CHAPTER 6

On Ice Accretion for Wind Turbines and Influence of Some Parameters

J.G. Pallarol, B. Sunden & Zan Wu
Department of Energy Sciences, Lund University, Sweden.

Abstract

The aim of this chapter is to find out the influence of the ice accretion on the wind turbine blade performance, to reveal how different icing variables affect ice accretion and to estimate the heat amount required to de-ice the blades at different icing events. Also different computational model simulations of ice accretion and the different de-icing technologies existing today are described. All the simulations of icing events are performed with a software called LEWINT, developed by NASA Glenn Research Centre, USA. The study emphasises the conditions that are most severe for ice accretion. However, the chapter is theoretical, so experiments are needed to validate and complement the conclusions reached in this chapter. It is pointed out that it is important to find the conditions for which ice accretion is formed and the heat amount required to avoid it, to design suitable blades for regions where ice accretion is formed regularly and develop suitable de-icing systems.

Keywords: Anti-icing and de-icing, cold climate, ice accretion, ice thickness, wind turbine.

1 Introduction

Wind turbines in cold climates are exposed to icing conditions and low temperatures outside the design limits of standard wind turbines. Standard turbines operating in such extreme environments are prone to production losses and increased loads, which in turn will cause a risk of premature mechanical failure and financial losses. Although exact numbers are hard to assess, some 60 GW of installed capacity is located in cold climate (CC) areas in Scandinavia, North America, Europe and Asia. Narrowing this assessment only to regions with high likelihood of extended CC operation; Scandinavia, Switzerland, Canada and northern parts of the United States and China, wind turbines to the power of 20 GW were conservatively
estimated to be installed in CC areas in 2011. Additionally, microclimates with similar conditions are found in more temperated areas such as central and southern Europe, China, Japan, many parts of the United States and locations in the southern hemisphere such as Australia, New Zealand and southern South America. Recent interest in offshore wind power development introduces further demands for knowledge in dealing with icing, as turbines installed in the shallow waters in northern Europe and in the coast of New England in the United States also face icing conditions.

Sites within CC constitute a vast wind energy production potential. Because fewer temperate sites are available and the offshore wind development faces higher costs than expected, large wind energy projects in CC become tempting and are likely to be implemented. Increased experience and knowledge, combined with improvements in technology directed to be used within CC, have enabled such projects to become more competitive when compared with those onshore with low wind resources and those offshore to be built at higher costs.

1.1 Wind energy

The power available in the wind for a wind turbine for use is given by

\[ P_w = 0.5 \rho_a A v_w^3 \]  

where \( \rho_a \) is in kg/m\(^3\), \( A \) is in m\(^2\) and \( v_w \) is in m/s, so \( P_w \) is in Watts. This means that the mechanical power depends mostly on the wind speed. A doubling of the wind speed will increase the power eight times. In Fig. 1, an example of the dependence of power with wind speed is shown. The range of wind speed depends on the power capacity of the turbine.

![Example of power curve](image_url)

**Figure 1**: Dependence of power on wind velocity.
After having described the power available, a presentation on how the wind turbines extract energy from the wind is given. Wind turbines extract energy by slowing down the wind, the wind hits the turbine blades and the energy sets the blades in rotation. Air blowing into a wind power station has to pass through the rotors but must have energy left for blowing away. Due to this, the maximum fraction of the energy which can be extracted is 0.59. This is known as the Betz limit. However, a wind turbine normally has an efficiency lower than this value. The constant used for the efficiency is called \( Cp \), so the power produced by a wind turbine is

\[
P = P_w C_p
\]

where \( P_w \) comes from eqn (1). Modern wind turbine blades are designed from one or multiple aerofoils, resulting in power coefficients of almost 0.5. The turbine efficiency \( C_p \) is a function of the tip speed ratio, for a given wind speed. This ratio is defined as

\[
\lambda_{sr} = \frac{V_{\text{tip}}}{V_w} = \frac{w_r R}{V_w}
\]

where \( V_{\text{tip}} \) is the speed of the blade tip, \( V_w \) is the wind speed, \( w_r \) is the rotational speed of the rotor and \( R \) is the radius of the rotor.

