## Final report

# TopNANO - Top-level nanoscale coatings and surface treatment to prevent and combat condensation of water, ice formation, ice growth and adhesion with applications in aircraft, wind turbines and heat exchangers for improved energy efficiency and safety

A project (#10054) within the Top-level Research Initiative administered by Nordic Innovation, 2010-2014 with participation from research and industrial partners in Denmark, Finland, Norway and Sweden.

Research partners: SP (coordinator), KTH, VTT and Aarhus University

Industrial partners*: Saab, Danfoss, Electrolux, FläktWoods, MW Innovation, n-TEC, Nibe, Re-Turn, Gränges, Vattenfall

* Advanced Marine Coatings participated 2010-13 and AkzoNobel Surface Chemistry 2010-12


## Summary

TopNANO largely accomplished its challenging goals. The Technology Readiness level (TRL) scale was implemented in the work structure. TRL goals were to take one technology from TRL 2 to 5, two from TRL1 to 4 and three from TRL 1 to 2. At the end of the project a technology readiness assessment concluded TopNANO took three concepts from TRL 2 to 5, two from TRL 1 to 4 and two from TRL 1 to 2.

TopNANO gathered relevant and strong Nordic research expertise in surface chemistry and ice physics and scaled up promising concepts from idea to lab and pilot testing and to field tests. Crucial elements for project success were strong industrial participation in the project group and the possibility for field tests and scaled-up tests in wind and heat exchanger applications. The main achievements were a well-functioning consortium and research collaboration in the Nordic countries and strong engagement from industry in advice, providing samples and testing and in the sub-groups specific for the field tests in wind and in heat exchangers.

A look ahead can be summarized like this. TopNANO has established a Nordic platform in ice and broadened to other industrial and societal challenges (maritime, off-shore, transport, power transmission, etc). It has attracted major public funding and industrial contracts for longer-term financing. It has initiated collaboration specifically with Nordic, German, Swiss and Canadian groups and industries. It has specifically chosen to work through the network of TopNANO industrial companies. TopNANO has described new phenomena in journals, at conferences and to general public in 50 publications. It has arranged three annual seminars with a total of >150 attendees. It has had one PhD student, three postdocs and two associated PhD students. It has benchmarked concepts in close collaboration with industry partners in shorter field tests during two winter seasons and in scaled up tests in collaboration with four heat exchanger companies.

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## Aim and objectives

The aim of the project was to develop coatings for **passive anti-ice protection in the wind, aircraft and heat exchanger industries**. The strategy for achieving this goal has been to **optimize the surface chemistry and the surface topography on the nanometer scale**. The lead ideas to reduce ice formation have been to use i) superhydrophobic, namely extremely water repellent surfaces, and ii) surfaces that expose chemical functional groups that are classified as water structure breakers. An important aspect of the work has been to understand on a fundamental level why or why not these concepts work. At the start of the project, a thorough literature review was performed to review the state-of-the-art.

The project objectives were to:

- Optimize the surface chemistry and surface topography on the nanometer scale to retard ice and condensation formation
- Investigate the effect of different surface anchored functional groups, polar uncharged and polar charged groups, on ice adhesion
- Develop robust superhydrophobic coating formulations
- Combat negative influence of biological fluid stains from impacted insects on wind turbines, aircraft wings and heat exchanger surfaces
- Develop novel nanotech coatings for anti-freezing
- Assess new surface materials and benchmarking against the existing technology, in terms of cost, performance and LCA
- Perform shorter up-scaled tests and longer field tests during the winter seasons
- Transfer to Nordic industries through direct industry-academia-research institute collaborations
- Develop Nordic platform for deicing and anti-icing and proliferate to other sectors
- Supply industry partners at the end of the project with one concept validated under relevant conditions, two more validated in lab and another three concepts tested in lab*.

  *) Assessed by applying TRL Technology readiness levels to the concepts under evaluation.

Technology Readiness Levels (TRLs) were introduced to ensure suitable evaluation of the technology concepts. TRL1 here means “Basic principles observed and reported”; TRL2 “Technology concept and/or application formulated”; TRL3 “Analytical and experimental proof-of-concept”; TRL4 “Concept validation in lab environment”; TRL5 “As above in relevant environment”; TRL6 “Prototype demonstration in relevant environment”; TRL7 “As above in suitable environment”; TRL8 “Actual system completed and “qualified” through test and demonstration”; TRL9 “As above in successful long-term tests”.

The TRL goals for TOPNANO were:

- Taking one technology concept from Technology Readiness level (TRL) 2 to 5, two concepts from TRL1 to 4 and three concepts from TRL1 to 2.

At the end of the project we made a technology readiness assessment which concluded:

- TopNANO took <u>three</u> concepts from TRL 2 to 5, <u>two</u> from TRL 1 to 4 and <u>two</u> from TRL 1 to 2.

## Introduction

There is a need to optimize surface chemistry and topography on the nanoscale to retard ice and condensation, retard ice and condensation growth, reduce ice adhesion and understand influence of erosion, corrosion and effects of proteins/lipids from impacted insects and contaminants in industrial applications in aircraft, wind turbines and heat exchangers so that one can:

- Develop world-class experimental techniques to understand ice and condensation phenomena
- Develop robust superhydrophobic coatings to combat ice and condensation
- Explore novel nanocoatings for deicing and for anti-freezing
- Use nanostructured hydrophilic/hydrophobic domains to counteract ice growth, and
- Transfer the knowledge to Nordic industry, and more importantly, through direct industry-academia-research institute collaborations evaluate new surface materials and benchmark against systems used today.


Figure 1 Ice accretion occurs on airplane, wind turbines and heat exchangers but is a general issue in transportation and in society as a whole.

There are different types of icing depending on the conditions, in which aircrafts, wind turbines and heat exchangers are affected but to a different degree. **In-cloud icing** occurs when supercooled water droplets hits a surface below 0 ºC and freezes upon impact to soft rime, hard rime or glaze. The formed ice has different size, shapes and properties depending on the number of droplets in the air (liquid water content – LWC), their size (median volume diameter – MVD), the temperature, the wind speed and the duration. **Precipitation** occurs primarily as snow or rain. Especially detrimental are: i) freezing rain when rain falls on a surface with a temperature of below 0 ºC and ii) wet snow which is slightly liquid at air temperatures between 0 ºC and -3 ºC and sticks to the surface. **Frost** appears when water vapor solidifies directly on a cool surface. It often occurs during low winds and during freeze/thaw cycles. The frost adhesion can be strong.

Ice exists in fifteen different forms, the most usual is the hexagonal form. Ice is a nanostructured material and technologies and methodologies to combat ice build-up is nanotechnology.

De-icing means removal of ice while anti-icing means prevention of ice accretion. Anti-icing can be active, such as mechanical or thermal methods (heating foils or hot air) or passive, such as chemical (freezing point depressants and anti-icing fluids) or surface coatings (permanent). Thermal methods require a lot of energy and chemicals may be harmful for the environment. Anti-icing coatings could be an ideal solution but few commercial products available on the market today.

The research and development of ice repellent and icing retarding technologies has received a lot of attention in recent years, see Figure 2 showing a large increase during the last 10 years in scientific citations and the number of both scientific publications while patents seem to show no such strong increase.

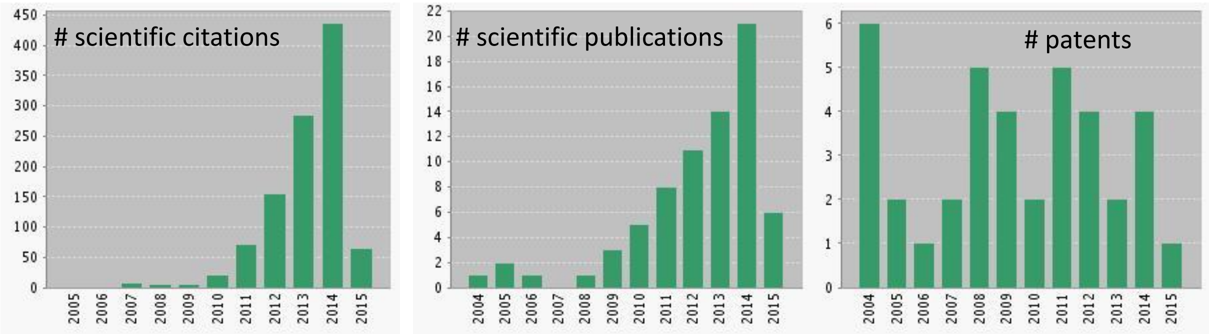



Figure 2. Number of citations, publications and patents related to the search words “antiicing” or “icephobic” during the last 20 years. Searches were made in Web of Science™ (Thomson Reuters). Patents searches in espacenet.com at EPO gave also no definite trend with years. Retrieved March 2015.

The TopNANO initiative started in early 2009 when Saab AB contacted KTH and SP (at that time through its former subsidiary YKI, Institute for Surface Chemistry). The resources needed for an ambitious project could be realized through the Top-level Research Initiative call on nanotechnology for increased energy efficiency.

## Organization and execution

The work package structure decided early 2011 when TopNANO was started in practice is given below. The project work was organized according to this structure, see Table 1, but several partners were exchanged or added as participants during the course of the project.

Table 1 Work package structure of TopNANO

| WP and task | Content | WP Leader | Comment (if no comment, work was done according to plan) |
|---|---|---|---|
| **WP0** | **Establishment of state of the art and progress beyond state of the art** | **SP** | |
| Task 0.1 | Literature survey | KTH | |
| Task 0.2 | Assessment of methods for development and characterization of anti-icing coatings | SP | |
| **WP1** | **Fundamental aspects of deicing and prevention of condensation** | **KTH** | |
| Task 1.1 | Ice formation on superhydrophobic surfaces and nanostructured coatings | KTH | Focus area for wind/aircraft |
| Task 1.2 | Ice formation on hydrophilic/hydrophobic nanostructured surfaces | Aarhus | Focus area for heat exchanger but not ‘nano-structured’ |
| Task 1.3 | Ice formation on surfaces exposing water structure breaking chemical groups | KTH | |
| Task 1.4 | Ice-adhesion measurements of the modified materials | VTT | |
| **WP 2** | **Anti-icing surfaces for aircraft, wind turbine and heat exchanger applications** | **SP** | |
| Task 2.1 | Different types of superhydrophobic coatings | SP | |
| Task 2.2 | Hydrophilic/hydrophobic nanostructured surfaces | Aarhus | |
| Task 2.3 | Surfaces exposing water structure breaking chemical | KTH | |

