May 2022

IEA Wind TCP Task 19

Technical Report

Definition of Best Practice for Testing Icephobic Surfaces

iea wind

Technical Report

Results of IEA Wind TCP “Definition of Best Practice for Testing Icephobic Surfaces”

Prepared for the
International Energy Agency Wind Implementing Agreement

Prepared by
Nadine Rehfeld, Fraunhofer IFAM, Germany
Charles Godreau, Nergica, Canada
Xianghui Hou, University of Nottingham, UK
Taeseong Kim and Holger Koss, DTU, DK
Jianying He, Norwegian University of Science and Technology, Norway
Claas Rittinghaus, Energiewerkstatt, Austria

3rd May 2022

Acknowledgements

The International Energy Agency (IEA) is an intergovernmental organization that works to shape a secure and sustainable future for all, through our focus on all fuels and all technologies, and our analysis and policy advice to governments and industry around the world.

The Technology Collaboration Program (TCP) is a multilateral mechanism established by the IEA with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of thousands of experts across government, academia and industry in 55 countries dedicated to advancing common research and the application of specific energy technologies.

Views of the IEA Wind TCP are not those of the IEA.

This report was developed under the International Energy Agency (IEA) Wind Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems Task 19: Wind Energy in Cold Climates.

Preface

The report provides guidance for material developers and potential end users of icephobic surface technologies for rotor blade applications. The definition of evaluation processes was missing at the time the IEA Wind TCP Task19 members discussed about anti-icing technologies and the need to harmonize and standardize test methods was identified.

This report is the first step in the definition of the evaluation process for icephobic surfaces and supports the identification of relevant tests for standardization. The activity was led by Fraunhofer IFAM as part of their research activities in the frame of the H2020 project Carbo4Power (EU H2020; Grant Agreement no. 953192).

Table of Contents

Executive Summary

Wind energy in Cold Climates needs to address various technical aspects in order to avoid lower energy production and liability issues, such as ice throw and noise. “Active” ice protection systems (mainly heating) for the rotor blades of the turbines were one of the first important technical steps to cope with icing phenomenon on surfaces. The use of so-called icephobic surfaces (referred to as “passive” ice protection in this report) appeared to be even more desirable, as the overall prevention of ice formations would solve many of the technical problems related to icing. However, the broad range of relevant icing conditions, the different icing scenarios the blade areas are facing at, and the harsh environmental conditions (UV, rain and particle erosion) combined with the required long-term performance of the material have so far prevented the integration of potential icephobic materials.

Despite the high obstacles the icephobic surfaces need to overcome, material developers are still convinced to achieve significant improvements for future coating and surface solutions. One of the most recent solution is to combine heating systems with icephobic materials in hybrid systems to significantly reduce the energy consumption of the heating system. Experiences from more than 20 years of work is available, not only related to the materials itself, but also to the testing strategies for efficient development processes (from low level laboratory tests to complex and expensive field tests).

This report summarizes parts of the experiences related to tests for icephobic surfaces. It is not intending to be exhaustive in the list of tests that have ever been used by different researchers. But it summarizes basic test designs with regard to lab based ice formation and ice adhesion tests, ice wind tunnel tests and field test campaigns for icephobic materials. It also highlights the need to address the material durability at an early stage of development, considering relevant ageing scenarios for rotor blade surfaces. This shall avoid premature expectations that finally cannot be met by the coating materials for rotor blade applications.

Addition to the test designs and durability aspects, surface properties relevant for the icephobic performance are addressed in this report. This is not only necessary to improve the basic understanding on the icephobic performances of surfaces, but also to identify appropriate monitoring tools and ageing models for the intended application. This aspect is also included in the final recommendations and future needs that are necessary to further improve the testing strategies of icephobic surfaces for rotor blade applications.

1. Background Information and Objectives of Task

In the context of wind energy in cold climate, icing accumulates on wind turbine blades and has three main consequences:

- Reduced energy production due to the degradation of the airfoil performance (loss of lift and increased drag)
- Health and safety issues due to ice throw of ice fall
- Increased load and vibrations on the wind turbine structure

Figure 1-1. Icing on wind turbine blades in different parts of the world (source: Task 19)

The objective of an ice mitigation solution, which can be passive (coating) or active (hot-air or electro-thermal) is thus to remove the ice from the blade and mitigate the effect of icing on either the energy production, health and safety hazards or loading.

Without the use of an ice mitigation solution, operators of wind farms in icing climate often deal with periods of production loss. The business case of any ice mitigation solution is therefore tied to the reduction of icing periods on wind turbine blades (referred to as rotor icing) and increased energy production.

The prevention of ice formation on technical surfaces is, therefore, of high interest for wind energy applications and extensive research has been conducted on the development of icephobic coatings, that reliably prevent ice formations and/or reduce ice adhesion. Despite the efforts there are no materials on the market that solely prevent ice formations under all relevant icing conditions. Main challenges are the high stress regimes that occur on rotor blades (rain/sand erosion, UV, contaminations), accompanied with the expected long term performance of the coatings over 20 years +.

More recent approaches aiming at a combination of active heating systems and a supporting icephobic coating to reduce the energy consumption. Also, the focus on the reduction of the ice adhesion instead of trying to completely prevent ice formations appears promising from material perspective. However, the lack of harmonized and reliable test designs for icephobic coatings impede the development processes. This report shall provide a guideline for material developers, but also for blade manufacturers and further parties that need to solve the challenges for wind turbine blades in cold climates.

There are different topcis to be addressed in this report to give an integrated view on icephobic coatings and the way how to test them. Background information include:

- Active ice protection systems, that are at the current stage necessary to guarantee ice free surfaces under all relevant icing conditions (section 1.1)
- Ice types that need to be considered in the test regimes (section 1.2)
- Application areas on the rotor blade (section 1.3)

The testing of icephobic materials covers lab-based ice formation (section 2.1) and ice adhesion (section 2.2) tests. The results of these tests can serve as a first decision gate for developers and potential users of such materials, but are not sufficient to predict the actual performance on rotor blades of wind turbines. The next steps for testing are further advanced ice wind tunnel tests (section 2.3), addressing actual environmental conditions and (ideally) the relevant component architecture. The scale and complexity of the test models decide about the adequate test facility to be selected and the resulting costs for the assessment.
Before starting field test campaigns on rotor blades (section 2.4) durability assessments for the coating materials (section 3) should be conducted. Additionally, a parameter set of surface characteristics, that can be used for the monitoring of the material life time (section 4) should be identified.

This document provides a roadmap for the evaluation of icephobic materials and provides examples for tests that are relevant for this evaluation process. It considers the application specific parameter for rotor blades of wind turbines and recommendations about the use of the test results. The document does not claim to be exhaustive in exemplarily shown test methods, but trying to increase the awareness about the needs for such test procedures.

1.1 Active and passive ice protection

The term “active” is dedicated to the external energy source that is required to operate the ice protection system. The IEA Wind TCP Task 19 report on “Available Technologies for Wind Energy in Cold Climates” summarizes the existing main technologies [1]. They can be divided to anti-icing (AI) and de-icing (DI) systems, which indicates the mode of action of the ice protection system. Anti-icing is aiming at preventing the ice formations on blades during operation of the wind turbine. De-icing is a method to remove the ice after it could build-up to a certain extent. This is generally accompanied with a shutdown of the turbine. Table 1-1 summarizes the technology alternatives for active ice protection systems and is adopted from the IEA report, which contains further technical information for these technologies.

Table 1-1. Summary of active ice protection technologies for rotor blades [1].

Technology	Advantage	Disadvantage
Hot air: heat source combined with a fan to circulate hot air to different areas of the blade	Simple, robust, Long history Lightning risks small	Low efficiency: long distance from heat source to iced surface, low thermal conductivity of blade materials
Electro-thermal: heating elements (mats, laminates, coatings) placed on the outer blade surface	Optimized efficiency: close to blade surface, installation in ice-prone areas only	Blade implementation and repair concepts required Increase lightning risk
Microwaves: generators inside the blade heat-up a specially designed outer coating	Wireless, Optimized power consumption	Unproven in field, Implementation difficult
Mechanical removal: manual de-icing and helicopter or drone de-icing using hot liquids	No initial investment (buy-when needed)	Case examples only, Potential damage to blade, Health and safety issues for workers

Addition to the active ice protection systems, the IEA report includes coatings as “passive” technology, which prevents or reduces ice formations and/or ice adhesion. The main advantage here is that icephobic coatings as solely used solution do not require additional energy sources. The main challenge is still the lifetime of such materials. As of now, none of the developed coatings could prove durable icephobic performances under relevant field ice conditions. However, the potential benefits are obvious, pushing the research activities further and further. This highlights again the needs for reliable and (ideally) harmonized tests, for which this report shall provide one important link in the chain.

This also complies with more recent development projects, e.g. the Carbo4Power project*. One of the project topics is the development of durable, multifunctional coatings. Amongst others, these shall be used in hybrid ice protection systems, in which active components (heating or mechanical) are combined with passive icephobic coatings. The idea behind is the reduction of the energy consumption of the active (thermal) system or the improvement of the (mechanical) de-icing performance. The technical challenges for such a supporting coating system appear less demanding compared to a solely working icephobic coating. Ice wind tunnel tests have proven far more than 50% energy reduction for a heating system that is combined with icephobic coatings [2]. Additionally, ice type dependencies were observed for different surfaces: the prevention of impact ice (due to impacting water droplets) requires rather smooth surfaces; for the prevention of ice films due to rain droplets or runback water superhydrophobic surfaces are of interest. There are further ice types to be considered for wind turbines. This will be further addressed before describing the main parameters for the ice-related testing of coatings and surfaces.