It is shown in Fig. 2 how the power efficiency coefficient evolves with the wind speed, but every turbine has its own \( C_p \) curve. In this case, the maximum value of the coefficient is achieved when the wind speed is 12 m/s. However, the effect of wind speed is much higher than the effect of the efficiency coefficient, so the optimal point is not the one at the best \( C_p \).

2 Cold Climates

Wind turbines in cold climates refer to sites that may experience significant time or frequency of either icing events or low temperatures outside the operational limits.
Apart from lower energy production, or even no production, which directly influences a wind farm’s economy, there are legal issues, such as ice throw and increased noise, fatigue loading and operations and maintenance aspects that need to be considered [2]. Areas, where periods with temperatures below the operational limits of standard wind turbine occur, are defined as low-temperature climate (LTC) and areas with icing events are defined as icing climate (IC). A region can be in a LTC or in a IC or both while they are still all denoted Cold Climate Sites. In Fig. 3, a description of different CC regions in part of Europe is given.

2.1 Low-temperature climate

Extremely low temperatures are typically caused by clear sky radiation during the winter time, which is often associated with high pressure zones. Furthermore, the elevation of a site plays an important role.

An LTC can have different effects on a wind energy project:

- Materials used in turbines can be affected by low temperatures.
• Maintenance work at low temperatures is more time-consuming.
• Cold start of wind turbine can be more difficult at low temperatures.
• Lubricants can lose their viscosity.
• Internal heat of wind turbines reduces energy production.

2.2 Icing climate

Atmospheric icing is defined as the accretion of ice or snow on structures, which are exposed to the atmosphere. There are two different types of atmospheric icing, in-cloud icing (rime ice or glaze ice) and precipitation icing (freezing rain, wet snow). The different forms of atmospheric icing are:

• **Rime ice**: Super-cooled liquid water droplets from clouds or fog are transported by the wind. When they hit a surface they freeze. Rime icing is common at high altitudes and at low temperatures. The most severe rime icing event occurs on freely exposed mountains or hilltops where air is forced upwards and consequently cooled. Depending on droplet size and air temperature during the icing event, rime ice can form structures of different density and strength, which leads to a division into two types of rime ice, hard and soft rime ice. Hard rime ice is opaque, usually white and it adheres firmly on surfaces making it very difficult to remove. The density of hard rime ice ranges between 600 and 900 kg/m$^3$ according to ISO 12494. Soft rime ice is thin ice with needles and flakes. The growth of soft ice starts usually at a small point and grows triangularly into the windward direction. The density of it is between 200 and 600 kg/m$^3$ according to ISO 12494, and it can be more easily removed. In Fig. 4, there is an example how rime ice is formed [4].

• **Glaze ice**: It is caused by freezing rain, freezing drizzle or wet in-cloud icing and forms a smooth, transparent and homogeneous ice layer with a strong adhesion on the structure. Traditionally, glaze ice forms at temperatures between 0°C and –4°C. Part of the water droplets freeze upon impact and remainder run along the surface before freezing, forming a profile shape of high density clear ice. Its density is around 900 kg/m$^3$ according to ISO 12494. Freezing rain or drizzle occurs when warm air melts snow crystals and forms rain droplets, which afterwards fall through a freezing air layer near the ground. Wet in-cloud icing occurs when the surface temperature is near 0°C, the water droplets which

![Figure 4: Rime ice [4]](image_url)
hit the surface do not freeze completely. A layer of liquid water forms, which may flow around the object and freeze also on the leeward side. Figure 5 shows the formation of glaze ice and the difference with rime ice [4].