| | | | |
|---|---|---|---|
| | groups | | |
| Task 2.4 | Explore conductive coatings for de-icing | n-TEC | Not focus area. Developed in related projects |
| Task 2.5 | Explore pyroelectric nanocoatings for anti-freezing | SP | Decided not be focus area |
| Task 2.6 | Selection of most promising concepts for testing in industrial applications in WP4 | SP | |
| **WP 3** | **Bio-inspired anti-icing surfaces** | **Aarhus** | |
| Task 3.1 | Covalent attachment and surface characterization of various hydrophilic functional groups such as ethylene oxide, thiols, alcohols and amines | Aarhus | Task 3.1 and 3.2 redirected towards … |
| Task 3.2 | Surface characterization of chemically heterogeneous surfaces containing polar and non-polar groups alcohols/hydrocarbons and amines/hydrocarbons | Aarhus | …surface functionality imparted counter ions for reduced ice adhesion |
| Task 3.3 | Studying the ice-adhesion properties of the modified surfaces | VTT | |
| **WP 4** | **Testing of anti-icing surfaces for aircraft, wind turbine and heat exchanger applications** | **SP** | |
| Task 4.1 | Tests on surface-modified heat exchanger materials and in test rigs to evaluate the new coatings at real conditions | Fläkt-Woods | |
| Task 4.2 | Evaluation, including corrosion tests, heat exchanger materials with surface-modified materials at real conditions | Fläkt-Woods | |
| Task 4.3 | Brazing trials on Al-based heat exchanger materials | Sapa | |
| Task 4.4 | Erosion, corrosion and biological fluid staining tests on coatings at aircraft conditions | Saab | |
| Task 4.5 | Erosion and corrosion tests on coatings at wind turbine conditions | Vatten-fall | |
| **WP 5** | **Scaling up promising coatings in shorter and longer field tests** | **Saab** | **Two sub-groups: SG1 wind/aircraft and SG2 heat exchanger applications** |
| Task 5.1 | Longer term testing at aircraft conditions | Saab | |
| Task 5.2 | Longer term testing at wind turbine conditions – Stor Rotliden wind park | Vatten-fall | |
| Task 5.3 | Longer term testing at heat exchanger conditions | Electro-lux | |
| Task 5.4 | Life cycle analyses of concepts in WP5 | SP | Not performed |
| **WP 6** | **Communication** | **SP** | |
| Task 6.1 | Internal/external communication | SP | |
| Task 6.2 | Annual seminars | SP | |
| **WP 7** | **Management and coordination** | **SP** | |

We now make a comprehensive summary of work performed in TopNANO under the work package headings.

## WP0 – Establishment of state of the art and progress beyond state of the art

### 0.1 – Literature survey

Extensive literature surveys were performed during the start of TopNANO and were continuously updated in connection with project meetings because of increasing interest in nanotech based icephobic coatings in the scientific and patent literature. One example is given in Figure 3 which shows that the parameter $(1 + \cos\theta_{rec})$ determined under non-icing conditions directly relates to the ice adhesion. This general dependency has been challenged and routes developed have in some cases been shown to deviate from this relationship. However, these aspects are still under debate in the scientific literature and conflicting results are reported.

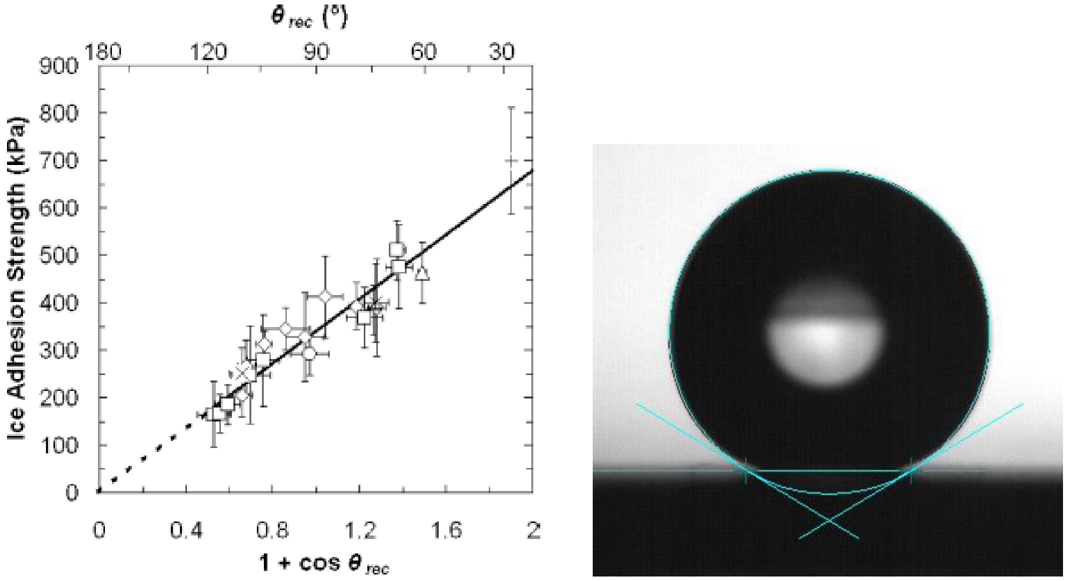



Figure 3 Ice adhesion strength (left) relates to the receding contact angle of water droplets (right) on a substrate as discussed by Meuler (2010).

Based on literature surveys and discussions it was decided for TopNANO to focus on:

- Preparation of superhydrophobic coatings
- Investigate surface energy recovery after soiling
    - Depends on the receding contact angle, making soiling a major issue
- Determine how superhydrophobicity relies on surface chemistry and topography, making wear resistance crucial

### 0.2 – Assessment of methods for development and characterization of anti-icing coatings

At the start of TopNANO the surface chemistry groups involved had a solid understanding of interfacial properties, including adhesion and molecular properties, but we lacked specific knowledge and practical experience on how these properties would be influenced by subzero temperatures. It was to further the fundamental understanding of ice adhesion and how it can be influenced by surface chemistry and surface topography. The main tasks of were to:

- Design instrumentation to allow fundamental studies of ice adhesion and the ice-solid interface at controlled subzero temperatures
- Explore the possibility of using specific ion effects to reduce ice adhesion by influencing the quasi-liquid layer at the ice-solid interface
- Explore the possibility that superhydrophobic surfaces, as often claimed in the literature, would provide a viable route towards low ice adhesion

One of the strategies we followed consisted in extending, or at least modifying the properties of the nanometer size "quasi-liquid layer" present between almost any surface and ice. In order to target the “quasi-liquid layer” and correlate its properties with macroscopic ice adhesion measurements, our instrumentation was first adapted or simply built-up from scratch. KTH specifically designed and built a device capable of measuring ice adhesion on any coating or material as a function of temperature (such a crucial instrumentation was actually not available from any of our partners). This measuring device allowed us to study the influence of surface chemistry, roughness and temperature on ice adhesion (manuscripts under preparation). At the same time, it allowed testing promising coatings produced by our partners, as well as reference substrates currently used by our industrial partners in their respective applications. On the other hand, to measure the sub-microscopic and molecular properties of the quasi-liquid layer we designed and built a cell that could be employed in our TIR Raman and Sum Frequency spectrometers. These latter studies were more fundamental in nature, and were limited to model hydrophilic and hydrophobic surfaces in contact with ice at different temperatures.

As one example of the instrument development within TopNANO, Figure 4 shows a schematic of the ice adhesion sample preparation and measurement which was specially adapted to small (1 x 1 cm) samples and used in both fundamental investigations and in screening of different candidates in preparation for field tests.

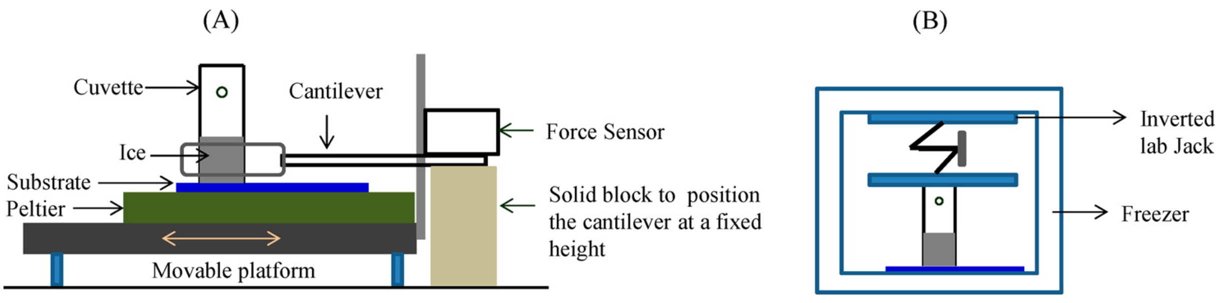



Figure 4 Schematic for ice adhesion sample preparation, adhesion, schematics and primary results on reduced adhesion employing this concept.

KTH designed and built a completely new set-up for even more detailed ice adhesion and ice shearing studies, see Figure 5. The set-up also allows preparation of samples for detailed surface spectroscopy studies of icing using total internal reflectance Raman spectroscopy (TIR-Raman).

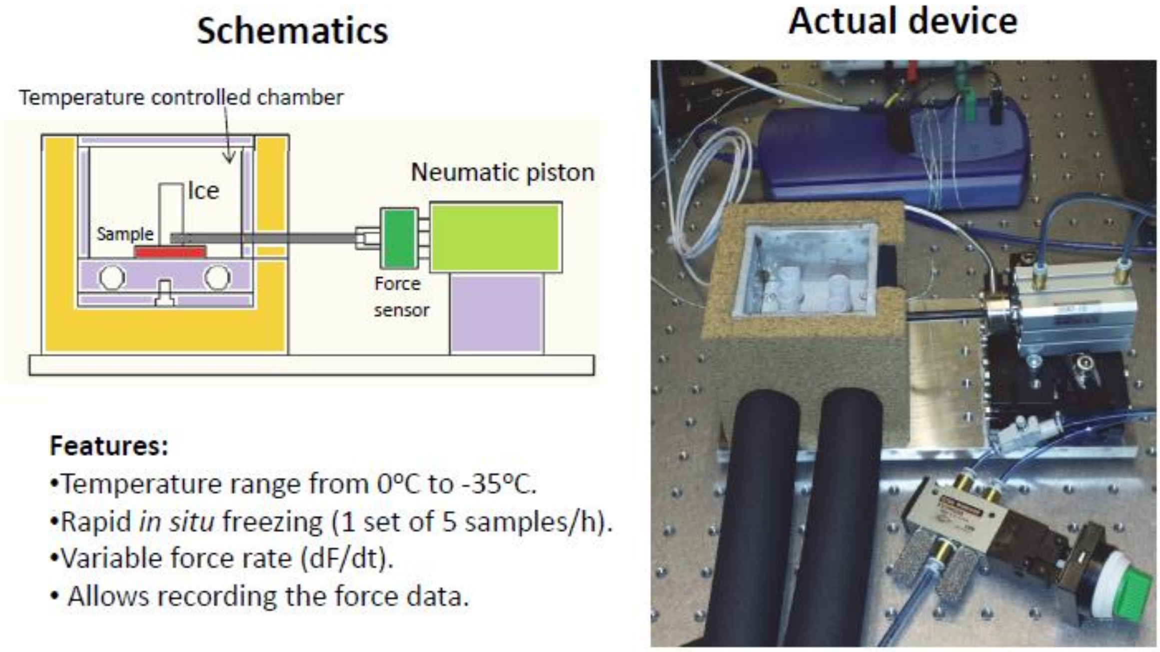



Figure 5 Schematic and photo of the ice adhesion preparation and testing equipment designed and used within the TopNANO project. The same temperature and relative humidity control also allows detailed surface spectroscopy studies of ice formation using TIR-Raman technique.