---

* Carbo4Power: New generation of offshore turbine blades with intelligent architectures of hybrid, nano-enabled multi-materials via advanced manufacturing (EU H2020; Grant Agreement no. 953192).

1.2 Ice types

Rotor blades are exposed to diverse climatic conditions. With regard to atmospheric icing, the IEA Wind TCP Task 19 report [1] defines in-cloud icing and precipitation icing as the most relevant conditions for wind turbines in cold climates. The characteristics of occurring ice types differ and are depending on the climatic conditions. Rime ice can form as soft or hard rime due to supercooled water droplets. Glaze ice has a higher density and forms a smooth and homogenous ice layer. Wet snow is based on partly melted snow crystals and can adhere to a surface because of its stickiness [1].
Additionally, ice formation is also depending on the mode of operation of the wind turbine: ice types and areas of ice build-up at a running turbine significantly differ from ice formations during stand still (see Figure 1-2). To address all ice types at an early development stage is certainly excessive. However, it needs to be addressed already in lab-based tests to a certain extent to avoid misinterpretation of results. The challenge is to identify the balance between realistic icing scenarios and efficient testing in an absolutely reproducible environment.

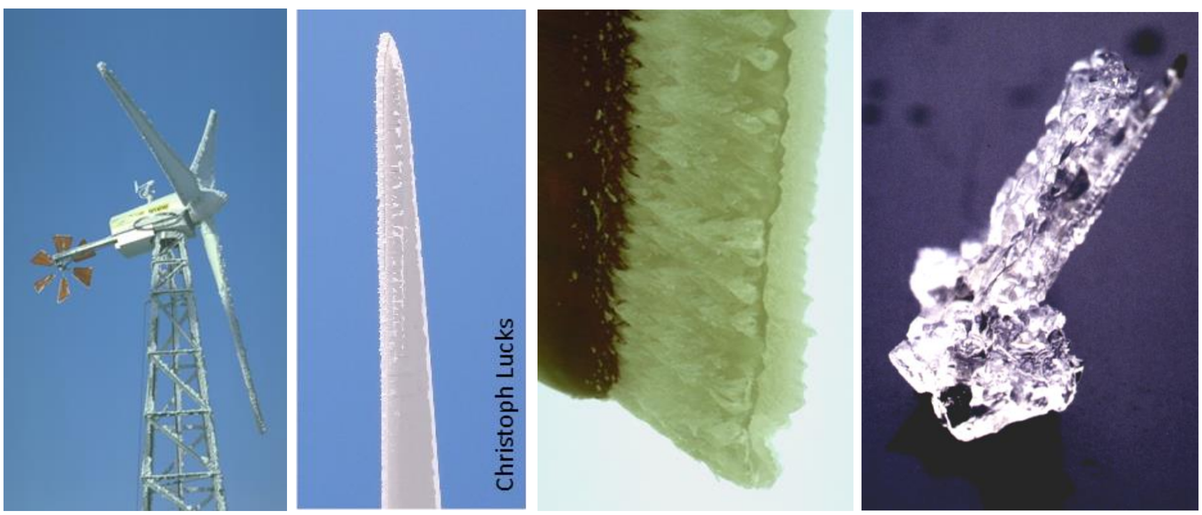


Figure 1-2. f.l.t.r.: Icing of wind turbines at stand still; Icing of wind turbines during operation; Rime ice at the leading edge; Glaze ice from rotor blade icing. All pictures from [3].

1.3 Application areas on rotor blades

The coating material needs to protect the underlying structure against different environmental stressors. Based on the predominant stressor, the areas require different materials to:

1) protect against UV light and further, environmental influences → main areas
2) additionally protect against erosion / abrasion due to rain, hail, dust, sand, salt → leading edge and tip

This in combination with the ice formation types to be expected and additional technical measures (e.g. active heating systems) gives the scheme as shown in Figure 1-3.

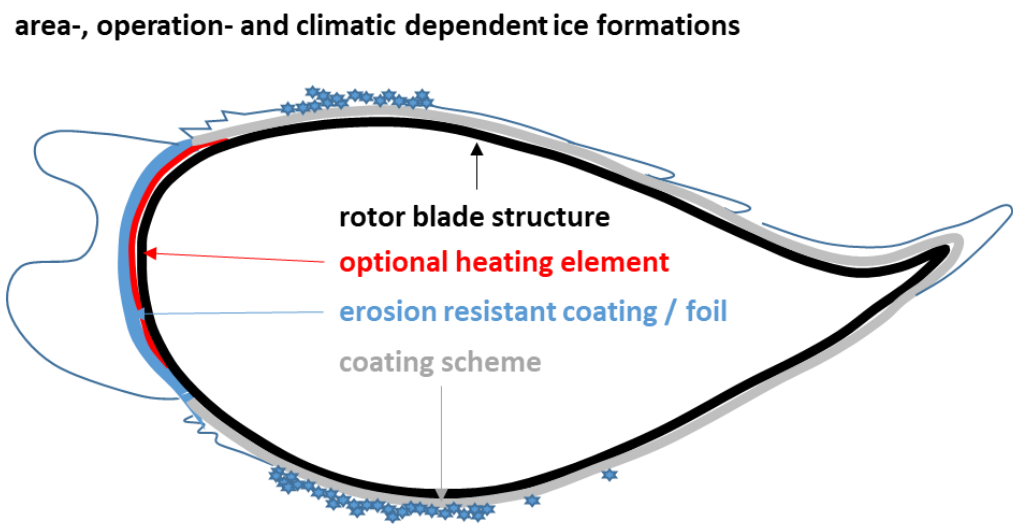


Figure 1-3. Scheme of a rotor blade with basic material scheme and ice formations to be expected. Aerodynamic profile taken from [22].

The complexity of different ice types, functionalities and technical requirements highlights the challenges, icephobic coatings need to cope with. It also shows that one simple test design is not adequate to predict the technical material performance. The following sections provide an approach on how to cost- and time efficiently test icephobic materials during the development phases.

2. Ice-related testing

Ice related tests for ice protection systems can be divided into “lab-based tests”, “ice wind tunnel tests”, and “field tests”. Laboratory based tests are initial decision gates for developers of icephobic coatings and necessary to provide cost and time efficient evaluation tools. Reproducible test conditions are mandatory to allow comparative tests against predefined benchmarks. These can be commercially available materials (e.g. conventional blade coatings) or unmodified surfaces / materials. The aim is to compare the material performance in the lab-based ice tests and give first indications about the potentials of the newly developed materials.

As of now, no international test standards are defined for lab-based ice formation and ice adhesion tests. This limits the comparability of different tests and hinders the definition of technical requirements for icephobic coatings. The user of the test facility is responsible for the definition of relevant and reliable test procedures.

The complexity of the tests should be low in this stage of development. Nevertheless, the actual ice types for the relevant application and the mode-of-action of the materials / systems under development should be considered as controllable as possible in the test design. Due to the limited environmental variances as well as the exclusion of disturbing parameters, (e.g. system integration aspects, dirt, coating irregularities and weather degradation) they cannot provide the final evidence about the performance of the coatings in the field. The complexity and the cost and time efforts are rather low for lab-based tests compared to the advanced tests in ice wind tunnels or the field tests (Figure 2-1). But, by completing the development with advanced tests (ice wind tunnel and field tests), researchers should study the correlations between the available results to significantly improve the knowledge about the relevance of the used lab-based test systems.

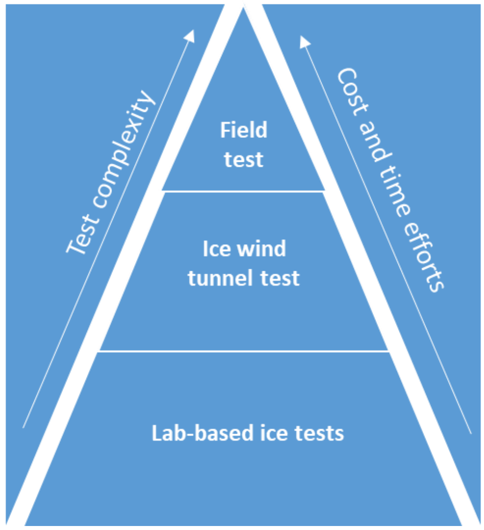


Figure 2-1. Scheme of ice-related testing during the development of icephobic coatings.

The following sections provide an overview about the different approaches for the evaluation of icephobic coatings.

2.1 Ice formation tests

Lab-based ice formation tests shall provide a fist indication about the icephobic potential of a designed surface and can be used as a first decision gate for material developers. All surfaces that behave better than predefined benchmark materials (e.g. commercial coatings, unmodified surfaces) are assessed as promising material with "potential icephobic properties". Once again, this does not mean that positive results guarantee a good performance in field, but negative results (equal or more ice formation after the test compared to the benchmark) indicate no icephobic performance at all.

