobic surfaces, compared to standard metallic materials.

2. Superhydrophobic and icephobic surfaces

Superhydrophobic surfaces are typically characterized by large contact angles (the angles calculated at the interface between liquid, solid and vapor) and by a low contact angle hysteresis ($\Delta\theta$, the difference between the advancing contact angle, θ_A, and the receding contact angle, θ_R). The generally stated definition of superhydrophobicity considers surfaces with contact angles (both θ_A and θ_R) greater than 150° and $\Delta\theta < 10°$. Recently, by performing controlled drop slide on a horizontal surface, Rioboo et al. (2012) found that only when the receding contact angle, θ_R was above 135° the drop slid and proposed to use this limit to define superhydrophobicity. Interestingly, the experimentally identified value is very close to the lower value of the stable receding contact angle for the Cassie–Baxter state, in which air pockets are present at the solid–liquid interface on pillar-like surfaces, on the basis of the thermodynamic principle of energy minimization (Li and Amirfazli, 2005). The gas pockets at the solid–liquid interface reduce the real ice/coating surface area, disrupting bonding by creating stress concentrations and minimizing frost formation (Boreyko and Collier, 2013). Thanks to the combination of high contact angles and low hysteresis, on a superhydrophobic surface drops show a high mobility (Pierce et al., 2008) and impacting drops can rebound after the collision (Antonini et al., 2013), even before ice nucleation occurs on the substrate (Boreyko and Collier, 2013; Boreyko et al., 2013; Mishchenko et al., 2010) in icing conditions. For this reason, superhydrophobic surfaces, which are characterized by very low liquid water adhesion, have started to attract interest for their potential in icing mitigation. This idea has led to the concept of icephobicity, a term which has been used with a variety of meaning in the literature, and in particular it has been associated to low ice adhesion (Kulinich and Farzaneh, 2009; Meuler et al., 2010; Varanasi et al., 2010), freezing temperature depression (Charpentier et al., 2013) or freezing time delay (Alizadeh et al., 2012; Tourkine et al., 2009), or minimization of frost formation (Boreyko and Collier, 2013). In the present paper, the term icephobicity is attributed to surfaces on which ice adhesion is low and that delay ice formation from condensed or incoming water in the situation where normally ice would form (Hejazi et al., 2013), since the interest is to find a coating to promote ice shedding from a rotor blade.

The reason why supercooled droplets impacting on a solid surface freeze and cause ice accumulations can be explained by means of the nucleation theory: if atmospheric water drops can stay supercooled in clouds because crystal nucleation and growth may take a long time, the contact with a solid surface acting as substrate for crystal nucleation would accelerate the crystallization process, a phenomenon known as heterogeneous nucleation (Sastry, 2005). In addition, the crystallization process becomes faster at lower temperatures, since the rate at which critical nuclei are generated, J, within the growing drop depends exponentially on the inverse of temperatures, i.e. $J \propto e^{-1/T}$.

Whether or not superhydrophobicity implies icephobicity and vice versa, it is a debated topic (Hejazi et al., 2013; Jung et al., 2011; Kulinich et al., 2011; Meuler et al., 2010; Nosonvsky and Hejazi, 2012), but generally it is a misunderstanding to believe that to design a surface with high contact angles should consequently lead to an icephobic surface. Nosonvsky and Hejazi (2012) explain that the microcracks induced by a Cassie state might not be big enough to ensure a weakening of the ice adhesion; Cao et al. (2009) find that the anti-icing capability of the surface depends not only on their superhydrophobicity but also on the surface morphology and Varanasi et al. (2010) found that icephobic properties of superhydrophobic surfaces can be compromised in the case of frost formation that occurs at below-zero temperatures (tests were performed at −5 °C, analyzing impact of millimetric water drops). Therefore, the purpose of this paper to study the icephobicity of superhydrophobic materials using conditions close to real icing conditions might be a valid topic.

3. Review of ice adhesion studies

Many studies presented in the literature focused on ice adhesion of common metals, as well as low adhesion materials. However, a critical issue is the comparison of reported results. Table 1 shows the results obtained by different authors in terms of adhesion strength for aluminum at the same temperature. Lack of accordance for ice adhesion strength is found even for this well-known standard material: comparing the data obtained for the same material (at −10 °C/−11 °C), values from the literature range from a minimum of 70 kPa (Itagaki, 1983), to a maximum of 931 KPa (Reich, 1994).

Multiple reasons can be found to explain such discrepancies (Brouwers et al., 2011). The first problem is the difference in test methodology and facilities, showed in Table 1 (Javan-Mashmool et al., 2006; LaForte and Beisswenger, 2005; Reich, 1994; Scavuzzo et al., 1987; Stallabrass and Price, 1962). Other authors used different shapes from airfoils in their experiments (Itagaki, 1983; LaForte and Beisswenger,