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INFLUENCE OF SUPERHYDROPHOBIC PROPERTIES ON DEICING

Nowadays the creation of anti-icing, or deicing, surfaces is one of the most important problems, as such surfaces are widely used in aeronautics, wind turbines, and telecommunication antennas. In this paper, we focus mainly on reducing the ice adhesion forces and easy ice removing, once ice has formed. Removal of a liquid from a surface can be provided by modification of the surface wettability by means of applying superhydrophobic coatings. Such coatings are water-resistant, i.e., are characterized by low water adhesion forces. To study the impact of superhydrophobic coatings, tests were performed on the surface of a wing in a wind tunnel. By spraying Teflon and polyphenylene sulfide (PPS) on the wing, we obtained a superhydrophobic film. This film has the structure that provides superhydrophobic properties, so that the wetting angle is above 140°. A comparison of the resulting surface with a clean Teflon one shows that adhesion of the Teflon + PPS mixture to an aluminum surface is five times higher. We also investigate the degree of ice formation on the surfaces of simple and superhydrophobic aircraft wings at a temperature of –18°C. It was shown that ice was formed on a simple wing within 40 s and on a superhydrophobic wing within 25 s. When the simple wing with a mass of 23 g was inserted into the wind tunnel, its mass reached 50 g, and for a superhydrophobic wing with a mass of 26 g the latter reached 42 g. The sample of the airfoil wing we prepared has a low adhesion, which helps in easy ice removing.

Keywords: *superhydrophobic properties, deicing, wettability, airfoil.*

Introduction. Deicing implies the removal of snow, ice or frost from a surface and is usually understood to be due to the application of chemicals or heat to remove the ice or delay its reformation for a certain period of time. Icing can also be mitigated, if ice accumulation on the surface is reduced by water shedding from it. Deicing can be enhanced by modification of the surface wettability, e.g., by the application of superhydrophobic coatings, i.e., water-repellent coatings characterized by low water adhesion forces.

The wettability of a solid surface can be determined by the shape of a drop deposited on it (a water drop in the present study). A surface with a high wettability (hydrophilic) tends to allow a drop to spread over a relatively wide area of the surface, i.e., to wet it. On a surface with a low wettability (hydrophobic), a drop tends to retain a spherical shape, and drops can be usually shed from the surface by a slight disturbance, e.g., by surface vibration or tilting (especially in the case of a superhydrophobic surface).

Anderson and Reich [1] conducted preliminary qualitative evaluations for removing impact ice (i.e., ice formed after impact of liquid water drops on a surface) from various surfaces. Their estimates of the ice adhesion force on coated and uncoated surfaces subjected to atmospheric icing in a wind tunnel showed that ice accretion was solely dependent on the tunnel and cloud conditions and not on the surface covered with ice. It was shown that as soon as a thin layer of ice is formed on the surface, the coating is not effective any longer due to the accumulation of impacting drops on the already iced surface. Furthermore, static ice-shear tests confirmed that the tested coatings did not provide a substantial reduction in the ice adhesion, which can promote better ice shedding compared to uncoated aluminum samples.

The typical parameter used to characterize the solid surface wettability is the contact angle which is the angle formed between the liquid–solid and liquid–vapor interfaces (see Fig. 1). A basic relation for the contact angle attributed to Young [2] can be derived by balancing the surface tensions γ_{ij} acting at each ij interface (liquid–vapor, liquid–solid, and vapor–solid):

$$\cos\theta_{eq} = \frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}}, \quad (1)$$

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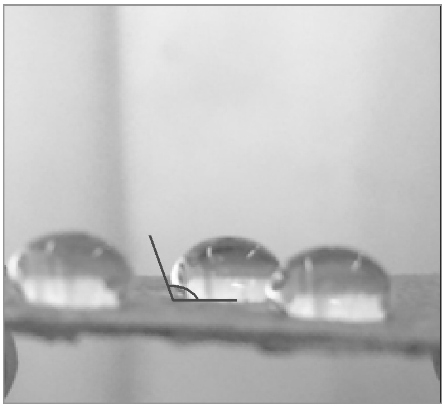

Fig. 1. Behavior of water droplets on a hydrophobic and deicing metal surface.