While defining the test set-up the following aspects should be considered:

- Ice types that are characteristic for the application
- Simple and robust test design for time and cost efficient assessments
- The mode of action of the surfaces under development (e.g. improved water run-off and/or reduced rime ice accretion)
- High accuracy of test conditions (e.g. temperature of air / test surface / water, humidity, air circulation, constant water cloud) to allow comparison tests against benchmarks
- Definition of control test surfaces to guarantee comparable test conditions for independent test campaigns
- Appropriate result documentation to allow fast result interpretation and allow the qualitative/quantitative evaluation, validity, and repeatability of the results.

- Keeping in mind, that test only reflects a specific condition window that allows no universal conclusions about the overall icephobic performance.
- Addressing the risk of misinterpretations (false-positive / false-negative).

Relevant ice types shall be addressed, keeping in mind that the complexity of the test is at this stage of development rather low. In practice, ice rain tests are often used to simulate water run-off from surfaces under freezing conditions. Test surfaces are exposed to freezing conditions and after the pre-conditioning phase, water is sprayed for a specific time onto the inclined surface. Afterwards, ice coverage is assessed (e.g. via optical inspection, software) and compared with the benchmark material. Figure 2-2 shows examples for increasing ice formations on different test surfaces, performed at Fraunhofer IFAM.

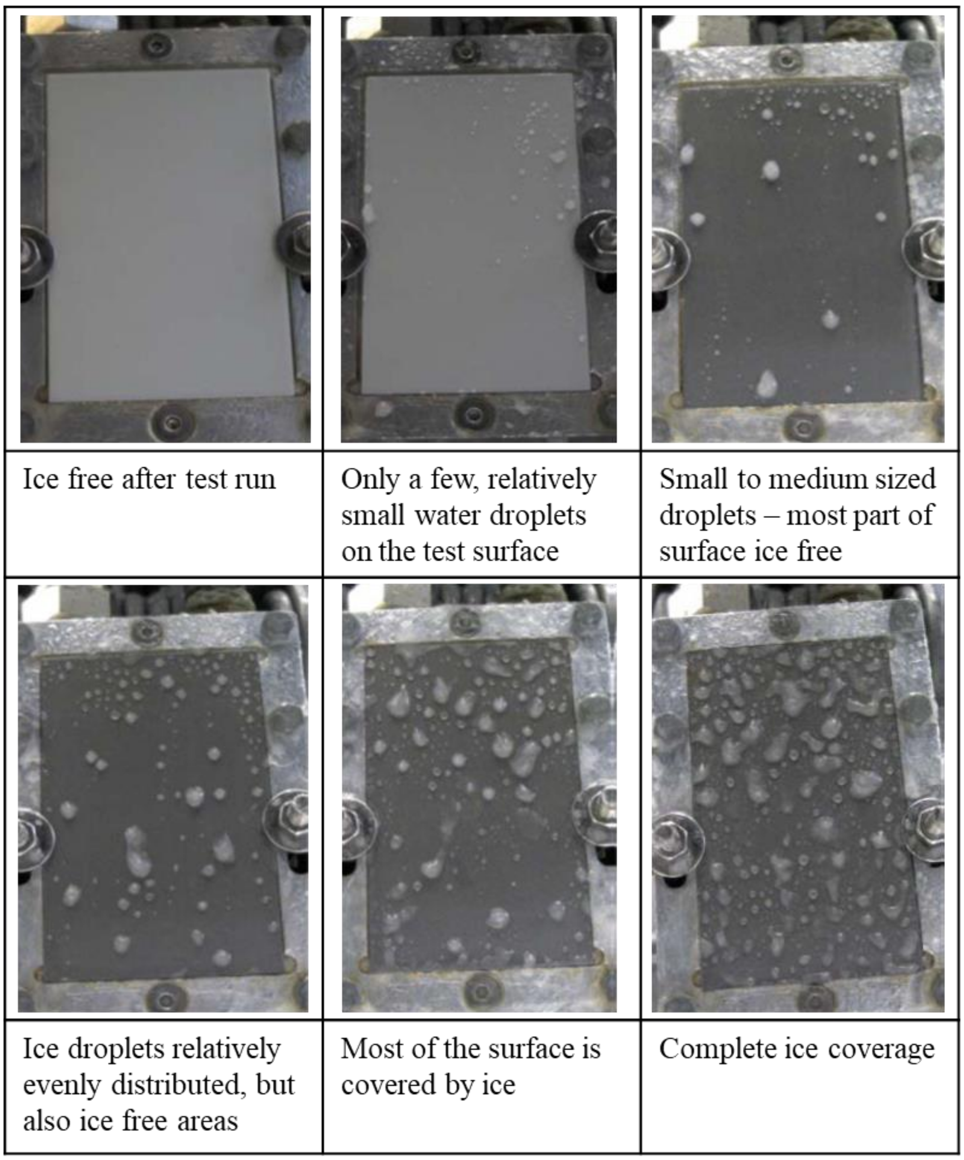


Figure 2-2. Reference pictures for ice formations on test surfaces (80 x 50 mm) after ice rain test at Fraunhofer IFAM with temperature -5 °C, wind speed 11.5 m / sec [4].

The ice rain test design is dedicated to surfaces that improve the water run-off and thus reduce the ice formation under freezing conditions. Coatings may address not only the ice rain formation, but also the prevention of e.g. icing from condensation / humidity sources, leading to frost / rime formations on surfaces. To account for this, test designs that induce this ice type by creating temperature deviations between the surface and the surrounding air are used (Figure 2-3). Here, mass or thickness of ice are evaluation parameter for the comparison test. In any case, it is mandatory to create reproducible test conditions with very low variances (≤ 1°C, etc.).

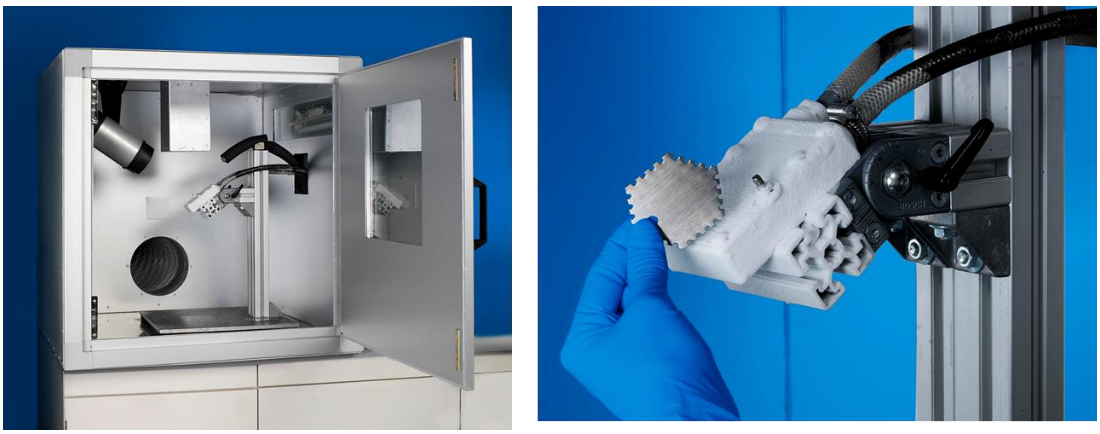


Figure 2-3: Example for a test chamber for lab-based ice tests (left) and frost/rime ice accretion on a test surface (80 x 50 mm) at test surface temperature -2 °C and air temperature +1 °C. Wet film thickness gauge used for ice thickness measurement (source Fraunhofer IFAM) [4].

Further tests on ice formations address icing conditions in a further advanced test design. For example, a custom-built rotor with six seats for coating samples and plate references was developed for rotary dynamic icing tests at University of Nottingham. Here, the samples are fastened by screws and the rotor is spun at 30 rpm under subzero temperature, as illustrated in Figure 2-4. To ensure repeatability and to expose the coated surface only, the backside or metallic side of the samples is covered by peel-able tape and the tape is peeled after the tests. The ice accumulation is recorded after an hour of test and an average ice accretion is calculated [5]. A video of this test is available [6].

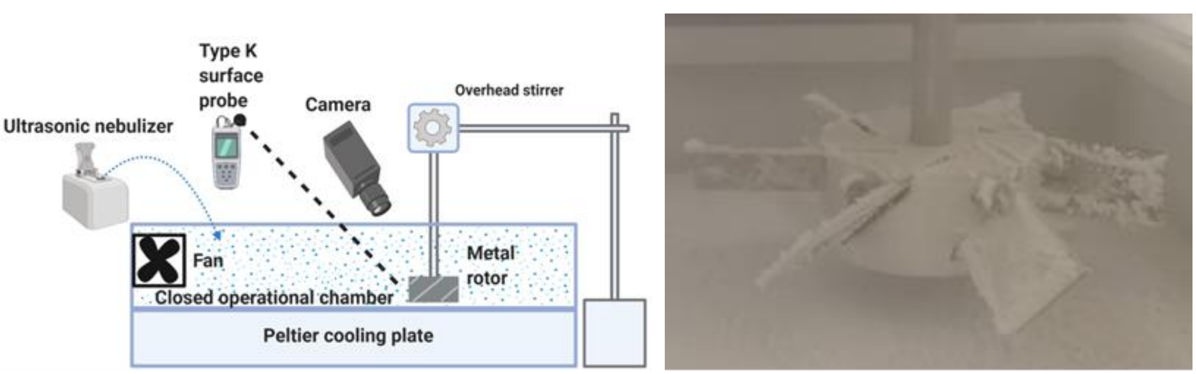


Figure 2-4: A rotary dynamic icing lab test developed at University of Nottingham: schematic diagram (left) and ice accretion on the tested samples (right) [5].

