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# Methods for Mitigation of Icing with Using Superhydrophobic Surfaces

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***Abstract –*** In many engineering applications such as aerospace, automotive and telecommunications, icing leads to mechanical and socio-economic problems such as efficiency reduction, decreased power transmission, security threat, material damage and energy waste. Therefore, it is important to investigate anti-icing applications. Nowadays, the methods used to prevent or reduce ice formation are inadequate, in addition this methods are costly (e.g. laser application) and harmful to the environment due to applications like chemical spraying. On the other hand, as a promising passive anti-icing application, superhydrophobic (water-repellent) surfaces come to the fore. Although anti-icing surfaces with low ice adhesion behavior are already used as a precaution. This method is applied to facilitate the separation of ice from the surface after the formation of ice. However, we know that icing is caused by the condensation of moisture in the environment on surfaces exposed to subzero temperatures or by the impact of droplets on the cold surfaces. In addition, studies show that once the ice has taken place, the water adhesion on the surface will increase and the icing process will accelerate. It is therefore more plausible to focus on the investigation and application of superhydrophobic surfaces instead of icephobic surfaces. The superhydrophobic surfaces, which have been proven to be applicable as an anti-icing measure, are characterized by the fact that the droplets form a large contact angle with the surface. While the surface-contacting interface of the droplet is thus reduced, its ability to move on the surface increases. Thus, the droplet can easily leave the surface by gravity and / or the flow of fluid in contact with the droplet after it has hit the surface or formed almost as a sphere on the surface. The parameters that affect the moving ability of liquids on a surface are of course not only surface properties. However, it should be noted that the common parameter for all liquids are the surface properties. Superhydrophobic surfaces have certain limitations besides the mentioned advantages. These include high precision in surface treatment and production; methods such as coating and painting applied to the surface are not resistant to extreme environmental conditions; at certain temperatures the surface is going to shed its superhydrophobicity. Although the constraints have been examined in the literature, there are very few and superficial information about the properties of the superhydrophobic surfaces in which environmental conditions are maintained.

***Keywords*** *– Anti-icing, Superhydrophobicity, Micro-structured Surfaces, Heat Transfer, Fluid Mechanics*

## I. Introduction

The formation of ice on the surfaces in cold environments leads to socioeconomic costs due to material damage, waste of energy and ongoing prevention of hazards. Many commercial sectors, such as the automotive, aerospace, railway, telecommunications and energy industries, are exposed to the negative effects of ice formation. Some of these effects are: Weight increase at the place where the icing occurs, unbalance of the weight, decrease in the force transfer, and decrease of the lifting force on the wings in aircraft. Therefore, there is a need to prevent the formation and accumulation of ice on the surfaces exposed to low temperatures. So far, the main methods to prevent ice formation are the coating with surface heating and surface anti-icing chemicals, which are both costly and environmentally problematic. In the automotive industry, for example, heating surfaces exposed to cold air not only causes energy wasting, but can also pose a danger as icing that occurs on windscreen causes poor visibility. Therefore, there is a real need for passive anti-icing prevention measures and an intensive effort has been made to investigate possible solutions [1].

## II. Superhydrophobic Surfaces for Anti-Icing Applications

Nowadays, as a candidate for more effective anti-icing applications, superhydrophobic surfaces appear to be at the forefront. Various anti-icing properties of superhydrophobic surfaces have been reported in several studies. For example, it has been shown that the adhesion force between the ice layer and the surface is lower than the untreated reference surfaces on the superhydrophobic surfaces. In addition, it is indicated that superhydrophobic surfaces can throw off cold water droplets waiting to freeze before ice nucleation has occurred. It was also observed that superhydrophobic surfaces exhibited very little ice-holding behavior under naturally occurring ice rain in the water-cooled laboratory experiments. Similar experiments demonstrate the feasibility of using superhydrophobic coatings as passive elements in anti-icing applications.

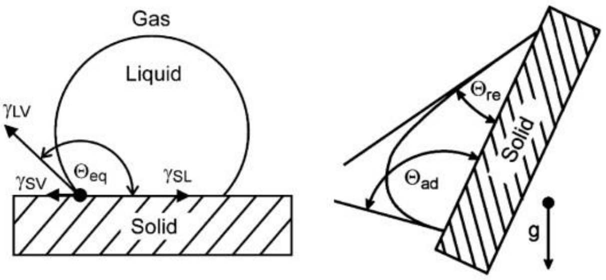


**Figure 1**: Static and dynamic contact angles over a surface. [2]

As can be seen in Figure 1, when reference is made to the equilibrium contact angle ($\theta_{eq}$) for the stationary droplet, the advancing contact angle ($\theta_{ad}$) and the receding contact angle ($\theta_{re}$) are referenced for the droplet in motion. The difference between the two contact angles of a droplet in motion is called contact angle hysteresis. Superhydrophobic surfaces have contact angles greater than 150° and very small contact angle hysteresis.