- **Wet snow**: Partly melted snow crystals with high liquid water content (LWC) become sticky and are able to adhere on the surface of an object. Wet snow accretion, therefore, occurs when the air temperature is between 0°C and 3°C. The typical density is 300–600 kg/m³. The wet snow will freeze when the wet snow accretion is followed by a temperature decrease [4].

- **Hoarfrost**: It is formed when water vapour sublimes to ice. This happens at very low temperatures and will form ice with very low density, which is normally not considered to cause any significant load on a structure.

### 2.3 Effects of icing on wind energy

Climatic conditions with turbulence, gusts, icing and lightning strikes in cold regions will affect wind turbine performance and cause idling of wind farms on windy days. Particularly, icing affects the wind assessment and the operation of wind farms. The following problems are related to icing and cold climates.

- **Measurement errors**: During the assessment phase, the anemometers, wind vanes and temperature sensors can be affected by ice. At icing conditions, wind speed errors can be as high as 30%. Another study identifies a maximum error of 40% for an ice-free anemometer and 60% for a standard anemometer during icing events [5].

- **Power losses**: Ice accretion changes the shape and roughness of the blade aerofoil (consequently affecting their aerodynamic characteristics) and introduces measurement errors from turbine instruments (wrong wind speed or direction, which affects yaw and power controls). Small amounts of ice on the leading edge of aerofoils significantly reduce aerodynamic properties of the blade and the resulting power production. Power losses may vary from 0.005% to 50% of the annual production, depending on icing intensity and its duration on the site, wind turbine models and the evaluation methodology [5].

- **Overproduction**: Higher air density related to low temperatures and aerofoil modifications can lead to overproduction of the wind turbine. Overproduction of up to 16% has been recorded.

![Figure 5: Glaze ice [4].](image-url)
• **Mechanical failures**: Ice accretion will increase the load on the blades and on the tower structure, causing high amplitude vibrations and/or resonance as well as mass imbalance between blades. Operation at low temperatures affects oil viscosity and changes the dimensions and mechanical properties of different components of the wind turbine. This results in possible overheating and higher fatigue charges on components.

• **Electrical failure**: Snow infiltration in nacelle and extreme temperature lead to condensation in the electronics [5].

• **Safety hazard**: The pieces of ice shed from wind turbines can be quite large, and are definitely not insignificant. It is likely that something will occur eventually if preventive measures are not implemented. Though the risks are greatest for service personnel who must approach the wind turbine, others can be at risk when the wind turbine is located near a road or recreation area [5].

### 3 Ice Accretion

#### 3.1 Physical model

Although estimation of icing on wind turbines and other structures is very important, no undisputed model has so far been developed. Due to the non-linear relationships between the parameters affecting ice accretion, most models include empirical formulas and none can be solved analytically. The most widely used model today is Makkonen’s algorithm for ice accretion. The Makkonen model [6] is originally developed for modelling of ice accretion on overhead power lines, and therefore models ice accretion on a cylinder resembling a power line. Now the Makkonen model will be explained and it is based on reference [6].

Irrespective of what kind of particles, liquid or solid, that cause ice on an object, the accumulation rate will be dependent on the flux density; in other words, the cross-sectional area of the object, the velocity of the particles and the mass concentration of particles in the air. Because not all particles will collide with the object and not all particles that do collide will stick or accrete, three efficiency coefficients need to be introduced

$$\frac{dM}{dt} = a_1a_2a_3wvA$$

(4)

where $a_1$ is the collision efficiency, $a_2$ is the sticking efficiency, $a_3$ the accretion efficiency, $w$ the mass concentration, $v$ the particle velocity relative to the object and $A$ the cross-sectional area relative to the particle velocity. The Makkonen equation can easily be used to model ice load and ice accretion rate. It is common to give the ice load and ice accretion rate in kg/m and kg/m/hr, respectively. The latter refers to per metre of the cylinder used in the model. The ice accretion rate is sometimes presented in terms of active ice hours, which refers to hours with ice accretion rate above a pre-defined threshold, commonly 10 g/m/hr.
3.1.1 The collision coefficient, $\alpha_1$