There are certainly further lab-based ice formation tests in use by material and system developers that address icing under environmentally relevant conditions. However, the given examples already represent the diversity of test approaches that do not necessarily provide comparable test results. The tests mainly base on the comparison with pre-defined benchmark surfaces to give first indications about potential improvements under icing conditions.

2.2. Ice adhesion tests

Lab-based ice adhesion tests address the second function of icephobic coatings. To measure the ice adhesion strength, different methods can be used and no test standards are currently defined. Work & Lian (2018) reviewed the existing test concepts with their benefits and drawbacks. They further concluded, that temperature, surface roughness, strain rate, and impact velocity (during ice formation) are the key parameters affecting ice adhesion [7]. This meets the expectation that different ice types lead to different ice adhesion strength values. To account for this, relevant icing scenarios need to be considered for the preparation of the test samples. Figure 2-5 gives examples for ice types, generated in ice wind tunnel and ice laboratory, respectively.

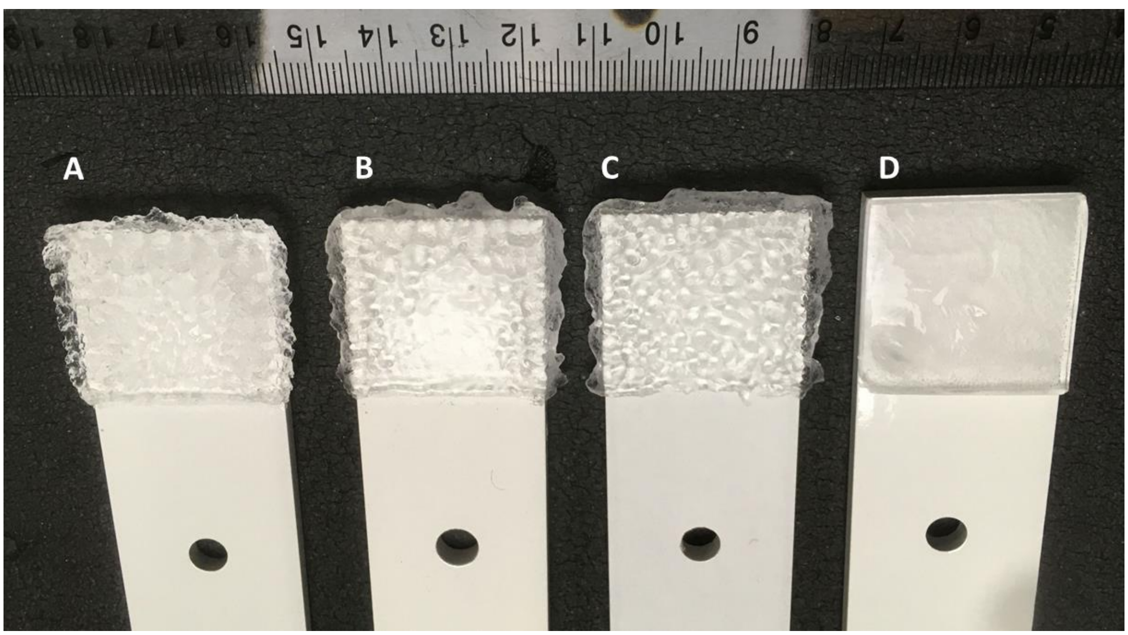
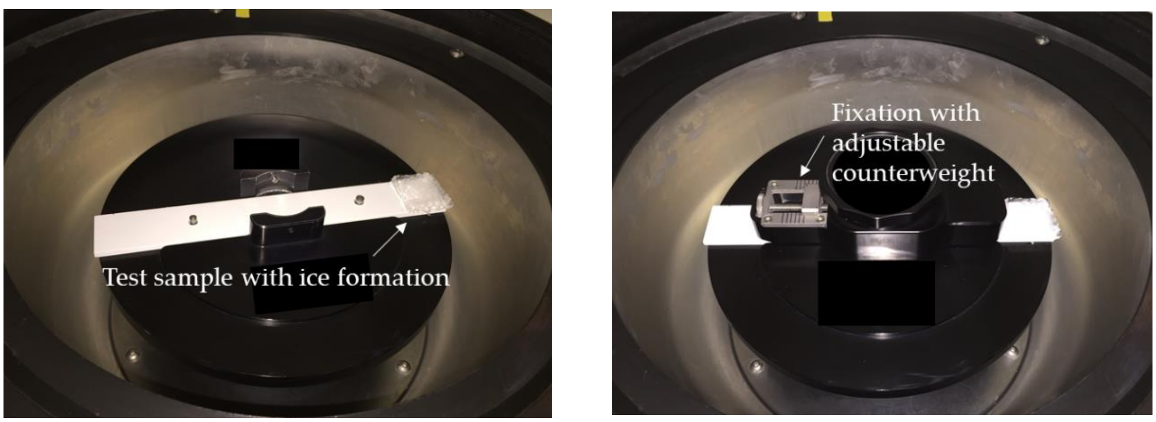


Figure 2-5. Ice types generated in ice wind tunnel at velocities of 95 m/s (A), 60 m/s (B), 40 m/s (C) and generated by filling liquid water in a mould to freeze at the test surface (D), respectively; all ice formations at temperature of -8°C (source: Fraunhofer IFAM).

One of the most used test devices for measuring ice adhesion strength is the centrifuge [8, 9, 10, 11, 12, 13, 14]. No standards nor commercial test devices are available and in most cases custom-made centrifuge with a modified rotor to place and fasten the prepared test samples is used as it was already described elsewhere [7]. Figure 2-6 shows an example. Opposite the ice is a counterweight that can be adjusted, according to the ice mass, to reduce vibrations. Generally, the centrifuge test uses centripetal forces to shear ice from the test surface. The prepared sample is fixed in the centrifuge, in which the iced sample is spun at a constantly increasing rate until the ice is sheared off. Separation is detected by a piezoelectric cell when the ice hit the centrifuge wall and is correlated to the rotational speed of the centrifuge rotor. This speed (angular velocity ω in rad/s) is used to calculate the shear strength of ice to the substrate, according to the following equation:

$$\tau = \frac{F}{A} = \frac{m_{ice}\,\omega^2\,r}{A} \qquad 1.\ (1)$$

where m_{ice} is mass of ice (kg), r is the radius of the rotating beam at the mid-length ice position (m), and A is the surface area of the adherent interface (m^2) [8].



(a) (b)

Figure 2-6. View inside the centrifuge test device with: (a) test sample with ice formation placed in the centrifuge; (b) test sample after fixation. (source: Fraunhofer IFAM)

A further example for ice adhesion test designs is a shear test, utilizing a force probe to push on the ice samples to induce detachment from the surface. This force probe records the exact moment when the ice detaches from the surface as a sudden decrease in registered force. For the vertical shear test, as shown in Figure 2-7, a load cell with an indenter applies a load to an ice cylinder, frozen onto a fixed coated substrate. The normal load induces a shear stress in ice/solid interface, which can be calculated from the recorded load. Here, the ice adhesion strength (τ_0) equals the shear strength, defined as the maximum force (F_{max}) divided by the ice/solid contact area (A).

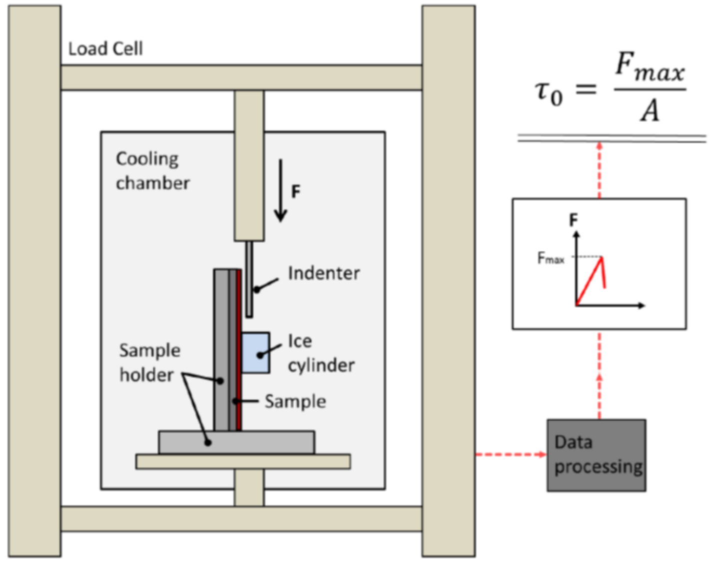


Figure 2-7. Schematic illustration of the working principle of the vertical shear test [15].

The ice tested in the vertical shear test is usually bulk water ice. The ice is frozen on the tested surfaces in a polypropylene centrifuge tube mold fastened with silicone grease to avoid leakage during water insertion. This may result in systematically higher ice adhesion strength than other testing methods like centrifugal adhesion test, especially when the ice adhesion strength to the tested surfaces is very low [16].

Regardless the test design, when ice is being removed, stress is distributed along the ice-solid interface until failure. This stress is not uniformly distributed over the interface, although it depends on the testing method. When ice adhesion results are not corrected with the stress concentrations at the interface, the results might be one order of magnitude lower than the local actual ice adhesion strength [17]. However, such stress concentrations are rarely accounted for in analyzing the experimental results [7]. The introduction of the Adhesion Reduction Factor (ARF) addresses this shortcoming by using test results in a comparative manner [8]. It is equivalent to the ice adhesion strength of a baseline material (e.g., state-of-the-art coating) divided by the adhesion strength of ice to the substrate of interest. ARF < 1 indicates an increase in ice adhesion strength compared to the reference material; ARF > 1 indicates an ice adhesion reduction.