In the past decade, the term icephobicity, which distinguishes the properties of a low ice-adhesion-based surface from the superhydrophobic, has been demonstrated. It is also important to note that a superhydrophobic surface does not always exhibit icephobic behavior. The spontaneous detachment of the ice under ambient conditions depends more on the ambient water content and the icing conditions, such as the droplet diameter in the same environment. Lower liquid water content and lower droplet diameter make it easier to remove superhydrophobic surfaces from ice [3]. In addition, despite the increased surface tension of water at low temperatures, the interface area between both the droplet-surrounding air and the droplet-surface increase. As can be seen in Figure 2, the droplet-surface contact area increases (in the case of a) and d), the contact area limits are shown with red dots) and the droplet contact angle decreases. As a result, the surface may tend to show hydrophilic properties at low surface temperatures. Therefore, it is seen that there is a need for superhydrophobic surfaces which will not lose its characteristic even under the freezing temperature of the liquid which will undergo phase change [2], [4].

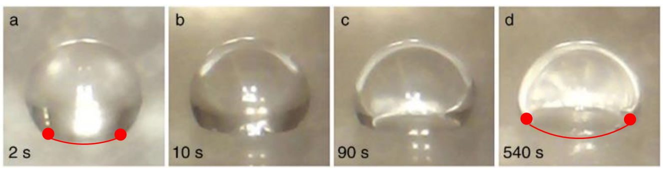


**Figure 2:** Structural transformation of the droplet on a superhydrophobic surface while cooling from room temperature to –10°C.

From hydrophilic to hydrophobic surface, contact angle hysteresis is reduced [5], [6]. This transition facilitates the movement of the liquid on the surface. In the experiments performed, it was seen that the droplets exhibited a low mobility due to the irregular shapes on the surface at low contact angle, high contact angle hysteresis. It has been reported that with the increase of contact angle, the shape of the droplet changes to a spherical-like regular structure and the droplet has a higher mobility with the reduction of contact angle hysteresis [7]. In addition, surface roughness and chemical heterogeneity of the surface can facilitate the initiation of a droplet movement [8]. As is often referred to in the literature, droplets are not detach from the surface only by gravity or by wind speed. Droplets can jump over the surface, even in very low amounts [9]. The more droplets coalescence on the surface, the more droplet jumping appears. The droplet jumping rate depends on the surface tension of the coalesced droplets. In addition, the symmetrical positions before the coalition were found to increase this situation positively.

Care should be taken to ensure that the droplets on the surface do not exhibit spreading, as we pay attention that the drops do not remain on the surface for a long time. There are two important dimensionless that influence the dynamics of droplet impact. These are Weber and Ohnesorge numbers:

$$We = \frac{\rho D V_0^2}{\sigma},\ Oh = \frac{\mu}{(\rho\sigma D)^{1/2}}$$

$\rho$: Density, $\sigma$: Surface Tension, $\mu$: Dynamic Viscosity, $V_0$: Impact Velocity, $D$: Droplet Diameter

In superhydrophobic systems, almost spherical complete rebound is observed in the droplet after impact to *We* = 0.07 (see Figure 3). After *We* = 18, partial rebound is seen instead of complete rebound (see Figure 4). In the conditions between these two values, the droplet forms a pyramid-like structure on the surface (see Figure 5) [8]. The spread of the droplet after it impacts the surface is increased by increasing the number of Weber, and it is narrowed by increasing the surface roughness and the Ohnesorge number [10]. On moving surfaces, the droplet carries out an asymmetric spread after the collision. The increasing vertical impact velocity leads to the diameter expansion of the lamella, while the increase of the surface velocity causes the lamella to extend in the direction of movement [11]. In terms of sloped surfaces, it can be said that as the surface temperature increases, the droplet shows partial or complete rebound [8]. The contact time of the droplet from collision to jumping did not make a significant difference by varying the impact velocity. The contact time mostly increases as the droplet diameter increases [12].