The collision coefficient, $\alpha_1$, is the ratio of the flux density of particles hitting the object to the total flux density. $\alpha_1$ decreases from 1.0 when particles are forced around the object instead of hitting it. Small droplets, large cross-sections and low wind velocity reduce $\alpha_1$. The droplet trajectory is determined by the aerodynamic drag and the inertia. For a small droplet, the inertia will be small and it will tend to follow the streamlines around the object instead of hitting it. If the inertia and drag forces are known, the collision coefficient can be calculated theoretically by numerical calculation of the droplet trajectories. Because this is computationally expensive, Makkonen suggests the simplification to assume a cylindrical object, and to use an empirical equation for $\alpha_1$

$$\alpha_1 = A - 0.028 - C(B - 0.0454) \quad (5)$$

where

$$A = 1.066K^{-0.00616}e^{-1.103K^{-0.688}} \quad (6)$$

$$B = 3.641K^{-0.498}e^{-1.497K^{-0.694}} \quad (7)$$

$$C = 0.00637(\phi - 100)^{0.381} \quad (8)$$

where $K$ and $f$ are dimensionless parameters

$$\phi = \frac{Re_d^2}{K} \quad (9)$$

where $Re_d$ is the Reynolds number based on the free stream velocity and is given by

$$Re_d = \frac{\rho_a dv}{\mu} \quad (10)$$

and

$$K = \frac{\rho_w d^2 v}{9\mu D} \quad (11)$$

where $d$ is the droplet diameter, $D$ the cylinder diameter, $\rho_w$ the water density, $\mu$ the dynamic viscosity of air and $\rho_a$ the air density.

Because $\alpha_1$ depends on the droplet size, one can safely assume $\alpha_1 = 1.0$ for wet snow and freezing rain as long as the structure studied is not extremely large. This means that $\alpha_1$ normally needs to be calculated only for occasions with in-cloud icing with small droplets.

3.1.2 The sticking coefficient, $\alpha_2$

The coefficient $\alpha_2$ represents the efficiency of collection of those particles that hit the object. It means that $\alpha_2$ is the ratio of the flux density of the particles that stick
to the object to the flux density of the particles that hit the object. The sticking efficiency $a_2$ is reduced from unity when the particles bounce from the surface. The particles here are considered to stick when they are permanently collected, or their residence time on the surface is sufficient to affect the icing rate due to, for example, heat exchange with the surface. For liquid droplets, it can normally be assumed that they do not bounce and hence $a_2$ equals 1.0. As soon as there is a liquid layer on the surface, combined with favourable conditions, basically all droplets will stick to the surface. For ice and snow particles, the ratio of particles that bounce off the object can be a significant share. For solid particles, such as dry snow, $a_2$ is close to or equal to 0.

There is presently no detailed theory for the sticking efficiency of wet snow. The available approximation methods of $a_2$ are empirical equations based on laboratory simulations and some field observations. The best first approximation for $a_2$ for cylindrical shapes is probably

$$a_2 = \frac{1}{v}$$

where the wind speed, $v$, is in m/s. When $v < 1.0$ m/s, $a_2 = 1.0$. The air temperature and humidity also affect $a_2$, but there are presently not enough consistent data to take them into account, despite several experimental studies on this problem. However, as pointed out above, $a_2 > 0$ only when the snow particle surface is wet. Thus, snow does not accrete effectively when the wet-bulb temperature is below 0°C. This criterion is very important because it allows determination of the duration of wet-snow events by climatic weather data.