As for the lab-based ice formation tests (section 2.1), the ice adhesion tests only reflect a specific parameter set-up and do not give answers to the actual performance in field for the aimed technical application. It gives indications about the potentials of the newly developed materials under freezing conditions. If promising results are obtained in these basic tests, advanced tests are required to proof the icephobic performance and consider further relevant parameters with regard to relevant icing conditions, component architecture and material durability. This is further described in the following sections.

2.3. Ice wind tunnel tests

For promising coating candidates the next step in the evaluation process is to include icing scenarios that are close to the aimed technical application. For wind turbines, this can be achieved by using ice wind tunnel. These test facilities are comparable to wind tunnels conventionally used for aerodynamic investigations, but with the addition of a cooling unit and a spray bar system that generates an icing cloud in the test section (examples shown in Figure 2-8). The test facilities should follow the SAE Aerospace Recommended Practice (ARP) 5905 to assure sufficient ice generation.

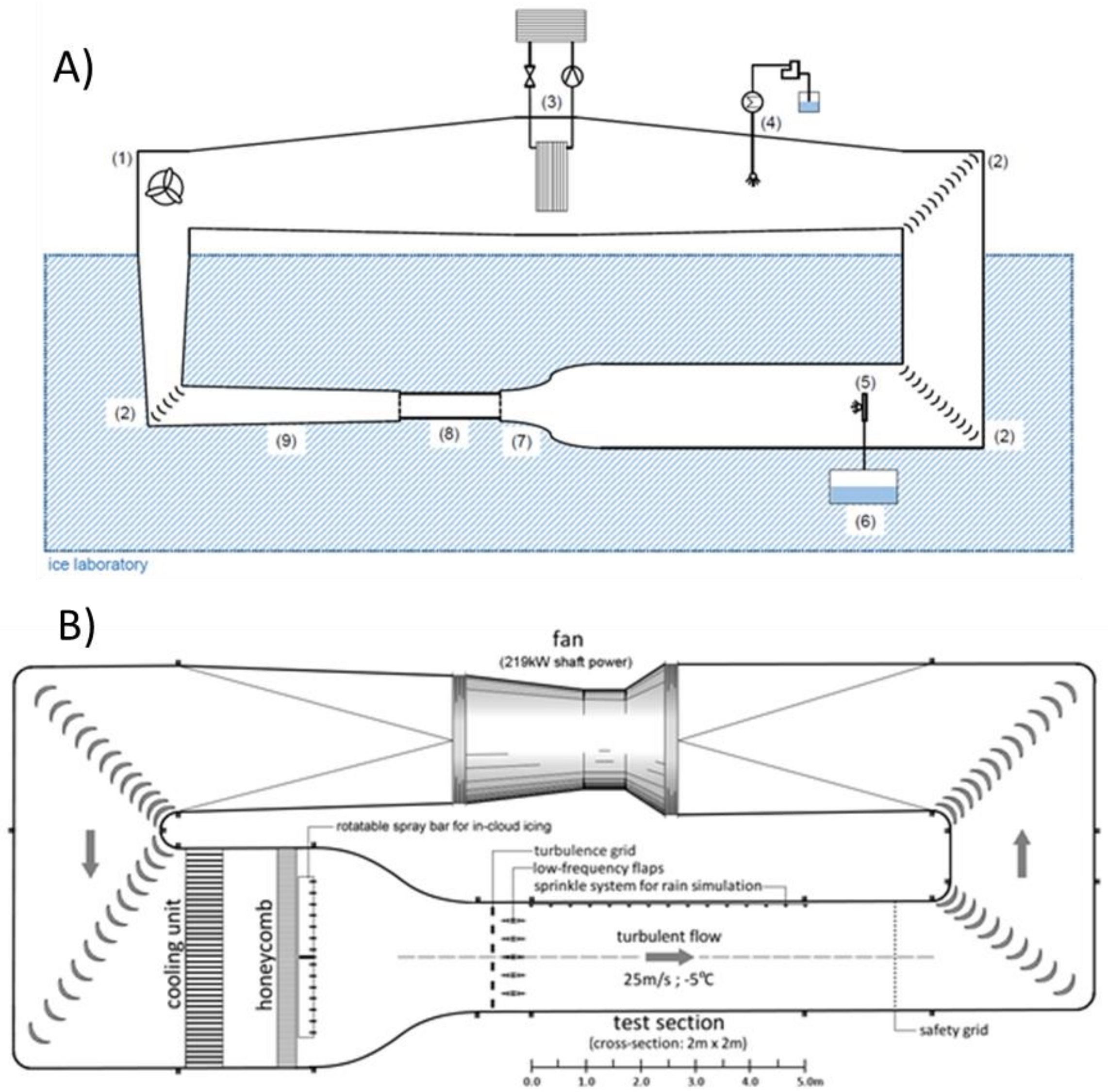


Figure 2-8. Examples for ice wind tunnel test facility: A – Fraunhofer IFAM with fan drive system (1), turning vanes (2), heat exchanger of refrigeration system (3), humiditystat (4), water spray bar (5), water reservoir and pumps (6), test section entrance (7), test section (8), diffusor (9)) and B – Overall layout of the cold climatic wind tunnel (CWT) airline at DTU. The wind tunnel is installed in vertical plane placing the fan above the 5m long test section.

Ice wind tunnel test facilities support the improved understanding of detailed icing phenomena depending on different environmental conditions. Amongst others, DTU performed wind turbine blade and rotating rotor tests. Figure 2.9 shows an example where NACA 0015 airfoil with three different pitch angles of $\alpha = 0°$, $5°$ and $10°$ were tested during one hour under rime ice conditions.

Figure 2-9. Rime ice accretion at different pitch angles of the airfoil. (a) AoA - 0deg, (b) AoA - 5deg and (c) AoA - 10deg. Left – leading edge with contour trace of ice layer, right – leading edge close-up [18].

The experiments give indications about the main areas to be protected against ice formation. The same applies to studies on the rotating rotor. Investigations at DTU with a small wind turbine model were performed at the CWT und various operational conditions, including stand-still. The images in Figure 2-10 show result of the accretion along the blade and at the tip for rime ice condition.

Figure 2-10. Small wind turbine model in CWT with rotation speed control and a force balance at the base of the tower to measure the overall thrust of the rotor disc during icing and to compare the prediction from numerical simulation to experimental data [19].

With the previous studies it is possible to identify relevant for ice formations on rotor blades. With regard to the testing of icephobic coatings an ice wind tunnel can be used to generate ice from supercooled water droplets for subsequent tests on ice adhesion properties (see section 2.2). Additionally, tests on ice formation processes can be conducted, ice shedding events studied, and the combination with active systems (heating or mechanical) assessed.
For the latter, one example was published in [4]. Aerodynamic profiles were equipped with heating devices and coated with different materials, providing deviating wettability and roughness parameters. Tests in the Fraunhofer IFAM ice wind tunnel were conducted in anti-icing mode, meaning that heating power is stepwise reduced to assess the operating point, at which ice formation can not be prevented anymore (see Figure 2-11). Out of this study, calculations on the reduced power consumption of heating elements can be conducted and correlated to the characteristics of the used coating types.

Figure 2-11. Ice formation at leading edges of an aerodynamic profile with heating elements: unmodified PUR reference coating (left); elastomeric icephobic coating (center), superhydrophobic coating (right). (Source: Fraunhofer IFAM [4])

A (not exhaustive) list of ice wind tunnel test facilities with respective size and test conditions can be found in [1].

2.4. Field tests

As shown in Figure 2-1, icephobic coatings field tests should only be conducted with products that have successfully passed lab and wind tunnel testing, since field tests involve higher costs and more complexity. The field-tested coatings shall have a demonstrated reduction of the ice adhesion strength as well as a proven durability as it is described in section 3 of this report.

Field tests of ice-phobic coatings enable the validation of laboratory test results under icing climate conditions. Depending on the development stage of the coating, different test designs are applicable, from small-scale side-by-side tests of several test surfaces to large-scale tests of several wind turbines with blades equipped with respective coatings.

2.4.1. Small-scale field tests

One example for an early-stage small-scale field test is an ice-formation test similar to the laboratory tests described in section 2.1. Several test surfaces are submitted to icing climate conditions at a given test location and the ice formation is monitored optically by one or multiple cameras. The collected data of the camera(s) as well as of the meteorological sensors is transmitted to a data logger and/or via mobile network connection. It is essential to arrange for an undisturbed placing of the test surfaces at the given location such that the meteorological conditions remain uninfluenced by the test set-up and are comparable to the intended application of the coatings. Depending on the icing frequency and (average) duration at the test location, the additional placing of a heat radiator facing the test surfaces can be of advantage to enable multiple ice formation processes during icing events of longer duration by actively de-icing the test surfaces.