**Figure 3:** Complete rebound movement of a droplet after impact on the surface under *We* < 0.07 conditions [8].

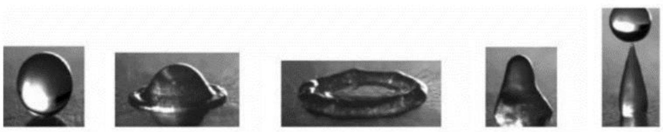

**Figure 4:** Partial rebound of a droplet after impact on the surface under *We* > 18 conditions [8].

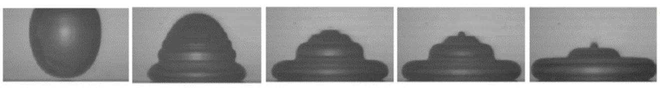

**Figure 5:** Pyramid-like spread of a droplet after impact on the surface at 0.07 < *We* < 18 conditions [8].

**Table 1: Parameters used in some original experiments selected from the literature.**

| Author | Material | Modification | Liquid | Liquid Properties | Ambient Conditions |
|---|---|---|---|---|---|
| Rioboo et al., 2001 | Glass | Laser Ablation | Water | Impact Velocity: 0.78→4.1 m/s Droplet Diameter: 0.07→3.5 mm | Room temperature and conditions |
| | PVC | | Ethanol | | |
| | Wax | | Glycerin + Water | | |
| | Alkylketenedimer | | Silicone Oil | | |
| Milne and Amirfazli, 2009 | Teflon | Spin Coating | Hexadecane | Droplet Volume: 0.5→100 μL | Room temperature and conditions Air Velocity: 0→30 m/s |
| | Superhydrophobic (SH) Teflon | | Water | | |
| | PMMA (Polymethyl Methacrylate) | | | | |
| Antonini et al., 2012 | Untreated Glass | - | Water | Impact Velocity: 0.9→4.2 m/s Droplet Diameter: 2.86 mm | Room temperature and conditions |
| | PMMA | Spray Coating | | | |
| | Teflon | | | | |
| | SH Teflon | | | | |
| | Zonyl | | | | |
| | OTS (Octadecyltrichlorosilane) | Grafting | | | |
| Mandal et al., 2015 | PMMA | Spin Coating | Water | Droplet Volume: 5→100 μL Temperature: 0.6°C | Air Temperature: –1→24.5°C |
| | Teflon | | | | |
| | SH Teflon | | | | |
| Chu et al., 2017 | Untreated Aluminum | - | Humid on the ambient air | - | Air Temperature: 20°C Relative Humidity: 50 % |
| | Fluoroalkylsilane (Aluminum) | Dip Coating | | | |
| | Etched Aluminum | Chemical Etching | | | |

Coating the surface with superhydrophobic materials or milling alone will not be sufficient to prevent icing. Nowadays, various anti-icing and ice-breaking systems have been developed to prevent and reduce icing on surfaces. Although the available techniques are still useful, they require additional energy, such as hot air, chemical or electrical energy [13]. However, the integration of the coating technique into existing systems will both increase the efficiency of these systems and significantly reduce the need for additional energy. Studies show that superhydrophobic surface formation techniques can be reduced by up to 80 % in the additional energy requirements required when applied together with the existing methods [1], [14], [15].

According to some studies that show the importance of preventing icing before it has already started, if the icing has started once, the surface wettability has no effect on the type of frosting [16]. In icing conditions, rather than hydrophobic-hydrophilic surface difference, frozen or not yet frozen surface difference effect to the droplet dynamics [16]. For this reason, the critical air velocity that starts to sweep of the droplet from the surface, which is suspended to freeze on the frozen surface, increases. That is, the frozen surface reduces the air friction coefficient ($C_D$) of the droplet [17]. In the case of the already frosted wing in the aircraft example, the airflow will cause the rapid icing, as it may not be sufficient to separate the droplet from the ice mass. This can reduce the lifting force of the wing as well as increasing aerodynamic imbalance.

## III. DISCUSSION

In the literature, conflicts, deficiencies and the needs they give rise to are as follows: Superhydrophobic surfaces are seen to be very effective in preventing icing. However, some important studies show that; The surface loses its superhydrophobicity at certain temperature ranges below the freezing temperature of water (–50°C to 0°C), which vary according to the material. A clear determination of the temperature ranges for superhydrophobicity is important to know the conditions under which these surfaces can be used in anti-icing applications.

Surface roughness is one of the most important parameters in the fabrication of superhydrophobic surfaces. Even when the surface is coated with a solution, the main factor affecting the liquid-solid relationship is the surface roughness. However, a remarkable study reported that the rotating coated surface showed higher liquid-solid surface contact angle values than others. On the contrary, in the past studies, it was stated that the coating area is limited as its thermo-mechanical working range is narrow. These contradictions in the literature have led to the need to clearly reveal the relationship between the coating types and the liquid-solid surface contact angle.

## IV. CONCLUSION

In the scientific studies carried out to date, the icing process has been examined in many ways by experimental and numerical methods. Table 1 summarizes the parameters examined in the original experiments. The limits of these parameters include other articles published on our topic. In particular, there are wide information on surface contact angles. However, there are quite a few reviews of the aforementioned aspects. There is also no comprehensive study on superhydrophobic surfaces under which conditions exhibit anti-icing properties.

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