Investigations using this apparatus are on-going. Ice adhesion depends on temperature, the nature of the substrate (surface chemistry), roughness and the shear rate. The influence of all these parameters can be accounted for by the presence of quasi-liquid layer (QLL), see Figure 6, similar to what was discussed in early ice physics literature (Jellinek 1960, Jellinek 1962, Ratary and Tabor 1958).

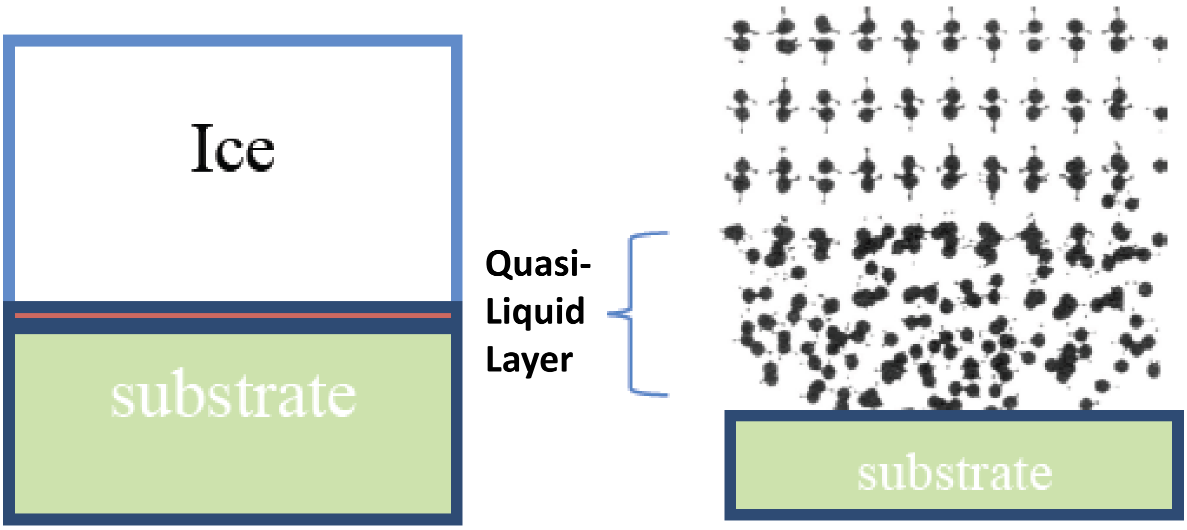



Figure 6 Schematic showing (left) ice formed on a substrate with a thin, nanometer liquid-like layer (QLL, quasi-liquid layer) close to the substrate. (Right) shows blow-up of the region depicting that water molecules in the QLL is much less ordered, i.e. liquid-like, compared to those in the solid ice.

Model surfaces have been studied, e.g. smooth hydrophilic silica surfaces and smooth hydrophobic silanized silica surfaces, see Figure 7.

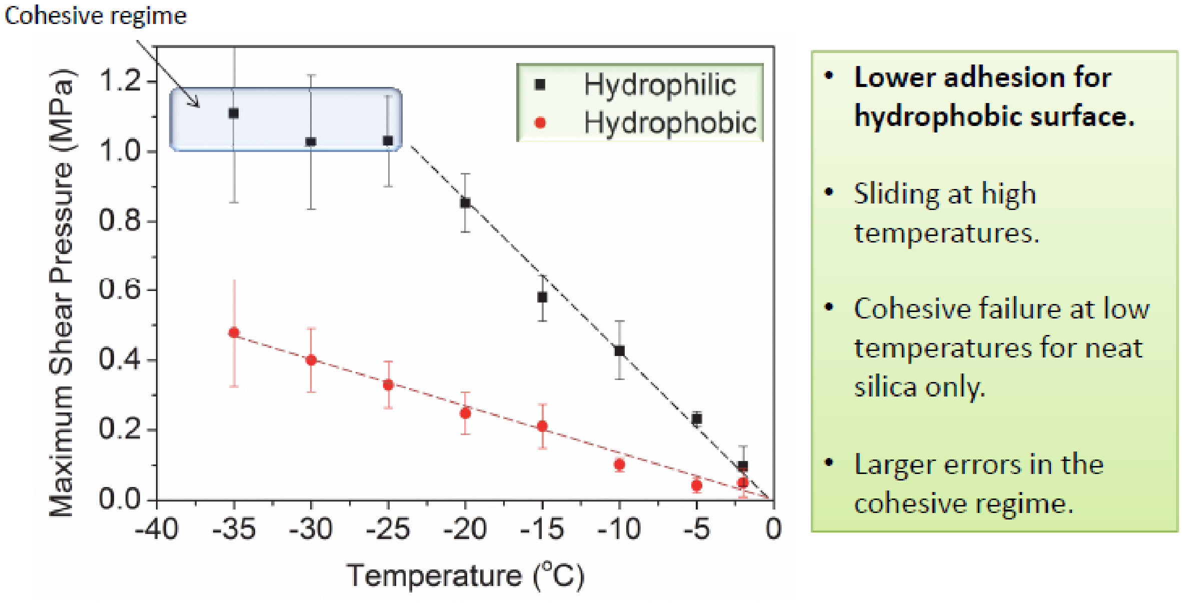



Figure 7 Ice adhesion as function of temperature for smooth model surfaces, either hydrophilic or hydrophobic.

VTT adapted their icing wind tunnel to TopNANO activities and developed a new ice adhesion testing concept and protocol for icing under relevant conditions of water droplets impacting a treated substrate installed in the test section to the right in Figure 8. Details of the new measurement principle and some experimental results given in Figure 9.

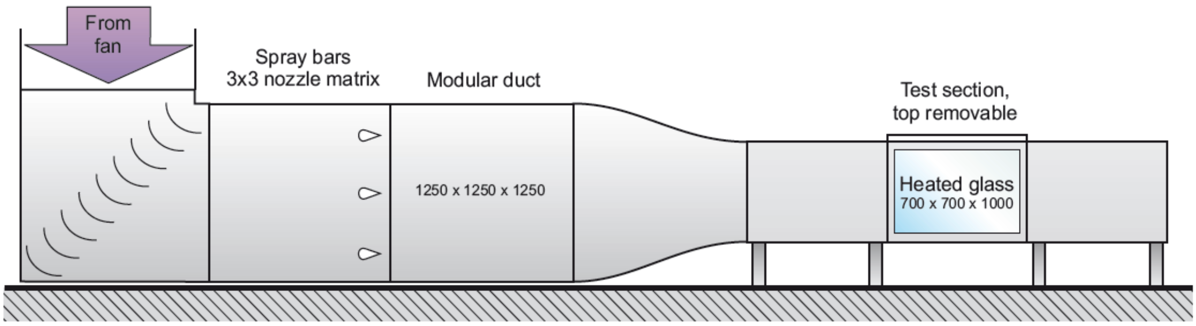
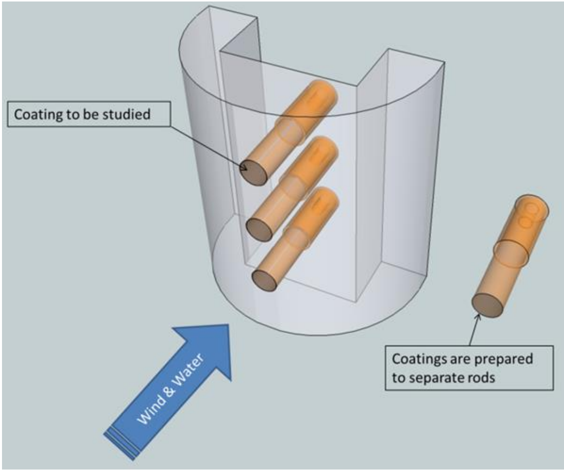



Figure 8 Icing wind tunnel (side view) at VTT laboratories which was adapted for TopNANO experiments and used to validate a new ice adhesion testing to be used under relevant icing conditions, see Figure 9.



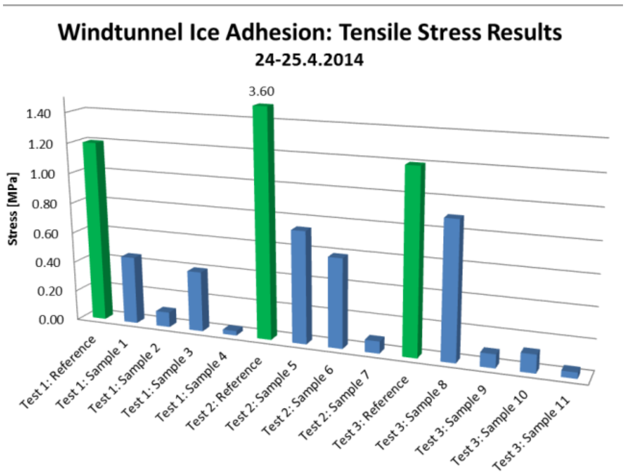




Figure 9 Schematic and experimental results from the new ice adhesion testing procedure developed in TopNANO and validated in the VTT icing wind tunnel. The ice is formed under impacting water droplets, builds up an ice layer on the semi-spherical mount (left). The actual coating to be studied is prepared on the rods being inserted into this mount before installation in the wind tunnel. (Right) Tensile and shear testing is performed directly after to get ice adhesion values.

## WP1 – Fundamental aspects of deicing and prevention of condensation

### 1.1 – Ice formation on superhydrophobic surfaces and nanostructured coatings

Superhydrophobicity is the extreme case of water-repellency at which water droplets bead up on material surfaces displaying water contact angles of more than 150º. The classical example is the lotus leaf, see Figure 10, which also imparts a self-cleaning effect. Numerous studies have focused on mimicking this effect and to use the water-repellency also for ice-repellency (ice-phobicity).

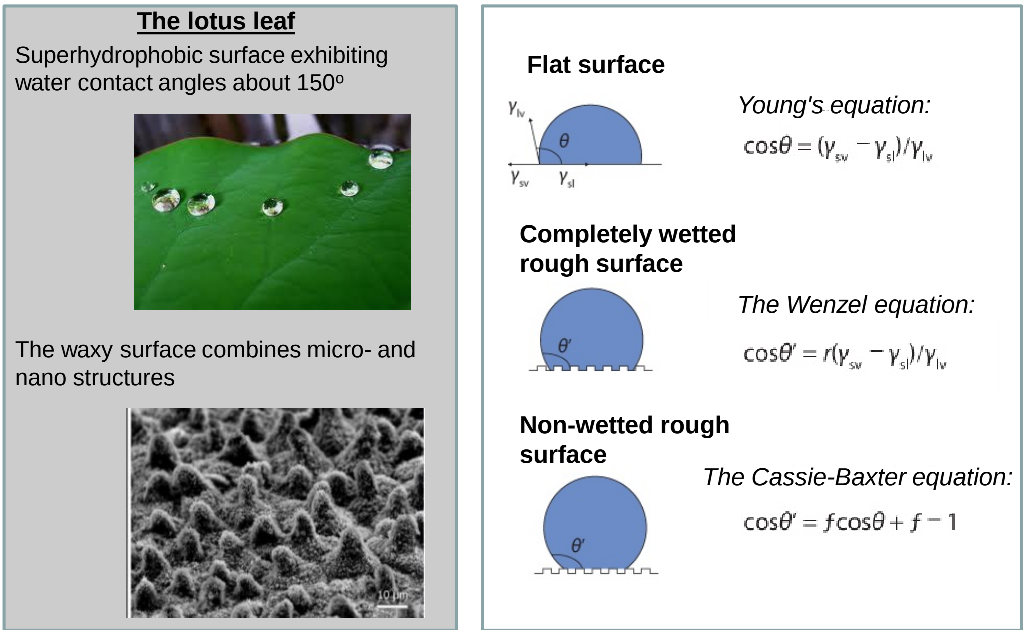



Figure 10 The combination of surface roughness in micro- and nanoscale and hydrophobicity gives extreme water-repellency and a water contact angle of more than 150º. Two idealized cases describe the wettability, in which the non-wetting Cassie-Baxter case is usually the aim in numerous studies using superhydrophobicity for ice-phobicity.