Another example of an early-stage small-scale test is a dynamic test scenario for the evaluation of coating/surface durability under icing climate conditions. Test surfaces are mounted onto the blades of a small wind turbine which is placed in icing climate conditions at a given test location. Small wind turbines are operating with much higher rotational speed (1.000 rpm) compared to regular wind turbines (20 rpm) and thereby offer similar relative speeds at the outer blade regions. Hence, abrasion effects are comparable to regular turbines and can also be studied in this small-scale scenario. Continuous monitoring of the test surfaces is done by one or multiple cameras and accompanying meteorological sensors connected to a data logger and/or mobile network connection. Microscopic evaluation of the icing- and abrasion-related durability of the test surfaces is done in a laboratory after the field test period.

Figure 2-12. Combined set-up for small-scale ice formation test (left) and dynamic test of coating/surface durability on the blades of a small wind turbine (right). Separate mast for overview camera and meteorological sensors (middle). (Source: Energiewerkstatt Verein)

2.4.2. Large-scale field tests

Task 19 has already proposed Performance Warranty Guidelines for Wind Turbines in Icing Climates [20] which outlines how the performance of an Ice Protection System can be tested in the field. Although it is aimed towards active IPS such as hot-air and electro-thermal technologies, the objective of the performance test of an icephobic and the expectations of the end-user remains the same: how much more energy can be recovered by a wind turbine equipped with the coating? This metric allows to evaluate the monetary gain from applying the coating and the payback time, which are essential for an ice mitigation to penetrate the wind energy market in icing climate.

As a minimum, at least one turbine shall be equipped with the icephobic coating on the three blades. The coverage of the coating on the blade surface shall be evaluated carefully. In most instances, active ice-protection systems cover the leading edge area of the outer third or half of the blade. This is because the apparent wind on the airfoil is much higher towards the blade tip and there is more power to be recovered from that region. Lamraoui et al. (2014) demonstrate that the outer 60% of the blade is responsible for 85% of the power generated by a wind turbine blade [21]. However, icing can still be present on the full length of the blade as can be seen in Figure 1-1. If the use case is reducing health and safety hazards, then a larger area of the blades should be covered.

The installation of the coating can be done in a paint shop for new rotor blades or by rope access technicians, suspended platform, specialized cranes or even drones. Given the cost involved to mobilize a team to coat one turbine, it can be best to equip other turbines with the coating in case an external issue arises on the test turbine (fault or unexpected downtime) which could affect the availability of the data.

In a field test context, the objective is to demonstrate the performance improvement of the coated turbine(s) over one or several turbines not equipped with it. Therefore, there must be a reference or baseline to compare the tested turbine. Since inter-annual variability of icing can be quite high, it is best that the reference turbines are in the vicinity of the tested ones. This is referred to as a Side-by-side comparison test.

Two other test methodologies are available for active IPS, namely self-comparison test and power performance test, which involves measuring the performance of the tested wind turbine against the expected energy production, but these are more relevant for demonstrated technologies in a warranty validation context.

The selected test method shall be:

- Practicable for the turbine, icephobic coating and selected site
- Cost-effective
- Based on criteria and parameters that are measurable and unambiguous, and with clear data sources
- Representative of the site conditions

- Carried out according to a well-defined performance criterion
- Sufficiently comprehensive to ensure statistical relevance

There also needs to be a clear definition of the following:

- Duration of test
- Required data coverage of the test
- Exclusions
- Icing event definition
- For the side-by-side tests, how to split the available data into reference and test datasets.

More details on these topics are provided in the Performance Warranty Guidelines for Wind Turbines in Icing Climates [20]; specifically in sections 4.2 (Data selection and filtering), 4.3 (Test methods) and 4.4 (Performance criteria).

While these guidelines rely on energy production during periods of icing to express the performance of an ice mitigation solution, other alternatives exist such as the use of icing detectors. Relying on energy performance is often the most cost effective solution since the required data is available through the turbine SCADA and does not require any additional equipment. Installing icing detectors or cameras has a cost, but can be useful in a technology validation context to better understand the conditions in which an icephobic coating is effective. A list of the different icing detection technologies available and which type of icing they are able to detect is available in Section 6 of [1]. If rotor ice detection is used, then the performance of the icephobic coating can be expressed as the reduction of rotor icing time on the tested turbine when compared to one or several references.

As detailed above, field tests require extensive resources and shall be targeted for coatings that present demonstrated performance in lab and wind tunnel testing. Following the Task 19 Performance Warranty Guidelines, it is possible to obtain measurable and unambiguous performance criteria when conducting field tests. If the field test is successful, the coating can be considered as a viable commercial solution for wind turbines in icing climates. It is therefore the last testing stage before commercialization.

3. Coating / Surface Durability

For blade surfaces, application specific technical requirements need to be fulfilled by icephobic coating materials. DNVGL-ST-0376 defines, amongst others, blade surfaces. The general need for all areas of the rotor blade is to be sufficiently resistant against environmental influences as well as the necessity of good adhesion properties between the coating layers itself and to the first structural laminate ply. Additionally, the laminate and bonding parts at the leading edge and tip area have to be protected against erosion [22].
These requirements need to be considered during the material development of icephobic coatings / surfaces in a sufficiently early development stage. DNVGL-CP-0424 defines requirements for “Coatings for protection of FRP structures with heavy rain erosion loads”

[23]. It serves as basis also for development processes of icephobic coatings that shall be applied on rotor blades of wind turbines. The following test hierarchy is proposed:

1) Identification of promising coating candidates in lab-based ice tests (compare section 2.1 and 2.2).
2) Assessment of basic technological properties on fresh coatings (adhesive strength, tensile properties, gloss, hardness) as defined e.g. in DNVGL-CP-0424.

These tests give first indications about the general applicability of the developed materials and provide information about modification needs.

3) If application in leading edge and tip area of the blade is addressed, conduct rain erosion tests, preferably by using rotating arm test.

Identify the actual performance in rain erosion test and compare with commercial products to identify potential gaps and duties.
For promising materials, continue as following:

4) Conduct ageing tests as e.g. defined in DNVGL-CP-0424 with 1000 hours at wet / cold / humidity cycles and ISO 6270-2, respectively. Assess not only the basic properties (adhesive strength and blistering), but also icephobic performance after ageing by using lab-based ice tests.
5) Implement surface characterization on fresh and aged surfaces in the test routines. This may include contact angle measurements for surface free energy, water contact angle, etc; surface roughness measurements; or analytical methods to assess the surface changes during ageing.

The knowledge about the surface changes during ageing is important for the identification of monitoring tools and should be correlated to lab-based ice test results.

6) Continue with UV exposure tests, e.g. as defined in DNVGL-CP-0424 and assess not only basic material properties, but also icephobic performance in lab-based ice tests and surface characterization parameters. Conduct tests at relevant time intervals to assess potential degradation behaviors.
7) If application in rain erosion prone areas is addressed, conduct rain erosion test after UV exposure as defined in [23].

The list of tests to be conducted prior to field tests on rotor blades highlights the need to early address durability of the surface. It is recommended to gather the durability results prior to the announcement of having developed icephobic materials for rotor blade applications. The provided test hierarchy was defined in the frame of the European Carbo4Power project, addressing durable multifunctional surfaces for rotor blade applications. An additional example is given in figure 3-1, providing results of a study conducted at Fraunhofer IFAM for aircraft coating applications. Ice adhesion strengths of potential icephobic coatings were assessed after defined intervals of UV(B) exposure (DIN EN ISO 16474-3: method 4).

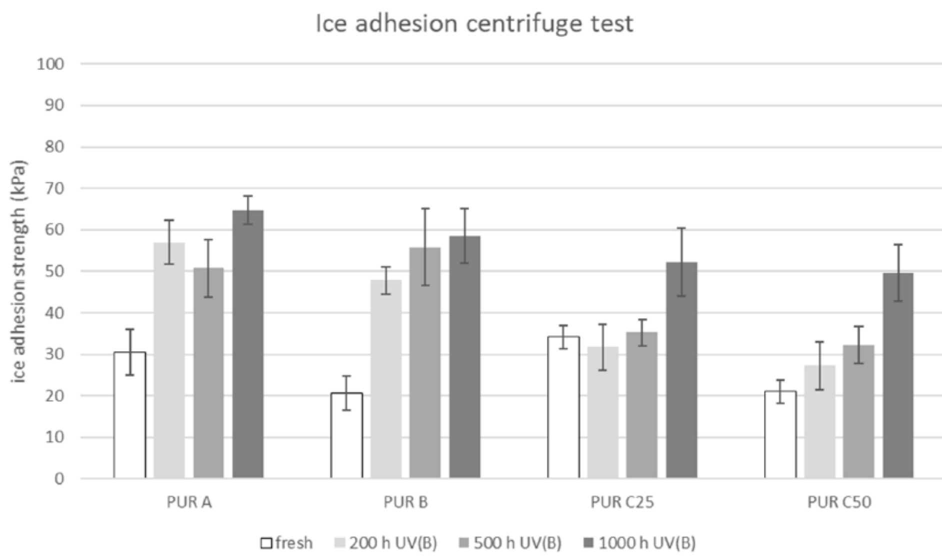


Figure 3-1. Results of ice adhesion centrifuge test (kPa) for coatings prior to and after accelerated UV(B)-ageing, as indicated [14].

Ageing test results give important information about the degradation behavior of the surfaces and also correlating surface properties (see section 4). In any case, lab-based ice tests for fresh and aged surfaces need to be proven in advanced tests in ice wind tunnel and finally field tests. These results are the only way to verify the relevance of the conducted ice-related lab tests.