### 3.1.3 The accretion coefficient, $\alpha_3$

The accretion efficiency coefficient, $\alpha_3$, is the ratio of icing to the flux density of droplets sticking to the object’s surface. During dry growth $\alpha_3$ equals 1.0 because there is no run-off. During wet growth, glaze icing, there is a liquid film on the adhesion surface and $\alpha_3$ will be less than 1.0. The freezing rate will then be determined by the rate with which latent heat from freezing can be transported away from the surface. A heat balance over the surface of the object can be used to determine the portion that will freeze

$$Q_f + Q_v = Q_c + Q_e + Q_l + Q_s$$

where $Q_f$ is the latent heat released during freezing, $Q_v$ is the frictional heating of air, $Q_c$ is the loss of sensible heat to air, $Q_e$ is the heat loss due to evaporation, $Q_l$ is the heat loss in warming the impinging supercooled water to the freezing temperature and $Q_s$ is the heat loss due to radiation.

The terms of the heat-balance equation can be parametrised using the meteorological and structural variables.

The heat released in the freezing is transferred from the ice-water interface through the liquid water into the air, and consequently there is a negative temperature gradient ahead of the growing ice. This kind of supercooling results in a
dendritic growth morphology, and consequently some liquid water is trapped within the spray ice matrix. Because the unfrozen water can be entrapped without releasing any latent heat, the term $Q_i$ in eqn (13) is

$$Q_i = (1 - \lambda) a_3 F L_f$$

(14)

where $\lambda$ is the liquid fraction of the accretion, and $F$ is the flux density of water to the surface ($F = a_1 a_2 w v$). Attempts to determine the liquid fraction, $\lambda$, have been made both theoretically and experimentally. These studies suggest that $\lambda$ is rather insensitive to the growth conditions, and that a value of $\lambda$ around 0.3 is a reasonable first approximation.

Another important consequence of the existence of porous ice is that the heat conduction into the ice does not need to be considered in the heat balance, because the mixture of ice and water is at the uniform temperature of 0°C and therefore involves no heat conduction through it.

The kinetic heating of air, $Q_v$, is a relatively small term (except at aircraft speeds), but, because it is easily parametrised by

$$Q_v = \frac{h r v^2}{2 C_{p_a}}$$

(15)

it is usually included in the heat balance. Kinetic heating of the droplets is insignificant and is ignored. Here, $h$ is the convective heat-transfer coefficient, $r$ is the recovery factor for viscous heating ($r = 0.79$ for a cylinder), $v_w$ is the wind speed and $C_{p_a}$ is the specific heat of air.

The convective heat transfer is

$$Q_c = h (t_s - t_a)$$

(16)

where $t_s$ is the temperature of the icing surface ($t_s = 0°C$ for pure water), and $t_a$ is the air temperature.

The evaporative heat transfer is parametrised as

$$Q_e = \frac{h \psi L_c (e_s - e_a)}{C_{p_a} p}$$

(17)

where $\psi$ is the ratio of the molecular weights of dry air and water vapour ($\psi = 0.622$), $L_c$ is the latent heat of vaporisation, $e_s$ is the saturation water vapour pressure over the accretion surface, $e_a$ is the ambient vapour pressure in the airstream and $p$ is the air pressure. Here, $e_s$ is a constant (6.17 mbar) and $e_a$ is a function of the temperature and relative humidity of the ambient air.

The term $Q_t$, is caused by the temperature difference between the impinging droplets and the surface of the icing object

$$Q_t = F C_w (t_s - t_d)$$

(18)

where $C_w$ is the specific heat of water, and $t_d$ is the temperature of the droplets at impact.
For cloud droplets, \( t_d = t_a \) can be assumed because of the small terminal velocity. This assumption must usually be made also for supercooled raindrops, although they are not fully adjusted to the temperature at the surface layer during their fall.