We have shown by AFM colloidal probe microscopy (combinations of hydrophobic/superhydrophobic as probe/surface) that superhydrophobicity displays a set of events when compared with hydrophobicity. Both attraction (due to capillary and wetting forces) and repulsion (most likely due to repelling air/vapor layers or micro-/nanobubbles) occur upon approach and when surfaces are pulled apart both shorter range (50-100 nm or more) and longer range (several micrometers) attractive forces are displayed. The interaction is explained by forces generated through the formation of air and water vapor cavities, in the shorter-range (>50 nm) case maintaining a constant volume of the cavity, in agreement with calculation of capillary forces, and in the longer-range (>1 μm) case through access of air to the cavity, in agreement with thermodynamics of cavity growth. An added sodium dodecyl sulphate surfactant gave a partially reversible wetting transition and reduced the longer-range interaction to shorter-range, suggesting a transfer from the Cassie-Baxter to the Wenzel wetting regime. The findings are of particular interest in development of practical applications, such as for anti-soiling and anti-icing within TopNANO but also widened to protection of electrical components and for extreme water-repellency in paper and textiles.

There is attraction due to capillary and wetting forces and repulsion due to repelling air/vapor layers or micro-/nanobubbles with interaction ranges from 50 nm to several micrometers. There are two cases as shown in Figure 11: i) constant volume of the cavity (air/vapor layer between surfaces) which is described by capillary force equation and ii) growing volume of cavity which is thermodynamically favourable.

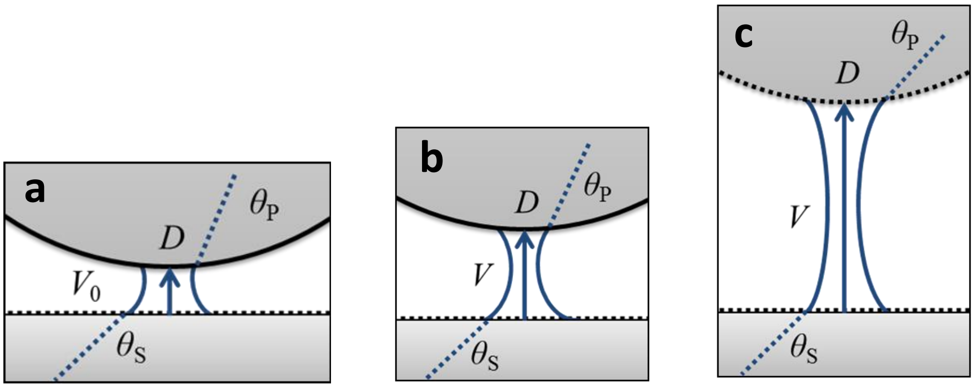



Figure 11 Two hydrophobic surfaces interact which is measured by interfacial force measurements, (a) shows the schematic diagram displaying a capillary force. When surfaces are pulled apart in (b) this capillary force maintains a constant volume for hydrophobic surfaces, whereas for superhydrophobic surfaces (c) the volume increases so that the interaction extends to micrometer distances.

Our findings suggest that the very extreme water- and also potential ice-repellency as seen in casa c above is the most probably required is required and that potential candidates for icephobicity should display these characteristics.

Superhydrophobic surfaces, having water contact angles above 150°, can be created by utilizing a combination of a low surface energy and a high surface roughness extending over several length scales. Air is trapped in depressions on such surfaces, which explains the very high water contact angle. Since water does not like to be on these surfaces it seems logical that ice also would avoid them, and thus ice adhesion would be expected to be low. However, as we showed in a published article, the situation is more complex. As the temperature is lowered first water vapor, and then, at lower temperatures, frost form on the superhydrophobic surfaces. This leads to increased water (and ice) wettability. Thus, a contact angle measured at room temperature says very little about the wettability at sub-zero temperatures, as demonstrated by our experiments. We also showed that the freezing delay time (i.e. the time it takes for a water droplet to freeze at a given sub-zero temperature) was not affected by surface roughness provided the surface chemistry was similar. From thermodynamic considerations we also draw the conclusion that one should not expect superhydrophobic surfaces to be iceophobic except under very special circumstances. Superhydrophobic surfaces may, however, have a kinetic benefit. If the drop rolls off quicker than it freezes, then ice will not accumulate on the surface.

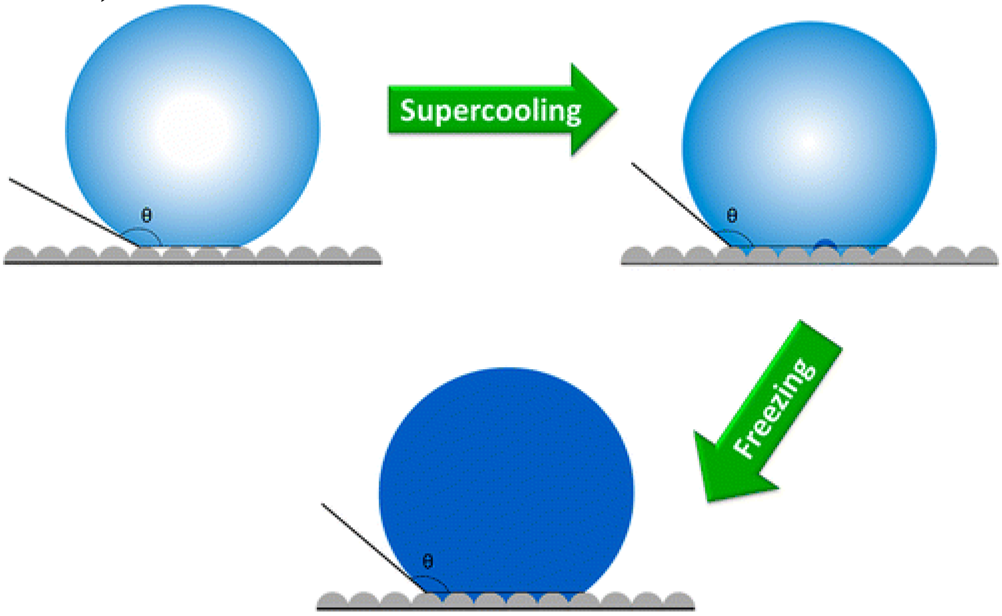



Figure 12 Schematic showing how a water droplet rests on a nanostructured superhydrophobic surface, becomes supercooled and then freezes in which both supercooling and freezing induces wetting of the surface, thereby reducing the icephobicity.

The freezing temperature and the freezing delay time were determined for water droplets resting on a range of surfaces with similar chemistry but different topography, including smooth and rough surfaces in either the Wenzel or the Cassie–Baxter state as characterized by water contact angle measurements at room temperature. We find that the water freezing delay time is not significantly affected by the surface topography and discuss this finding within the classical theory of heterogeneous nucleation, see Figure 13.

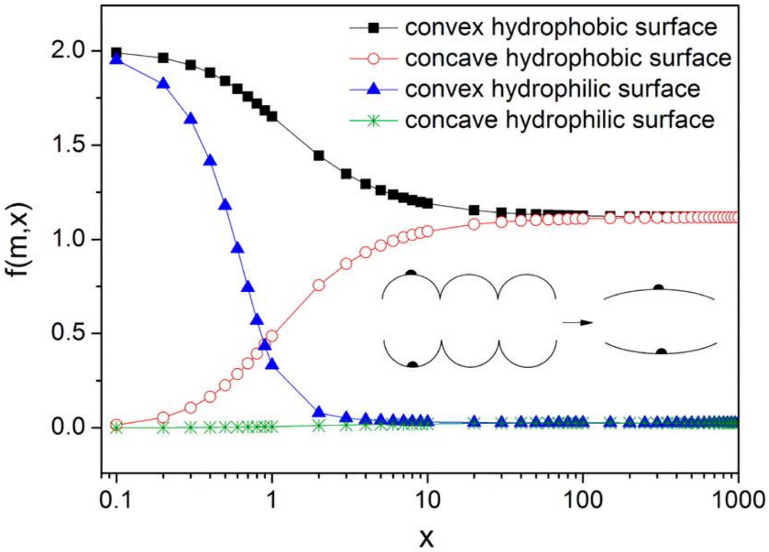



Figure 13 The function $f(m,x)$ vs the roughness parameter $x$ plotted for contact angles of 94° (“hydrophobic”) and 30° (“hydrophilic”). The scheme in the figure illustrates the small $x$ (where the critical radius of ice nucleus is comparable to the size of the surface features) toward large $x$ (where the critical radius of ice nucleus is much smaller than the size of the surfaces features), top scheme for the convex and bottom scheme for the concave surface features. An increasing radius of surface features $X = r/r^*$, where $r$ = radius of surface feature, $r^*$ = critical ice nucleation radius ≈ 9 nm at -5 °C and about 4.5 nm at -10 °C

Large surface features should not have any effect since *r** is small. All real surfaces have both concave and convex features. Freezing occurs most readily in depressions (concave) and least readily on concave sites.

### 1.2 – Ice formation on hydrophilic/hydrophobic nanostructured surfaces

This task was decided not to be a focus.

### 1.3 – Ice formation on surfaces exposing water structure breaking chemical groups

Our instrument development efforts have resulted in that we now can spectroscopically probe the ice-solid interface and investigate how the structure of the quasi-liquid layer is affected by surface chemistry and temperature. The results showed that in spite of being thinner than 5 nm in thickness, the quasi-liquid layer appears to play a central role in controlling ice adhesion. These latter studies have opened a new window of research pursued beyond TopNano.

The effect of surface hydrophilicity on anti-icing property has been investigated systematically. A range of surfaces covering hydrophilic to superhydrophilic property was designed at Aarhus University, using surface initiated atom transfer radical polymerization method to ensure controlled polymer thickness. The hydrophilic surface consisted of polyethyleneglycol brushes and the superhydrophilic surfaces were prepared by surface synthesis of polyelectrolyte brushes with various counter ions. The ion types were chosen based on their ability to structure water molecules – ions such as $Li^+$, $Ca^{2+}$ $Ag^+$ and $La^{3+}$ known as *kosmotropes* have the tendency to disrupt water hydrogen bonds, whereas ions such as $K^+$, $Cl^-$, and $BF_4^-$ known as *chaotropes* do not coordinate water molecules strongly. The passive anti-icing property of the surfaces has been characterized by ice adhesion tests performed at -10 °C and -18 °C. The ice adhesion tests were carried out at SP. In general, the result has shown that the anti-icing property of ion incorporated superhydrophilic brushes is superior compared to hydrophilic brushes both at -10 °C and -18 °C. In particular the *kosmotropic* ion such as $Li^+$ has reduced ice adhesion by 40 % at -18 °C and 70 % at -10 °C compared to unmodified bare surface, see Figure 14 for sample preparation, adhesion, schematics and primary results on reduced adhesion employing this concept.