where θ_{eq} is the equilibrium contact angle and the subscripts indicate the corresponding interfaces. The drop shape can be approximated by a truncated sphere [3], if the drop size is smaller than the capillary length $l_{cap} = (\gamma/\rho g)^{1/2} \approx 2.7$ mm, where ρ is the water density and g is the acceleration due to gravity. Equation (1) is valid only for a sessile drop placed on an ideal, homogeneous, and smooth surface. When a surface is rough, two wetting states, namely, the Wenzel [4] and Cassie–Baxter [5] states, can be observed. In the Wenzel state, the liquid penetrates the surface grooves and wets the surface completely. The contact angle under these conditions is given as [4]

$$\cos \theta_W = r \cos \theta_{eq} , \quad (2)$$

where the roughness factor r is the ratio of the surface area of a solid in contact with a liquid to its horizontal projection ($r > 1$). In the Cassie–Baxter state, the liquid bridges are formed across the tops of the surface protrusions, and the drop sits upon a composite surface of solid and vapor pockets. Here the contact angle is given by

$$\cos \theta_{CB} = f \cos \theta_{eq} - (1 - f) , \quad (3)$$

where f is the fraction of the area, when the liquid is in direct contact with the surface ($f < 1$). Figure 1 shows the behavior of water droplets on a hydrophobic surface. A combined state, where a liquid partially penetrates the surface grooves, is also possible.

The results of the icing wind tunnel tests demonstrated that the surface wettability is an important controlling factor not only for reducing ice accretion on the wing, but also for reducing (by about 80%) the energy required to avoid such an accretion.

The authors of most of the works generally try to attribute the ice accretion reduction to low ice adhesion [6–10]. However, some studies [11–13] pointed out that even if the ice adhesion can be reduced by icephobic or superhydrophobic coatings, compared to metal surfaces, such a reduction is not sufficient for shedding ice by means of an external force, e.g., by gravity or aerodynamic forces. Hydrophobicity was used as the working principle of icing mitigation, e.g., by correlating the contact angle and the strength of ice adhesion. Nevertheless, no universally accepted quantitative correlation between the hydrophobicity and ice accretion has been proposed as yet. Moreover, only the value of the static contact angle is normally applied to define the surface wettability, and the contact angle hysteresis, another important parameter to determine liquid shedding of a coating, is often neglected. The majority of studies dealing with coatings focused mainly on reducing the ice adhesion forces to easily remove ice, once it formed.

In this study, we focus on an alternative strategy that consists in promoting the shedding of liquid water to reduce the total amount of water present on the surface that can freeze.

The aims of our work are: to quantify the benefits that application of anti-icing and superhydrophobic coatings can provide in terms of energy saving, to provide a mechanistic explanation of the liquid drop–surface interaction under icing conditions, and to explain why wettability can have a positive effect in structure protection against ice formation.

Experiments. Deicing of an aircraft is accomplished by applying a protective layer with the use of a viscous fluid, called an anti-icing fluid, over a surface to absorb the contaminants. All anti-icing fluids offer only limited protection, dependent on the type of frozen contaminants and the prevailing weather conditions. The fluid fails when it can no longer absorb contaminants, and it essentially becomes a contaminant itself. Even water can be a contaminant in this sense, as it dilutes the anti-icing agent and the latter becomes no longer effective. Figure 2 presents the schematic of an open-loop icing wind tunnel taken from [13]. Figure 3 shows the picture of the test rig provided with cord net icing used for experiments.

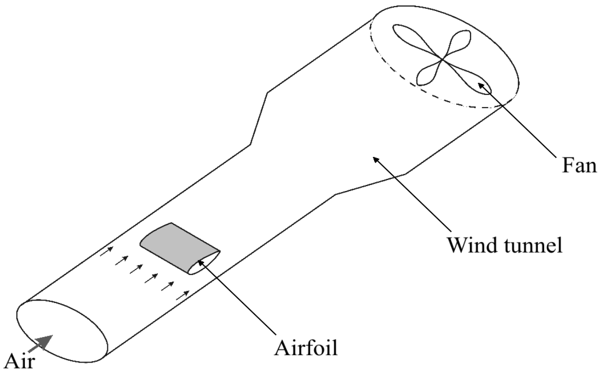

Fig. 2. Schematic of the open-loop icing wind tunnel [13].

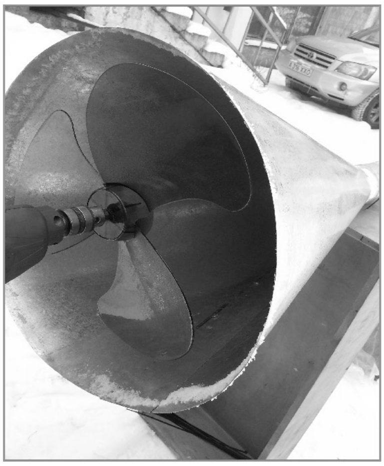

Fig. 3. Experimental setup for an icing wind tunnel.

The advantage of the test rig is its low cost and simplicity which allows quick screening of various coatings and can be of assistance in educational training. This setup can be used outdoor in cold winter months. The same setup is applied in a refrigeration system.