The heat loss due to long-wave radiation may be parametrised as

\[
Q_s = \sigma a (t_s - t_a)
\]

where \( \sigma \) is the Stefan–Boltzmann constant \((5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4)\), and \( a \) is the radiation linearisation constant \((8.1 \times 10^7 \text{ K}^3)\). This equation only takes into account long-wave radiation and assumes emissivities of unity for both the icing surface and the environment. Short-wave radiation of the sun is neglected because, in practice, atmospheric icing always occurs in cloudy weather. Using the parametrisation of eqns (14–19) in the heat-balance eqn (13) and solving the accretion efficiency result in the following equation:

\[
a_3 = \frac{1}{F(1 - \lambda)} \left[ (h + 6a)(t_s - t_a) + \frac{\nu L_e}{C_p \rho} (e_s - e_a) \frac{h r^2}{2C_p} + FC_w(t_s - t_d) \right]
\]

### 3.1.4 Limitations of the model

Although Makkonen’s model for ice accumulation is widely used, it is limited by the fact that it models ice accretion on a cylinder. To translate the ice load on an ideal cylinder to a complex structure such as a wind turbine is computationally expensive and so far not possible for the general case. To model ice accumulation on a wind turbine, one needs to break down the structure into small elements, still taking into consideration shadowing effects from other elements and ice growing elements together to form a single element.

One of the more practical problems is that the LWC of the air, the cloud droplet density and the median volume droplet size, MVD, in the air are required values. These parameters are not routinely measured nor does there exist a satisfactorily way to measure them. The average droplet diameter has to be approximated, and the average number of droplets in-cloud has to be known. The LWC can be modelled, but the result has a high uncertainty. There is an uncertainty in the model when \( a_1 \), the collision efficiency, is small, because \( a_1 \) depends on the droplet diameter and errors are introduced in estimating MVD. Also, the effects of droplet trajectory angle on the collision efficiency are poorly known, which means that the effects of wind direction and rotational speed of a wind turbine are uncertain. Another uncertainty regarding \( a_1 \) concerns that low velocities are introducing uncertainties in the Reynolds number and flow patterns.

Modelling of ice accretion also requires modelling of the ice density, because the icing rate depends on the dimensions of the iced object. The density of the ice can be modelled using ballistic models, but for rime-ice best-fit equations have been developed in wind-tunnel experiments

\[
\rho_{\text{ice}} = 0.378 + 0.425(\log R) - 0.823(\log R)^2
\]
where $R$ is the Macklin parameter, a dimensionless density parameter. It is given by

$$R = -\frac{v_0d_m}{2t_s}$$

(22)

where $v_0$ is the droplet impact speed, $d_m$ is the droplet median diameter and $t_s$ is the surface temperature. $t_s$ can be approximated as the air temperature. To solve the equation, the impact speed must first be calculated from the heat balance equation. A difficulty with solving the heat balance equation is the convective heat transfer coefficient. Even assuming a simple structure such as a cylinder, to determine the heat transfer coefficient is complicated.

Another limitation of the model is that it takes into account only accumulation of ice. Ice will be removed only due to the sign of the heat balance. Melting is not included, neither is shedding of ice nor sublimation.

### 3.2 Computational models

Nowadays, there are several ice accretion codes in the international aircraft icing community such as LEWINT (USA), ONERA (France), DRA (UK), CANICE (Canada) and more recently CIRA (Italy) based on the physics of icing. But the main two codes for ice accretion in wind turbines are TURBICE, which is the most specific code for the field of wind power; and LEWINT, which can be adapted for ice accretion in wind turbines. The second one is the code chosen for the practical part of this chapter.

LEWINT integrates the ice accretion code LEWICE (version 3.2.2) with American Kestrel's user interface, icing analysis tools and automated plotting. LEWICE was developed by the icing branch at the NASA Glenn Research Center in Cleveland, Ohio. The LEWICE base is an ice accretion prediction code that applies a time stepping procedure to calculate the shape of an ice accretion. The atmospheric parameters such as temperature, pressure, wind velocity and the meteorological parameters such as LWC, droplet diameter and relative humidity are specified as input information and used to simulate the shape of the ice accretion. The software consists of four major modules:

1. Flowfield calculation.
2. Particle trajectory and collision calculation.
3. Thermodynamic and ice growth calculation.
4. Modification of the current geometry by adding the ice growth to it.