With regard to the material durability, DNVGL-ST-0376 defines that it is required to specify suitable inspection and maintenance intervals, if the lifetime of the leading edge coating is less than the lifetime of the blade. This may also be applicable for icephobic materials, if the expected benefits are significantly higher than the expected costs for material and maintenance efforts. In this context, the life time assessment of the materials (steps 3 – 7) help with the identification of the expected material durability and applicable monitoring tools. Finally, there are also options to develop materials that are not applicable to leading edges (due to limited rain erosion resistance), but provide substantial benefits for the remaining areas of the blade (e.g. improving water shedding in unheated areas of a rotor blade).

4. Key surface properties for monitoring icephobic performance

The functionality of icephobics is related to surface properties that significantly reduce the interactions between the surface and water/ice. The key properties are controversially discussed, but there is a basic agreement that an increase in roughness leads to an increase in ice adhesion strength [7]. The surface roughness can be determined by using profilometer devices that work via contact or optical methods. For the assessments, profile parameters such as R_a and R_z are calculated from a mean line of the profile to quantify the surface roughness. R_z is the maximum peak to valley height within a single sampling length; R_a is the arithmetic average of the roughness profile (Figure 4-1).

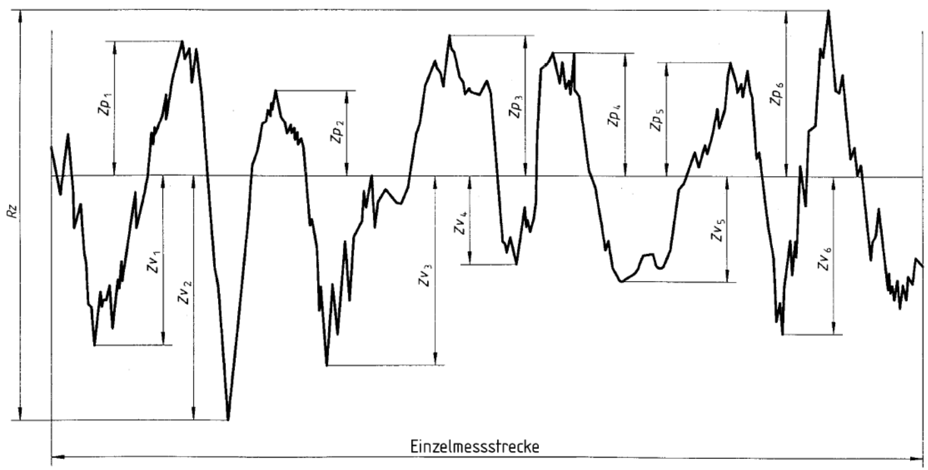


Figure 4-1. Example for a surface roughness profile [24].

As indicated in figure 4-2, ice adhesion strength is increased on metallic substrates (Aluminum – Al; stainless steel – SS) dramatically by increasing the surface roughness. This also applies to polymeric coatings and (less significant) to superhydrophobic surfaces [25].

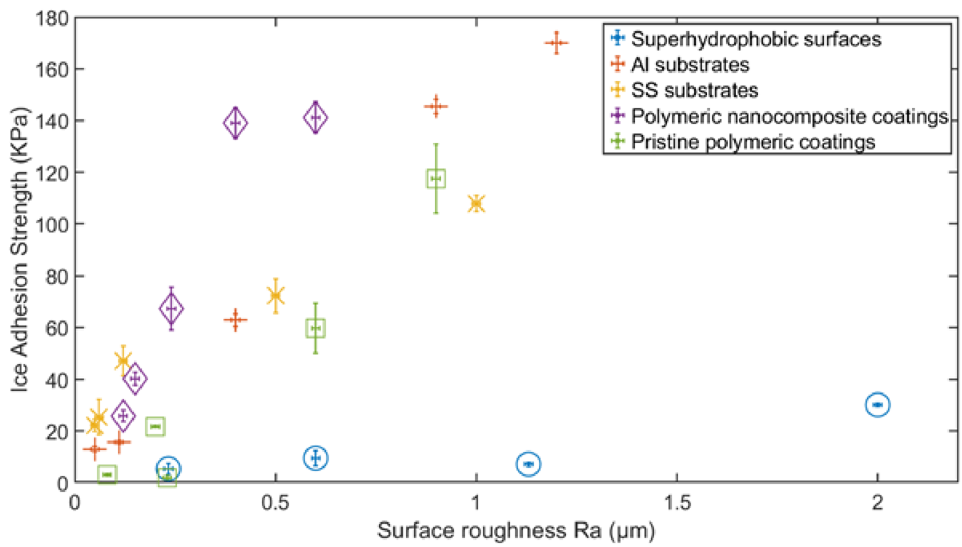


Figure 4-2 Ice adhesion strength on variable surface roughness R_a for different material types [25].

Addition to the roughness, the chemical composition of the surface affects the functional performance. Both define the <u>wettability</u> of a surface, which is the second main character for the description of icephobic surfaces. The commonly used parameter is the water contact angle (WCA), that appears between the surface of the liquid water and the solid surface (Figure 4-3). WCA values < 90° indicate hydrophilic, > 90° hydrophobic; and > 150° superhydrophobic surfaces.

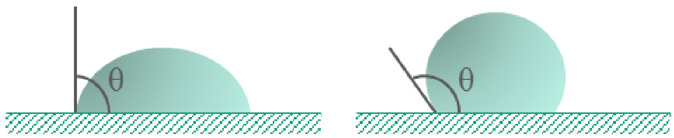


Figure 4-3. Wetting of a surface by a droplet with contact angle θ 90° (left) and >90° (right)

However, there is a common agreement that hydrophobicity is not necessarily linked to the icephobic performance. Even superhydrophobic surfaces with a very low wettability can show contrary effects due to dynamic processes during ice formation processes (impingement of droplets into the surface structure) and the rose petal effect (high adhesion with water) [26]. The latter can be assessed by measuring the water sliding angle (WSA). It is defined as the surface angle (α_{slid}) at which the advancing (θ_{adv}) and receding (θ_{rec}) angles of a water droplet moved at least 1 mm during tilting of a test surface (Figure 4-4).

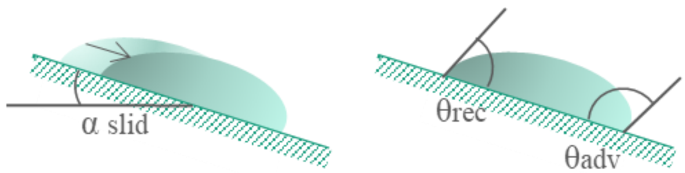


Figure 4-4. Water droplet sliding angle α_{slid} (left); receding θ_{rec} and advancing θ_{adv} contact angle of a droplet (right).

By calculating the difference between advancing (θ_{adv}) and receding (θ_{rec}) contact angles, the contact angle hysteresis (CAH) can be defined as a further parameter to describe icephobic surfaces: The lower the CAH, the higher the probability for an icephobic performance.

The surface free energy (SFE) finally describes the wettability of surfaces in a more complex way. A minimum of two liquids with deviating surface tensions are used to measure contact angles as it was described for the determination of the WCA. The data are used to calculate the SFE; the smaller this value, the less interactions with liquids, thus the poorer the wettability of a surface.

For the determination of wettability data, devices for use in laboratories as well as in field are available and tests should basically follow procedures as described in e.g. DIN EN ISO 19403-2,-6,-7. The data can be used to characterize fresh surfaces and to monitor changes of surface properties during ageing processes. The challenge here is to identify the most relevant parameter for the material under investigation and correlate the data with the icephobic performance.

A study on how the surface properties change during accelerated UV ageing tests was conducted in combination with ice adhesion centrifuge tests. Figure 4-5 gives two examples of different coating materials, showing the change ratios (%) of surface properties and ice adhesion strength during a standardized UV (B) ageing test (DIN EN ISO 16474-3) [14].