In our study, a NASA 0021 airfoil was used, as shown in Fig. 4. The mixture contained 20% PPS and 80% triton X-100. We sprayed the prepared mixture on an Al surface, and the surface was dried at a temperature of 80°C for 10 min. Then we heated it in a muffle furnace at temperatures of 320–380°C for one hour. The resulting mixture was used as a spray at an angle with the horizon of 45°C. We repeated spraying three times. As a result, we obtained a superhydrophobic surface which had the wetting angle above 140°. Figure 5 shows the drop impact on a superhydrophobic surface.

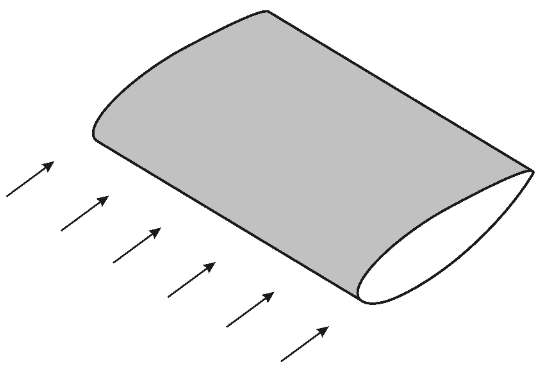

Fig. 4. Schematic of the NACA 0021 airfoil.

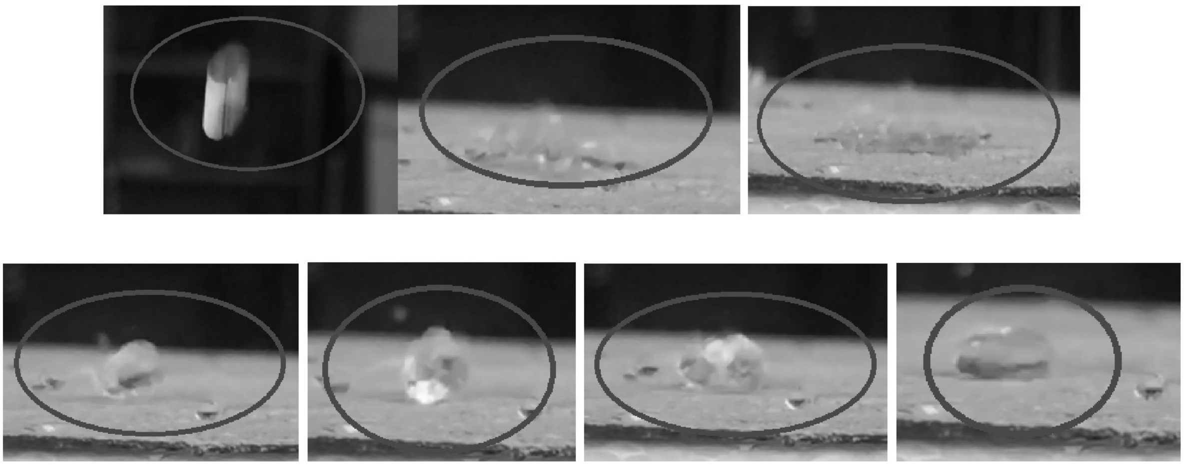

Fig. 5. Sequence of drop impact on a superhydrophobic surface.

Results and Discussion. The present results of the icing tests were obtained on the polythenylsulfyd-coated hydrophilic untreated aluminum surfaces and superhydrophobic Teflon-coated etched aluminum surfaces. As a solution, we used triton X-100 (0.5 %).

Before an airplane takes off, a surfactant is sprayed on its surface. However, this process is not economically advantageous and efficient in time. For this purpose, the wing must be made of a material that reduces adhesion. Icing occurs, because the water easily gets on an airplane wing. To avoid this, we need to make the wing superhydrophobic.

By spraying Teflon [14] and polyphenylene sulfide (PPS) on the wing, we got a superhydrophobic film. The film had the structure that gave superhydrophobic properties to the resulting surface. A comparison of the resulting surface with a clean Teflon one enables us to conclude that the adhesion of Teflon + PPS mixture on an aluminum surface is five times higher.

Polyphenylene sulfide is one of the newest high-tech engineering thermoplastics. It has a good fire-, heat-, and chemical resistances, high strength and elasticity, good dielectric properties, the possibility of molding of complex parts and components with very precise dimensions. It is a polymer used in automotive and aerospace industries, mechanical engineering, oil and gas industries, electrical and electronics, light engineering, etc. It successfully replaces not only other thermoplastics and thermosets, but also metals. We used triton X-100 as a solvent for PPS.