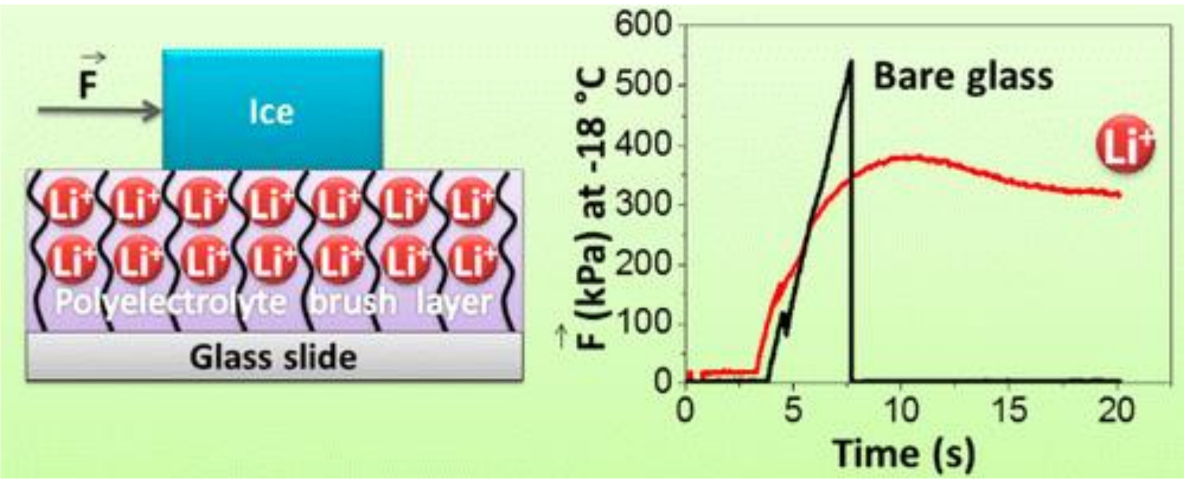



Figure 14 Schematic (left) and key features (right) of the water structure breaking properties in reducing ice adhesion using a polyelectrolyte superhydrophilic substrate with Li counter ions. This surface treatment shows 40-70 % lower ice adhesion and a different sliding mode of failure instead of the sharp breakage.

As a next step efforts were made to incorporate lithium ions in sol-gel type anti-icing coatings. To this end diblock spherical polymer brush comprising of Lithium ion exchanged polyanionic-*block*-poly(glycidylmethactylate) brush was synthesized on 30 nm silica particles. The NMR spectroscopy has confirmed that the synthesis step has been successful. Furthermore the glycidyl unit was opened by reacting with (3-aminopropyl)trimethoxy silane, which will serve as the precursor unit during sol-gel coating.

How surface chemistry and temperature affect ice adhesion was explored in a joint work with Aarhus University and SP, resulting in a published article. The results of this work demonstrate that ion specific effects can reduce ice adhesion. Our hypothesis, which we now are testing experimentally outside TopNANO, is that the specific ion effect arises through modification of the quasi-liquid layer.

### 1.4 – Ice-adhesion measurements of the modified materials

This task was integrated with tasks 1.1 and 1.3

## WP2 – Anti-icing surfaces for aircraft, wind turbine and heat exchanger applications

### 2.1 – Different types of superhydrophobic coatings

Fundamental studies of superhydrophobic coatings are reported in WP1 above and candidate selection and optimization in WP5 below

### 2.2 – Hydrophilic/hydrophobic nanostructured surfaces

This task was decided not to be a focus.

### 2.3 – Surfaces exposing water structure breaking chemical groups

See above.

### 2.4 – Selection of most promising concepts for testing in industrial applications

See below.

## WP3 – Bio-inspired anti-icing surfaces

### 3.1 – Covalent attachment and surface characterization of various hydrophilic functional groups such as ethylene oxide, thiols, alcohols and amines

### 3.2 – Surface characterization of chemically heterogeneous surfaces containing polar and non-polar groups alcohols/hydrocarbons and amines/hydrocarbons

### 3.3 – Studying the ice-adhesion properties of the modified surfaces

The original ideas of WP3 was to mimick nature by attaching chemical functional groups onto substrates which are similar to those found in plants and insects which are capable of sustaining low temperatures without freezing. The experimental results of this original WP3 were not promising even after thorough studies and was abandoned in favour of the counter-ion polyelectrolyte brush investigations reported above.

## WP4 – Testing of anti-icing surfaces for aircraft, wind turbine and heat exchanger applications

Both commercially available coatings and coatings developed within the consortium were investigated in the project. The general work flow in the project has consisted of an initial characterization of the coatings on the lab scale. Primary characterization methods have been surface wettability determination in the form of contact angle measurements and ice adhesion measurements. A considerable amount of work was put on the development of the ice adhesion measurements. Other characterization methods that have been employed are SEM, XPS, profilometry, surface spectroscopy, and AFM. The most promising coatings were further tested in field tests. The scaled-up and field testing were planned into two subgroups, one for the wind/aircraft area and another for the heat exchanger area.

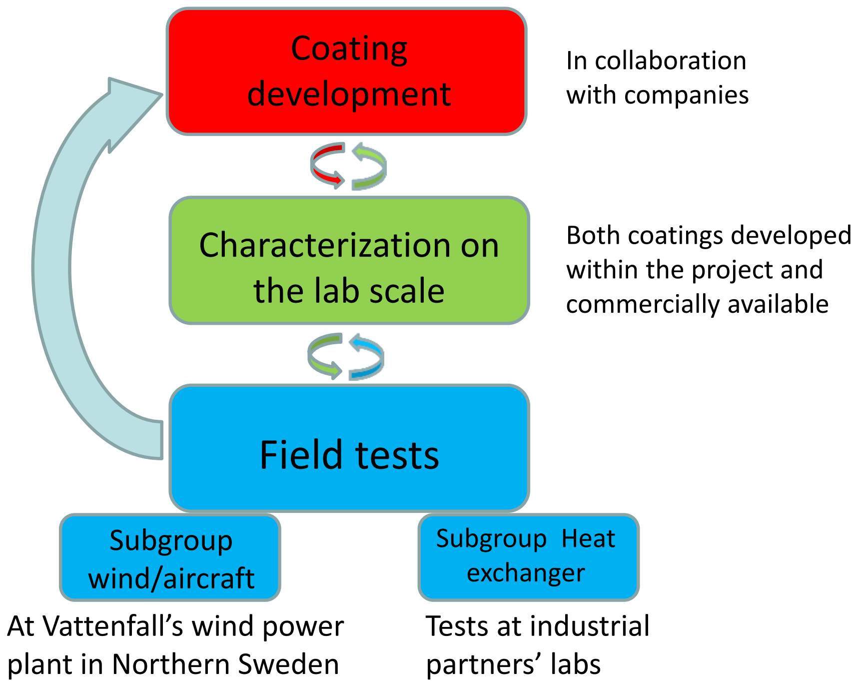



Figure 15 Schematics of the iterative work flow in TopNANO to develop and test passive anti-icing coatings for wind/aircraft and heat exchanger applications.

The substrate materials used in subgroup wind/aircraft were mainly aluminium, with and without anodization, and gelcoat. Some samples were also exposed to sandblasting, in order to increase the surface roughness to enable superhydrophobic properties. All anodization and sandblasting work in the project was performed at SAAB. The subsequent surface modification was performed by SP. Different hydrophobic coatings were utilized, e.g. plasma polymerization, stearate treatment, and fluorosilane treatment. The most promising coatings identified in the lab scale tests were subjected to rain erosion tests, icing wind tunnel experiments and field tests. The erosion tests were performed at SAAB's facilities in Linköping. The tests gave a very good indication of the durability and wear resistance of the coatings. The icing wind tunnel experiments were performed at VTT in Espoo, Finland. The tunnel was modified to incorporate a specially developed device onto which ice accreted at relevant icing conditions to allow ice adhesion measurements. These ice adhesion data are very useful to compare with those from the measurements in KTH's and SP's lab, especially since the ice formation mechanisms are different.

A coating on aircraft aluminium alloys with improved icephobic properties was developed.

Field tests were performed during two winters at Vattenfall's wind park at Stor-Rotliden in the northern part of Sweden. The selected coatings were applied on cylinders made of anodized aluminum and placed on the roof of a nacelle of one of the wind turbines approximately 100 m above ground, at in-cloud icing conditions, from November to April during 2012/13 and 2013/14 winters. The snow and ice accretion on the samples were recorded by a VIS webcam and an IR camera on an hourly basis and the surface wetting characteristics of the coatings were checked before and after the test. It was found that some superhydrophobic coatings performed better than other.

Top priority in operating a wind power plant is safety, for third party, technicians and generation equipment. Vattenfall has participated in the project to find means for reducing operational costs from production losses and damages.

The work in subgroup heat exchanged followed the general work flow (Figure 15). In the lab scale experiments all coatings were applied on free-standing aluminum foils. Test methods, besides those mentioned above, included SWAAT corrosion test. In the scaled-up tests, commercial heat exchangers supplied by the industrial partners in the project (Nibe, FläktWoods, Danfoss, Electrolux) were coated. The coatings, one hydrophobic and one hydrophilic, were prepared by VTT in Tampere by spray coating and sent back to the industrial partners. Each partner then tested and evaluated its own heat exchanger, before and after coating. All test results were compiled and compared by SP. It was concluded that in all cases, the uncoated reference heat exchanger performed better than the coated dittos. There was an indication that the heat exchanger with the hydrophilic coating performed slightly better than the one with the hydrophobic ditto. It was concluded that large scale heat exchangers are difficult to coat and that there is only a limited number of coatings available for large scale heat exchangers.

### 4.1 – Tests on surface-modified heat exchanger materials and in test rigs to evaluate the new coatings at real conditions

### 4.2 – Evaluation, including corrosion tests, heat exchanger materials with surface-modified materials at real conditions

### 4.3 – Brazing trials on Al-based heat exchanger materials

### 4.4 – Erosion, corrosion and biological fluid staining tests on coatings at aircraft conditions

### 4.5 – Erosion and corrosion tests on coatings at wind turbine conditions

Tasks 4.1-4.5 were integrated into the optimization plan depicted in Figure 15 in order to prepare for surface treatment and coatings to be tested in longer-term upscaled testing at the wind park for aircraft and wind turbine applications and at companies' laboratories for heat exchanger applications, see further below under Tasks 5.1-5.3.

## WP5 – Scaling up promising coatings in shorter and longer field tests

### 5.1 – Longer term testing at aircraft conditions

This task was decided to be integrated with Task 5.2 because under normal conditions aircraft conditions can resemble conditions encountered in wind turbines.