LEWICE applies a time-stepping procedure to grow the ice accretion. The flowfield and droplet collision characteristics are determined for the clean geometry. The particle trajectories and impingement points on the body are calculated from a potential flow solution that is produced by the Douglas Hess-Smith 2-D panel code included in LEWICE. Alternately and if specified, the flow solution can be obtained from a grid generator and grid-based flow solver or read in as a solution file from
this flow solver. The ice growth rate on each segment defining the surface is then determined by applying the thermodynamic model. When a time increment is specified, this growth rate can be interpreted as an ice thickness and the body coordinates are adjusted to account for the accreted ice. The ice growth rate on the surface body is calculated from the icing model that was first developed by Messenger. This procedure is repeated, beginning with the calculation of the flow field about the iced geometry, and continued until the desired icing time has been reached.

LEWICE can perform modelling of both dry and wet (glaze) ice growth. In addition to simulating the ice accretion, LEWICE incorporates a thermal anti-icing function. Calculation of the power density to prevent ice formation is performed by LEWICE. Two anti-icing modes are possible: running wet and evaporative.

It can generate not only anti-icing values, but also data about droplet trajectories, collection efficiencies, collision limits, energy and mass balances, ice accretion shape and thickness. Ice accretion shapes for cylinders and several single-element and multi-element aerofoils have been calculated using this software. The calculated results have been compared to experimental ice accretion shapes obtained both in flight and in the Icing Research Tunnel at NASA Glenn Research Center.

Comparison of available experimental data and LEWICE simulation results shows that based on the overall assessment factor, the variation in the experimental data was 4.4% and the LEWICE predicted ice shape, which differed from the experimental average by 12.5% [7].

4 ADIS

Icing mitigation systems result from two main strategies: anti-icing and de-icing systems (ADIS). Anti-icing prevents ice to accrete on the object while de-icing removes the ice layer from the surface. Both strategies can also be divided into two methods: passive and active. Passive methods take advantage of the physical properties of the blade surface to eliminate or prevent ice, while active methods use external systems and require energy supply that is either thermal, chemical or pneumatic. Many of the strategies from the aerospace industry can be transferred to the wind energy sector, although some scaling has to be done to adjust parameters (wind speed, chord length and aerofoil).

Consequently, because most ADIS are based on heating, wind turbines need more power to operate. The extra power will be added to the consumption of the cold climate package. Also, additional maintenance should be planned. In global values, the de-icing consumption translates into a 1%–4% loss of annual energy production, depending on icing severity [8].

An investment of 5% of the cost of a 600 kW turbine has been estimated for the purchase and installation of ADIS. Cost percentage decreases as turbine size increases. Depending on icing severity on the site and the price of electricity, ADIS’ payback time will vary from 1 to 18 years. For a site with medium icing severity, with an average of 30 icing days per year, the payback time should be less than 5 years.
Most of the information described in this section is based on the article by Parent and Ilinca [8]. In addition, some information has been provided by the company ENERCON.

4.1 Passive ADIS

4.1.1 Passive anti-icing systems
The passive anti-icing systems are: black paint, special coating and chemicals.

4.1.1.1 Black paint. Black paint allows blade heating during daylight and is used with an ice-phobic coating. When tested in Yukon (Canada), this method showed immediate and noticeable improvement in performance. This method may be sufficient in sites where icing is slight, infrequent and where icing periods are followed by temperatures above 0°C or in areas with high winter solar intensity at lower altitudes. Most of the time, it is not sufficient to prevent icing. The temperature of the blade’s surface may affect the properties of glass-fibre reinforced plastics, as they are sensitive to high temperature. However, another study shows that black blades do not overheat in the summer.