The main purpose of the coatings considered is to minimize the force of adhesion of ice to the surface and to retain this property over a long period of operation. It is well known that the strength of adhesion of ice to a coating is determined by the chemical nature of the film formed, and, according to the thermodynamic concept of adhesion, it is a function of the surface energy or surface tension. We placed water droplets on the surface obtained. It was shown that the superhydrophobic properties resulted in the wetting angle above 140°, as presented in Fig. 6.

The value of the surface tension of liquid determined experimentally and the critical surface tension characterizing the surface tension of polymer surfaces were used. With increasing difference between them, the fluidity of the coating layer covering the surface is reduced. The reduced wetting of the surface reduces the contact area between water and the coated frozen surface and, as a consequence, reduces adhesion of ice to the coating. In other words, the formation of ice occurs on the surface and anti-icing coatings, but the use of paint materials with a low surface energy allows one to significantly reduce the cost of mechanical removal of ice from the surfaces of various structures and constructions. From a scientific point of view, the hydrophobic properties of coatings are provided by their chemical composition and physicochemical properties of their surfaces.

Fig. 6. Al surface obtained.

Icing of a surface is conditioned by its hydrophobicity, because, despite the specific conditions of the state of the object exposed to icing (slope and roofing, the presence of a warm air flow, etc.), from the physical point of view, the area of contact of a water droplet with a surface is the decisive factor. Therefore, the contact angle characterizes the hydrophobic and deicing surface properties. Currently, several known methods impart hydrophobic properties to the surfaces. The most radical way is the creation of a special topology, or architecture, of the surface. Figure 7 shows such polymer chains as an example.

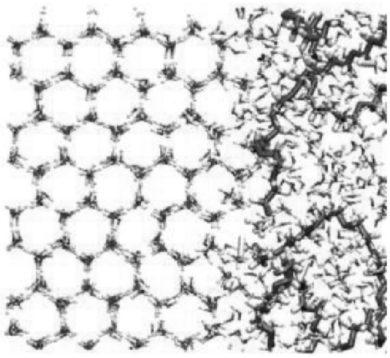

Fig. 7. Polymer chains.

To compare the degree of ice formation on the surface of simple and superhydrophobic aircraft wings at a temperature of –18°C, water and air were injected into a wind tunnel (see Fig. 8).

The surface area of the simple aircraft wing was equal to 60 cm^2. The wing with mass m_1 = 23 g was inserted into the wind tunnel. As a result, within 40 s the mass reached the value m_2 = 50 g. The surface area of the superhydrophobic aircraft wing was also 60 cm^2, and its mass was equal to m_1 = 26 g. After its insertion into the wind tunnel, within 125 s its mass reached m_2 = 42 g.

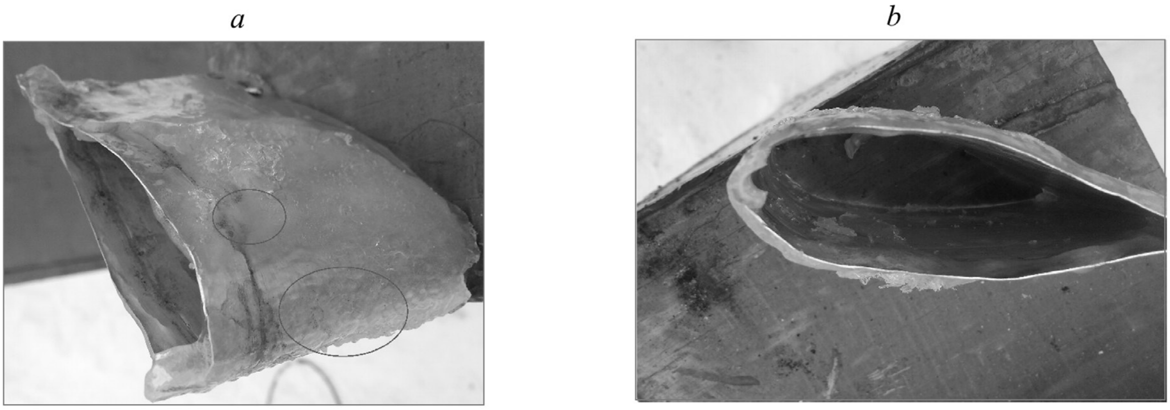

Fig. 8. Ice formation on the aircraft wings: simple wing within 40 s (a) and superhydrophobic wing within 125 s (b).

Conclusions. High adhesion usually takes place between the surface and ice, which results in the ice formation. The sample of an aircraft wing we prepared has a low adhesion that helps in easy ice removing. The prepared anti-icing surface has benefits, namely, it delays the reformation of ice for a certain period of time, or prevents ice adhesion, so that mechanical removal becomes easier. The application of anti-icing and superhydrophobic coatings can provide energy saving. The results obtained can help in explanation of a positive effect of wettability in the structure protection against ice formation.

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