### 5.2 – Longer term testing at wind turbine conditions – Stor Rotliden wind park

Two winter seasons during the TopNANO project (2012/13 and 2013/14) was devoted to installation, supervision and post-analyses of substrate candidates based on laboratory and scaled-up tests. The testing site was offered by Vattenfall at their Stor-Rotliden wind park outside Dorotea, Lapland, Sweden, see Figure 16 and close-up of samples installed on the sample mount on top of a wind turbine, see Figure 17.

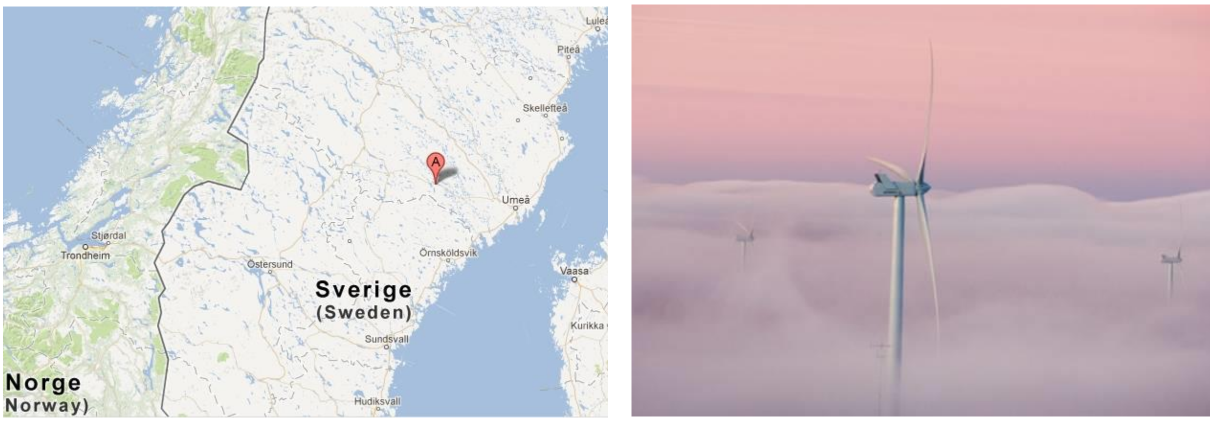



Figure 16 Location of the TopNANO field test site at Vattenfall's wind park Stor-Rotliden at which sample were mounted on top of the wind turbine (no treatment of rotor blades!) during two winter seasons 2012/13 and 2013/14.

Figure 17 Samples for anti-icing testing at Stor-Rotliden wind park were monitored using web-based daylight and IR cameras.

Selection of candidates was made by using the optimization scheme in Figure 15. An example is given in Figure 18 of the many ice adhesion tests that were evaluated in one set of experiments in order to determine best candidates.

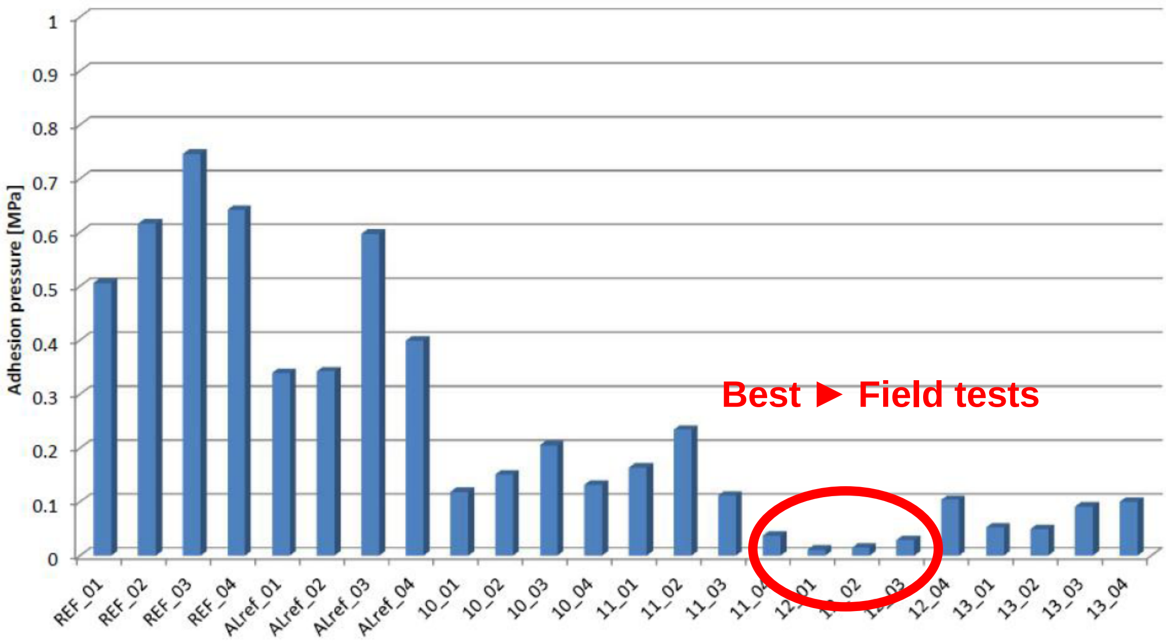



Figure 18 Ice adhesion values for a set of potential candidates examined before selection of sample treatments for the second winter's field tests.

A simplified experimental procedure for water wetting of samples was used to assess the samples before mounting, see Figure 19, which shows two snapshots of superhydrophobic coating #2 during testing.

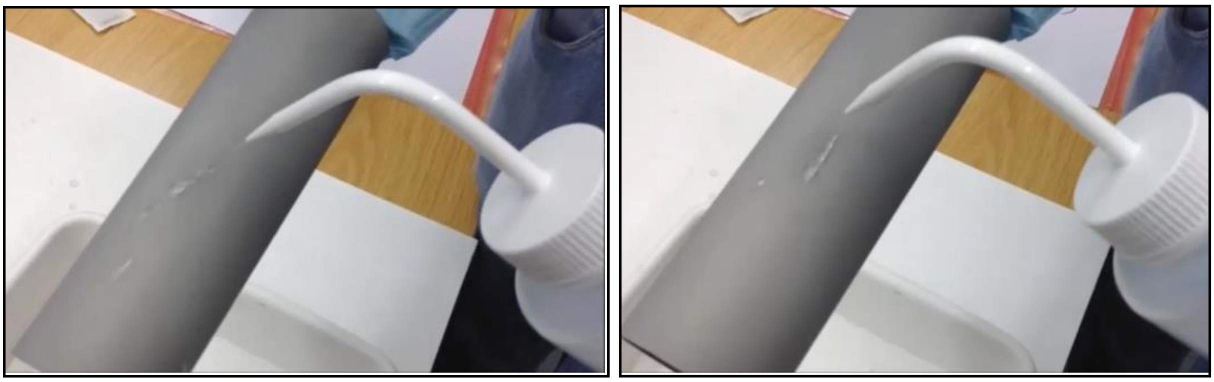


Figure 19 Two camera snapshots from water wetting analyses in the laboratory in preparation for the second winter's field tests showing superhydrophobic coating #2. Before field tests – water runs off very easily.

Figure 20 shows a camera snapshot from the sample mount on top of the wind turbine during the second winter's field tests. Apparently superhydrophobic coating #2 is performing the best, showing at least part of the time an ice-free surface. It should, however, be pointed out that this sample was also iced and covered with wet snow but had on multiple occasions an ice-free surface.

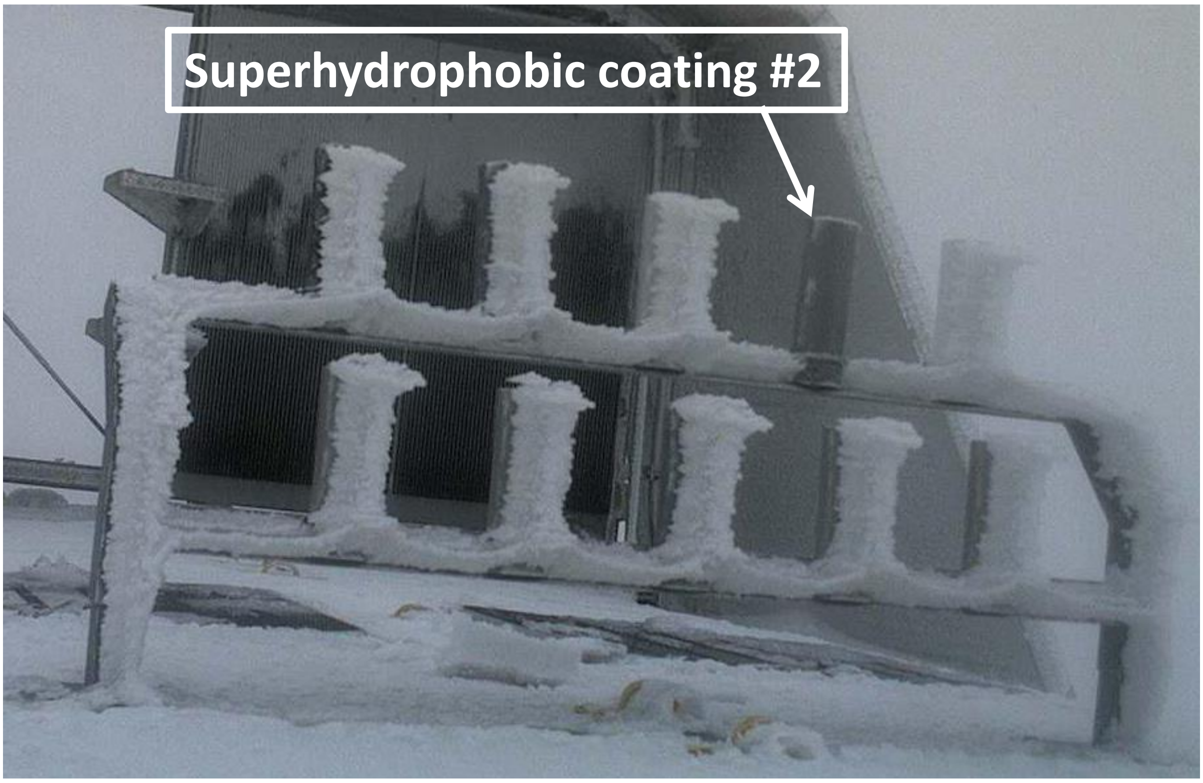



Figure 20 Camera capture of the sample mount on the top of a wind turbine during the second winter's field testing.

After the second winter's field tests, samples were brought back to the laboratory for repeated wetting tests, see Figure 21 for the superhydrophobic #2 sample.

Figure 21 Camera snapshots from water wetting analyses in the laboratory after the second winter's field tests again showing superhydrophobic coating #2. (Left) Front side – exposed to harsh winter weather conditions. (Right) back side, not exposed.

After the field tests, water still runs off and this is the best performing coating during the field tests. This is still the conclusion that a superhydrophobic coating is the best performer, eventhough fundamental laboratory investigations within TopNANO clearly demonstrate that superhydrophobic coatings are not, due to basic thermodynamic considerations, not candidates for anti-icing.