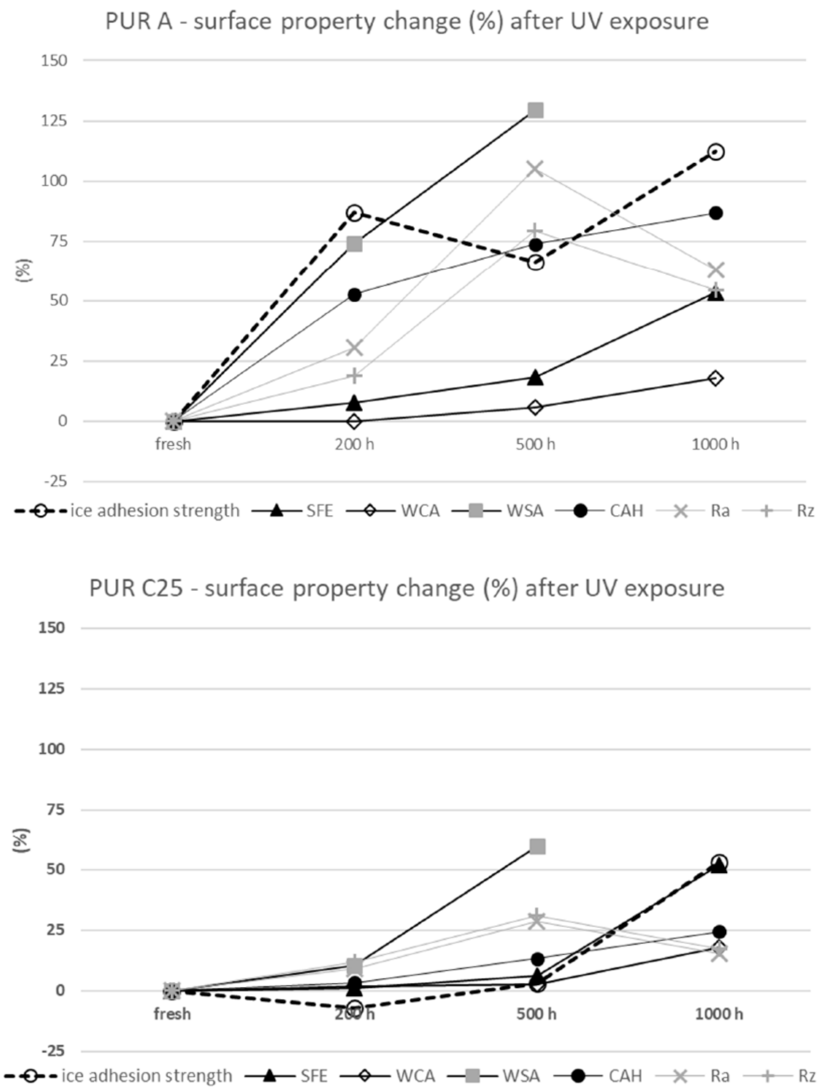


Figure 4-5. Change in surface properties and ice adhesion strength (%) due to UV(B)-ageing for exemplary coatings [14].

The dotted lines in Figure 4-5 indicate the change in ice adhesion strength during the accelerated degradation test. In comparison with the surface properties, it was identified that for coating PUR A water sliding angle (WSA) and contact angle hysteresis (CAH) follow the trend of the increasing ice adhesion strength best. In contrast, for coating PUR C25 the surface free energy (SFE) is the best correlating parameter. The findings emphasis the needs to define relevant, material-specific surface properties in order to monitor and predict the performance of icephobic materials.

There are further material characteristics that are under discussion to have significant impact on the icephobic performance, including the elastic modulus of a material [[27], [28]]. If applicable, this temperature and coating thickness depending parameter is to be considered and should further improve the understanding on the needs for best balanced material characteristics.

5. Key Conclusions/Recommendations/Future needs

This report highlights the needs for the evaluation of icephobic coatings for the application on rotor blades of wind turbines. At an early stage of material development, tests with low complexity and high throughput are necessary, bearing the risk of result misinterpretation (under- or overestimating of the actual icephobic performance). The selection of benchmark materials (e.g. state-of-the-art materials with known "field" performance) is highly recommended to guide the evaluation process and identify material improvements with regard to the reduction in ice formation and ice adhesion in lab based test designs.

It is further recommended to address performance durability of the coating material in an early development stage. This shall avoid unrealistic expectations, especially with regard to the requirements on UV and erosion protection.

High potential materials with improved lab test performance and proven durability shall undergo further assessments under more realistic icing conditions, using ice wind tunnel test facilities and field tests.

There are still open topics to be addressed in future research activities, including:

- The harmonization and standardization of ice related lab tests.
- The knowledge about the transferability of lab based test results and actual field test performance.
- The identification of correlations between icephobic performance and surface characterization parameters.
- Data-driven methods for improved performance analysis.

Reference report(s)

[1] IEA Wind Task 19, 2018. Available Technologies for Wind Energy in Cold Climates, 2nd edition; https://iea-wind.org/task19/t19-publications/

[2] Rehfeld, N.; Berton, B.; Morita, K.; Kimura, S. A Way Forward to Design Efficient Wing Ice Protection Systems. In Proceedings of the Greener Aviation Conference, Brussels, Belgium, 11–13 October 2016. GA2016_135.

[3] Seifert, H. Cold climate solutions. Operation of wind turbines under icing conditions. Ice & Rocks III, Zadar, Croatia, 2010 May 5th.

[4] Rehfeld, N.; Stake, A.; Stenzel, V. Development and Testing of Icephobic Materials: Lessons Learned from Fraunhofer IFAM. In Contamination Mitigating Polymeric Coatings for Extreme Environments; Wohl, C.J.; Berry, D.H., Eds.; Adv Polym Scie 284; © Springer International Publishing AG Switzerland, 2019, pp. 145-166; doi: 10.1007/12_2017_37

[5] Memon, H.; De Focatiis, D.S.A.; Choi, K.-S.; Hou, X., Toward Exceptional Icephobicity with Chionophile-Inspired Durable Biomimetic Coatings, ACS Applied Polymer Materials 2021, 3, 4184–4194

[6] https://pubs.acs.org/doi/suppl/10.1021/acsapm.1c00623/suppl_file/ap1c00623_si_002.mp4

[7] Work, A.; Lian, Y. A Critical Review of the Measurement of Ice Adhesion to Solid Substrates. Prog. Aerosp. Sci. 2018, 98, 1–26.

[8] Laforte, C.; Beisswenger, A. Icephobic Material Centrifuge Adhesion Test. In Proceedings of the IWAIS 2005, Montréal, QC, Canada, 12–16 June 2005.

[9] Kulinich, S.A.; Farzaneh, M. Ice adhesion on super-hydrophobic surfaces. Applied Surface Science 255, 2009, 8153–8157; doi:10.1016/j.apsusc.2009.05.033

[10] Koivuluoto, H.; Stenroos, C.; Ruohomaa, R.; Bolelli, G.; Lusvarghi, L.; Vuoristo, P. Research on icing behavior and ice adhesion testing of icephobic surfaces. In Proceedings of the IWAIS 2015, Uppsala, Sweden, 28 June – 3 July 2015.

[11] Orchard, D.; Clark, C.; Chevrette, G. Reducing Aviation Icing Risk: Ice Adhesion Measurement in the NRC's Altitude Icing Wind Tunnel. In Proceedings of the SAE AeroTech Conference, FortWorth, TX, USA, 26–28 September 2017.

[12] Janjua, Z.A.; Turnbull, B.; Choy, K.-L.; Pandis, C.; Liu, J.; Hou, X.; Choia, K.-S. Performance and Durability Tests of Smart Icephobic Coatings to Reduce Ice Adhesion. Appl. Surf. Sci. 2017, 407, 555–564.

[13] Soltis, J.; Palacios, J.; Eden, T.;Wolfe, D. Evaluation of Ice-Adhesion Strength on Erosion-Resistant Materials. AIAA J. 2015, 53, 1825–1835.

[14] Rehfeld, N.; Speckmann, B.; Schreiner, C.; Stenzel, V. Assessment of Icephobic Coatings—How Can We Monitor Performance Durability? Coatings 2021, 11, 614. https://doi.org/10.3390/coatings11060614.

[15] Rønneberg, S., J. He, and Z. Zhang, The need for standards in low ice adhesion surface research: a critical review. Journal of Adhesion Science and Technology, 2020. **34**(3): p. 319-347.

[16] Rønneberg, S., et al., Interlaboratory Study of Ice Adhesion Using Different Techniques. Coatings, 2019. **9** (10).

[17] Schulz, M. and M. Sinapius, Evaluation of Different Ice Adhesion Tests for Mechanical Deicing Systems, in SAE 2015 International Conference on Icing of Aircraft, Engines, and Structures. 2015: Prague, Czech Republic.

[18] Mattiello, E. Aerodynamic forces on a NACA 0015 airfoil in dry and iced states; Proceedings of In-Vento 2014 Genova, Italy

[19] Johnbeck, M. Investigation of ice formation and performance of a model scale wind turbine, BSc thesis, 2021, DTU

[20] IEA Wind TCP Task 19, 2020. Performance Warranty Guidelines for Wind Turbines in Icing Climates; https://iea-wind.org/task19/t19-publications/

[21] Lamraoui F.; Fortin, G.; Benoit, R.; Perron, J.; Masson, C. Atmospheric icing impact on wind turbine production. Cold Regions Science and Technology 100; 2014; 10.1016/j.coldregions.2013.12.008

[22] DNVGL-ST-0376: Rotor blades for wind turbines. Edition December 2015; http://www.dnvgl.com

[23] DNVGL-CP-0424: Coatings for protection of FRP structureswith heavy rain erosion loads. Edition May 2016; http://www.dnvgl.com

[24] DIN EN ISO 4287:2009-11. Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters.

[25] Memon, H; Liu, J; De Focatiis, D.S.A.; Choi, K.-S.; Hou, X., Intrinsic dependence of ice adhesion strength on surface roughness, Surface and Coatings Technology 2020, 385, 125382.

[26] Rehfeld, N; Stake, A.; Stenzel, V. Development and Testing of Icephobic Materials: Lessons Learned from Fraunhofer IFAM. In Contamination Mitigating Polymeric Coatings for Extreme Environments; Wohl, C.J., Berry, D.H., Eds.; Springer International Publishing AG: Cham, Switzerland, 2019; pp. 145–166.

[27] Yeong, H.Y.; Milionis, A.; Loth, E.; Sokhey, J. Self-lubrificating Icephobic Elastomer Coating (SLIC) for Ultralow Ice Adhesion with Enhanced Durability. Cold Reg. Sci. Technol. 2018, 148, 29–37.

[28] Kool, N.; Chevrette, G.; Orchard, D.M. Testing of Elastomer Icephobic Coatings. In Proceedings of the Conference Paper for 2018 Atmospheric and Space Environment Conference, Atlanta, Georgia, 25–29 June 2018.