### 5.3 – Longer term testing at heat exchanger conditions

The longer term testing was made at participating heat exchanger companies with surface treatment of substrates at SP and VTT. The different types of heat exchanger set-ups spanned a large part of available techniques and were:

- Outdoor Air Heat Pump (Fin-coil)
- Exhaust Air Heat Pump (Fin-coil)
- Air-to-Air heat Recovery Unit (Heat Plate Exchanger)

Figure 22 shows schematics of the different techniques.

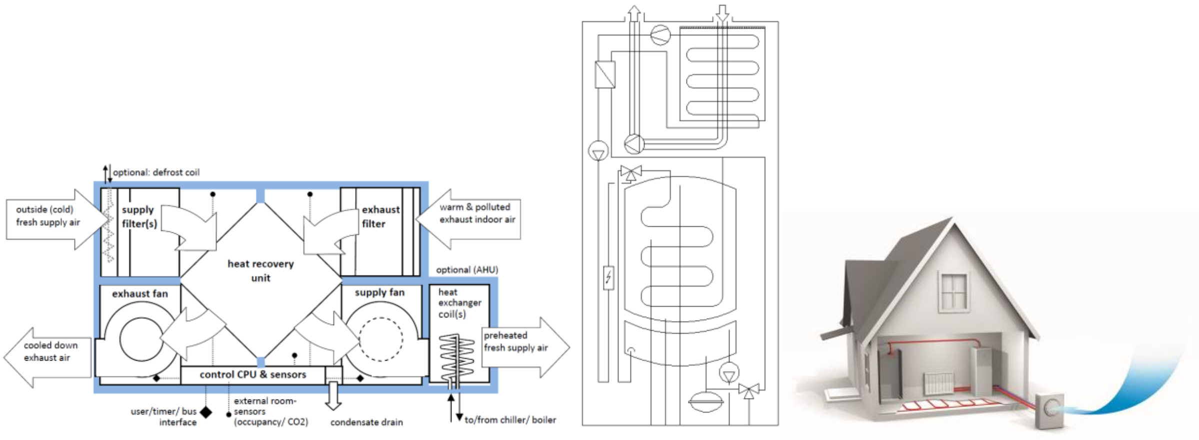



Figure 22 Schematics of the different heat exchanger techniques used in the scaled-up longer-term test performed at industrial companies of TopNANO.

For the out-door air heat-pump the different coatings (hydrophilic or hydrophobic, both prepared by VTT) resulted in, see also detail photos in Figure 23:

- Different defrost intervals
- Different length of the defrosts
- Different heat required to complete the defrosts
- Different heating capacity in heating mode
- Considerable differences, but often one advantage is combined with a disadvantage – equals out each other
- Drop-in solutions, i.e. to retrofit existing installations, do seem not to be possible

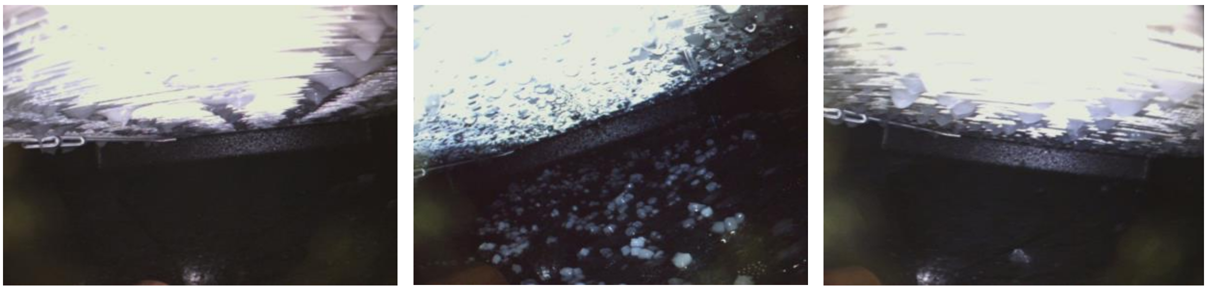


Figure 23 Photos of liquid-air-surface interface at the heat-pump fin: (left) standard, non-treated, (middle) hydrophobic coating and (right) hydrophilic coating. The standard non-treated gave the best overall performance.

On the exhaust air heat-pump the set-up was to prepare standard (no surface coating), hydrophobic (by VTT) and hydrophilic (by VTT) and resulted in that:

- The standard non surface treated evaporator gave the best overall performance
- The hydrophobic surface exhibited lower average heat output than standard heat exchanger (airflow reduced quickly)
- Absolute time required for defrost is the same for all three test items
- 100 % of moisture captured in heat exchanger with hydrophobic coating
- The hydrophilic coating has a lower average heat output than the two other
- Longer time between defrost, but thicker (insulating ice layer) for the hydrophilic coating
- 60 % of moisture captured in heat exchanger with hydrophilic coating (similar to standard)

For the plate heat exchanger, the set-ups were standard, hydrophobic and hydrophilic, see Figure 24. To summarize, the standard performed best. The coated heat exchanger showed an increased pressure drop for the hydrophobic coating which can be explained by the beading water droplets occupying the distance between fins and thereby reducing the air stream.


Figure 24 Photos from the plate heat exchanger longer-term testing. Left shows detail and simulation of condensation at the extract air. Right shows experimental set-up overall: (1) outdoor air intake, (2) supply fan, (3) extract air and (4) exhaust air.

In conclusion:

- The application method for the coatings on the heat exchangers works
- It is possible to affect the performance of the heat exhangers by different coatings
- Some characteristics are improved by hydrophilic coatings, some by hydrophobic coatings
- Drop-in solutions with the evaluated coatings are not possible
- Detailed, systematic tests with modified design parameters are needed to proceed

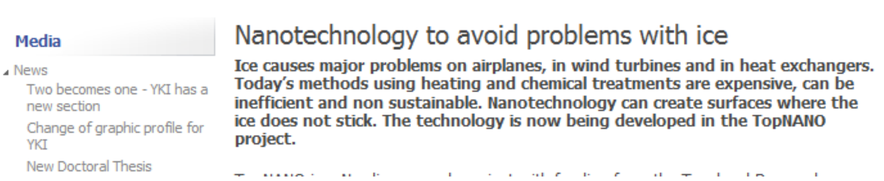
- Superhydrophobic or superhydrophilic coatings are yet to be evaluated in full-scale tests

## WP6 – Communication

A detailed communication plan was suggested in the 2nd stage proposal, presented and decided at the kick-off project meeting in September 2010. The plan was since then not formally updated but reviewed and updated with new communication activities at each project meetings. A web page www.topnano.se was set up with easy login for project participants to access internal pages.

### 6.1 – Internal/external communication

TopNANO was press-released in 2010:


Media
News
Two becomes one - YKI has a new section
Change of graphic profile for YKI
New Doctoral Thesis

Nanotechnology to avoid problems with ice

**Ice causes major problems on airplanes, in wind turbines and in heat exchangers. Today's methods using heating and chemical treatments are expensive, can be inefficient and non sustainable. Nanotechnology can create surfaces where the ice does not stick. The technology is now being developed in the TopNANO project.**

http://www.yki.se/en/media/news/Sidor/101008.aspx, which also attraction attention from popular technical journals such as NyTeknik, http://www.nyteknik.se/nyheter/innovation/forskning_utveckling/article2484943.ece

TopNANO was presented externally already in early 2011 at an SP customer event in Stockholm in February 2011 and, since 2011, in yearly presentations and participation at the Winterwind conferences. For example, the first presentation was in Umeå, Sweden entitled "TopNANO – new Nordic research using nanotechnology to avoid problems with ice" and the latest in Piteå, Sweden entitled "Breaking the ice using passive anti-icing coatings – Lessons learned from the Nordic TopNANO research project", http://windren.se/WW2015/.

### 6.2 – Annual seminars

TopNANO arranged three annual seminars with a total of more than 150 attendees from outside TopNANO group, see www.topnano.se for further information.

## WP7 – Management and coordination

## Results and success criteria

Apart from the applied research performed in the project, the fundamental part has been of importance. Examples of fundamental work in the project are:

- Study of contact angles at subzero temperatures and freezing of supercooled water droplets (KTH-SP)
- Effect of counter-ions on anti-icing properties of superhydrophilic polyelectrolyte brushes (Aarhus-SP-KTH-VTT)
- Systematic ice adhesion measurements on model and industrial samples (KTH-SP-VTT)
- Ice adhesion measurements of model surfaces with varying roughness (SP-KTH)
- New ice adhesion (shear and tensile) methodology under icing wind tunnel conditions (VTT)
- Methodology for evaluation of soil and stain removal through surface energy recovery (SP-KTH)
- Frost and ice formation studies by AFM and Environmental SEM (SP)

- Mechanism for long range (> 1 µm) attraction between superhydrophobic surfaces explained (KTH-SP)
- Advanced instrumentation (as well as experimental and theoretical competence) for contact angles, ice accretion and adhesion, TIR and Raman spectroscopy

### Industrial perspective of TopNANO

From the industrial viewpoint, the TopNANO project had been a very positive experience in several respects. In the first place should be stressed the fact that cooperation between industry, research institutes and university has always been a rewarding experience for industry. On the other side, the economic constrain imposed to industry during the last years of international crisis has forced priorities and therefore it can be noticed a kind of slowing down in the level of engagement in some areas. At the same time it should be mentioned that significant tests were performed in the evaluation of some surfaces made in Lapland, Sweden at high latitudes windmills that made possible the assessment of surfaces while exposed to extreme winter Nordic conditions.

The main goals of the project where to accomplish a deeper understanding of the ice adhesion to different substrates (metallic and polymeric) and the consequences of organic contamination to surfaces (impinging of insects and alike to windmills propel blades and aircraft wings). The outputs of the project, although significantly successful in many respects is yet far from giving a clear understanding of the physics and chemistry of the true nature of the adhesion problem. This statement should be understood properly, i.e. we claim understanding of a phenomenon the moment we are able to use results in the design and dimensioning of systems as heat exchanger, aircraft wings or wind turbine blades that avoid or significantly diminish the impact of ice accretion on them. Las year of the project however resulted in significant initial results in the understanding of the quasi-melted layer at the interface ice-substrate. The very nature of this phenomenon however will demand advanced efforts in quantum mechanical studies to understand the true impact on ice adhesion and thereby on the possibilities of removing or eliminating ice accretion. This accomplishment per se put forward the very complex nature of the ice accretion problem and its understanding.

Although some publications accomplished in the field of organics layers at the interface ice-solid substrate, the outputs are still far from being of use for industry in the understanding of ice accretion and the effect of lipids and proteins gathered at the surface of wind turbines propels blades or at the wings of aircraft as a result of impacts of insects, birds, etc. Once again, the complexity of the problem has been demonstrated, some steps had been made in the gain of a better understanding, however we are yet far from being able to take advantage of results in industrial designs. In this respect however, the project resulted in a significant departure of initial goals.

Other significant outcome worth of mentioning of the TopNANO project are the triggering of new projects and ideas with tasks already in progress aimed to deicing techniques (spin-off effect).

From the industrial viewpoint, the most significant outcomes of the project is the consolidation of a true and solid expertise along with a real improvement of advanced experimental tools for the study of fundamental issues on the complex phenomena of solid-ice interface, hydrophobicity, the physicochemical aspects of ice-adhesion, water-ice-solids interfaces, etc. Other facilities like field testing and evaluation, although valuable, are not comparable with the consolidation of a solid know-how and scientific expertise as those gathered (team building and scientific expertise are seldom gathered with such a level and therefore needs all the support to be maintain and developed as a resource in Scandinavia).

(Eduardo Figueroa-Karlström, Saab AB and member of the TopNANO executive committee).

### Publications

Makkonen, L., 2012. Pintojen fysiikkaa uusiksi (Surface physics revised). VTT **Impulssi / VTT Impulse** (in Finnish and in English), 2/2012: 40-41.

http://issuu.com/mcipress/docs/impulse0212?e=2237972/2269400#1b1b1b

1 An article in the Finnish **Kemia/Kemi** Magazine, see: http://www.kemia-lehti.fi/wp-content/uploads/2014/02/Lasse_Makkosella_on_lumen_taju_Kemia-lehti_05_02_2014.pdf
2 An article in the main engineering magazine for the public **Tekniikan Maailma**
3 Makkonen, L., Lehtonen, P. & Hirviniemi, M., 2011. Relevance of ISO Ice Classes to tower structures. XIV International Workshop on Atmospheric Icing of Structures (IWAIS), 8-13 May 2011, Chongqing, Proceedings (CD), China, State Key Lab of Power Transmission Equipment & System Security and New Technology 4 p.
4 Nygaard, B.E.K., Kristjansson, J.E. & Makkonen, L., 2011. Simulations vs. observations of supercooled cloud liquid water at ground level; Sensitivity to model resolution and cloud microphysics parameterizations. XIV International Workshop on Atmospheric Icing of Structures (IWAIS), 8-13 May 2011, Chongqing, Proceedings (CD), China, State Key Lab of Power Transmission Equipment & System Security and New Technology 5 p.
5 Makkonen, L., Thompson, G., Nygaard, B.E.K. & Lehtonen, P., 2013: Icing of a 326 m tall tower – a case study. Proceedings, XV International Workshop on Atmospheric Icing of Structures (IWAIS), 8-11 September 2013, St. John's, Canada.
6 Podolskiy, E.A., Nygaard, B.E.K., Nishimura, K., Makkonen, L. & Lozowski, E.P. 2012: Study of unusual atmospheric icing at Mount Zao, Japan, using the Weather Research and Forecasting model. **Journal of Geophysical Research** 117, D12106, doi: 10.1029/2011JD017042.
7 Makkonen, L., 2012: Misinterpretation of the Shuttleworth equation. **Scripta Materialia** 66(9), 627-629.
8 Makkonen, L., 2013: Comments on "The Gibbs Equation versus the Kelvin and the Gibbs-Thomson equations to describe nucleation and equilibrium of nano-materials". **Advanced Science Focus** 1, 367-368.
9 Makkonen, L., 2012: A thermodynamic model of sliding friction. **AIP Advances** 2(1), 012179. doi:10.1063/1.3699027.
10 Nikkola, J., Jämsä, S., Virtanen, S., Pelto, J., Kanerva, U., Makkonen, L. & Mahiout, A., 2012: Active coatings utilizing encapsulation technologies. TEKES Functional Materials Summer Festival 2012, Finlandia Hall, Helsinki, 29 - 30 May 2012.
11 Makkonen, L. & Tikanmäki, M., 2014: Modelling the friction of ice. **Cold Regions Science and Technology** 102, 84-93.
12 Makkonen, L., Lehtonen, P. & Hirviniemi, M.,: Determining ice loads for tower structure design. **Engineering Structures** 74, 229-232.

In addition there are ca 30 peer-reviewed conference abstract and proceedings, in total 50 TopNANO publications.

## Nordic platform and exit strategy

1. Optimization of **surface chemistry and surface topography on the nanometer scale** to retard ice and condensation formation

2. Effect of different **surface anchored functional groups**, polar uncharged and polar charged groups, on ice adhesion
3. Develop **robust superhydrophobic** coating formulations
4. Negative influence of **biological fluid stains** from impacted insects on wind turbines, aircraft wings and heat exchanger surfaces
5. Novel **nanotech coatings for anti-freezing**
6. New surface materials and **benchmarking** against the existing technology, in terms of cost, performance and LCA
7. **Shorter and longer field tests** during the winter seasons
8. Transfer to Nordic industries through direct industry-academia collaborations
9. **Develop Nordic platform for deicing and anti-icing and proliferate to other sectors**
10. **Industry partners at the end of the project have one concept validated under relevant conditions, two more validated in lab and another three concepts tested**

**Main achievements**

- Built up a well-functioning consortium and research collaboration in the Nordic countries
- Strong engagement from industry: advice, samples/testing, field tests

**Crucial elements for project successes**

- Strengthen/increase industrial participation from TopNANO consortium
- Field tests and scaled-up tests for wind and heat exchanger applications

**Exit strategy**

- Established Nordic platform
- Broadened to other industrial and societal challenges (maritime, off-shore, transport, power transmission, etc.)
- Attracted major public funding and industrial contracts for longer-term financing
- Collaboration specifically with Nordic, German, Swiss and Canadian groups and industries
- Work through the network of TopNANO industrial companies.
- Described new phenomena in journals, at conferences and to general public. **Three annual seminars with a total of 150 attendees. Approx. 50 publications including new phenomena, conference presentations, and articles**
- 2 PhD, 3 postdocs and 3 associated PhD. PhDs started finalized through other funding. **One PhD student, 3 postdocs and 2 associated PhD students**

- Benchmarked concepts at industry partners. Shorter field tests during three seasons. Field test of 3500 h in last season for most promising concept. LCA analyses of coatings. **Field tests at wind park during two winters (nov-mar, about 3000 h/winter). Tests of heat exchangers at four industry partners**

- Technology Readiness Levels (TRLs) to ensure suitable evaluation.

- TRL goals for TOPNANO:

    - Taken one concept from Technology Readiness level (TRL) 2 to 5

    - Two concepts from TRL1 to 4

    - Three concepts from TRL1 to 2

- **Took three concepts from TRL 2 to 5, two from TRL 1 to 4 and two from TRL 1 to 2**

## Self-assessment among TopNANO project partners

A detailed self-assessment among TopNANO partners was made at the final project meeting. A form containing a number of criteria was firstly filled out individually and then discussed in groups. The criteria were:

- Scope and relevance
    - Addressed societal and industrial needs
    - Built strong R&I environment
    - Has given large collaboration effects
    - Has redesigned research areas and developed new areas
- Execution of the project
    - Project management
    - Plan versus deliverables
    - Efficiency, access to labs and equipment
    - Supervision, personnel development
- External collaboration
    - co-financing
    - Relation to funding agencies
    - EU and other international financing
- Collaboration
    - Academia
    - Institutes
    - Between industrial companies
- Results
    - Reports, quantity
    - Scientific quality, break-throughs
    - Longer-term effects (sustainable growth)
- Competence and excellence
    - Conference presentations
    - Seminars, courses
    - PhD students, postdocs, guest researchers

- MSc thesis
- Personnel exchange

- Success criteria
  - TRL level criteria
  - Number of PhDs, postdocs
  - Personnel exchange
  - Establish Nordic platform
  - Describe new or current phenomena
- Impact
  - Industrial benefits
  - IPR, know-how
  - Created economical potential
  - Addressed societal needs

All of these were rated according to expectation, ranging from much lower, to lower, to meeting and finally exceeding expectations.

Among the criteria which the project group rated to meet expectations the project addressed societal and industrial needs, built a strong R&I environment and redesigned research areas. The criteria of plan versus deliverables remain a challenge, whereas supervision and access to labs and equipment met expectations. The collaboration between institutes, academia and companies rated meeting expectations, as was results in terms of conference presentations and seminars.

Among more detailed comments can be mentioned: “Open and good discussions, meetings more frequently, 3 per year”, “Annual seminars very good”, “Slow start of the project, a common low level of knowledge/expertise, undecided direction initially”, “Make self-assessment also mid-term”, “Several spin-outs into new projects among partners”, “A 3+3 year project with mid-term evaluation for second stage would have been better”, “Collaboration generally good but in some cases isolated activities, in others very good”, “Industrial benefits lower than expected but relates to the application area”

## Personnel exchange

Two postdocs employed at Aarhus University, one now have a research position and one has moved to DTU, Denmark. One PhD student at KTH will defend her thesis in late 2015 or early 2016. One researcher at KTH, Sweden has now a permanent position at DTU, Denmark. Extended visits from Aarhus University to SP and KTH, Sweden.

A number of researchers are associated to TopNANO through external funding but with projects in the same or related areas. Eric Tyrode, KTH, works part-time in TopNANO (this has also constituted KTH in-kind). Petra Hansson, SP, on structured surfaces for ice adhesion and finalizing superhydrophobic manuscript. Lina Martinsson, KTH/SP, on the applicability of durable superhydrophobic coatings for corrosion protection, another highly interesting application (2010-2015). Mikko Tuominen, SP and Tampere University. Postdoc on aerosol based coating techniques for superhydrophobicity and SLIPS surfaces.

## Nordic platform 

### Spin-in and spin-out from TopNANO

The idea behind these activities within the project was to primarily to use TopNANO as Nordic platform to initiate new projects and activities but also to inform us of recent and ongoing projects and activities related to TopNANO. The list of initiatives and information exchange is too long to give in detail, instead a few examples are given together with a summary of all research proposals that have been submitted with TopNANO as a platform.

- Saab in project AEROMUCO – evaluate and benchmark existing coatings for aerospace, part of EU Clean Sky Joint Technology Initiative
- Low-fouling, self-healing, anti-ice – new Tekes project at VTT. Fouling on heat exchangers, Aarhus University industry funding
- SSF material research programme "Surface modified (nano)particles for functional coatings: A new approach for combating icing, fouling and soiling"
- Canadian roadmap at New Foundland with VTT participation.
- NFR proposal on maritime/offshore deicing/anti-icing with Polytec, Haugeland Företagspark, Statoil, Gassco, UNIS at Spetsbergen and others.
- KAW Knut and Alice Wallenberg Foundation on pre-melting surface layers from KTH
- Micro Deice from Swedish Energimyndigheten – wind power in cold climate. Active deicing with SP, Re-Turn, MW Innovation, Pegil Innovation and Vattenfall. Granted 3,9 MSEK
- Energimyndigheten – Breaking the ice. 30 MSEK applied for 3 years. Postdocs and senior personnel. (SP, KTH and Stockholm University)
- ICECONTROL, EU project proposal (SP etc.)
- Retrofit-Deice, KIC Innoenergy project (SP, Re-Turn, etc).
- KNOW ICE – flagship project in a Nordic Energy call (SP, VTT, Vattenfall, etc.)

A total of more than 150 MNOK was applied for to TopNANO partners in different reseach proposals, around 13 MNOK was awarded. This may seem like a very low success rate in funding but reflects that the R&D&I area of surface chemistry and ice physics is new and novel and may need to be established before fundamental KAW and ERC grants can be funded. The areas of more applied research may also need to be established or even refined and focused to a particular technology need.