4.1.1.2 Special coating. In theory, ice-phobic coatings prevent ice from sticking to the surface because of their anti-adherent property, while super-hydrophobic coatings do not allow water to remain on the surface because of repulsive features. Reducing the shear forces between the ice and the surface will also reduce sensitivity to dirt and bug. Currently, most manufacturers use epoxy or polyester matrix composites reinforced with glass and/or carbon fibres, although polyester and glass fibres remain the material of choice due to their lower cost. Current research is heading towards nanocomposite coatings, polymers reinforced by minute, nanometre-scale particles. These nano-composites create very high contact angles with water. Advantages and disadvantages are listed below.

**Advantages:**

- Low cost.
- No special lighting protection needed.
- Easy blade maintenance, protects the whole surface.
- Easy to apply.

**Disadvantages:**

- Several materials tested but no good solution has been found.
- Icing occurred even on coated surfaces regardless of the temperature.
- Material degradation, coating becomes porous.
- A clean and smooth surface is preferable.

4.1.1.3 Chemicals. When applied on a blade surface, chemicals reduce the water freezing point. It is mostly used during aircraft take-off. It is a pollutant and it
needs special application and a lot of maintenance. It cannot remain on the surface of the blade for a long period.

4.1.2 Passive de-icing systems
The passive de-icing systems are flexible blades and active pitching.

4.1.2.1 Flexible blades. Flexible blades help to crack the ice and lose its contact with the surface. Blade flexing is known to help shedding the ice but very little information is available on the subject.

4.1.2.2 Active pitching. The active pitching is a semi-active method that uses start/stop cycles to orient iced blades into the sun. The method may work in light icing environments but it has not been scientifically validated and may damage wind turbines.

4.2 Active ADIS

4.2.1 Active anti-icing systems
The active anti-icing systems are used to prevent the ice accretion on blade surface and are based on resistance heating, air layer or microwave heating.

4.2.1.1 Resistance heating. Heating resistance and warm air can be used in anti-icing mode to prevent icing. The blade temperature should be kept around 0°C to prevent icing. The advantage is that no ice accumulates on the blades. A blade can be kept at −5°C, instead of 0°C, in good condition. In this way, 33% of power can be saved which represents 2.3% of winter production. The inconvenience is that it requires a lot of energy. If it is used to prevent runback at 100°C, it is close to the softening point of some epoxies and resins (although thermosetting plastics that are designed for higher operating temperatures are available). The continuous operating temperature should be less than 50°C with current blade materials [8].

4.2.1.2 Air layer. The air layer consists of an air flow originating inside the blade and pushed through rows of small holes near the blades’ leading and trailing edges to generate a layer of clean and, if necessary, heated air, directly around the blade surface. This method would deflect the majority of water droplets in the air and would melt the few droplets that manage to hit the surface but very little information is available for its application.

4.2.1.3 Microwave. Microwave heating consists of heating the blade material with microwaves to prevent ice formation. The objective is to maintain the blade surface at a temperature slightly above 0°C, in order to save some energy that will be used for defrosting. It is recommended to cover the surface of the blade with a material that reflects microwaves (metallic material such as wire mesh) and apply paint to improve the final surface. Another method consists in heating the blades
when they pass in front of the tower by fixing an emitter on the tower. It has been tested at the LM Glassfiber workshop on a LM19.1 blade with a 6-kW power, a frequency of 2.45 GHz and an emitted power less than 0.01 W/m² but is still to be implemented commercially.

### 4.2.2 Active de-icing systems
The active de-icing systems are used to eliminate ice accreted on the blade using a heating resistance, hot air, flexible pneumatic boots and electro impulsive/expulsive devices.

#### 4.2.2.1 Heating resistance.
The electrical heating uses an electrical resistance embedded inside the membrane or laminated on the surface. The idea is to create a water film between the ice and the surface. Once a film is created, centrifugal forces will throw the ice away. Electrically heated foils can be heating wires or carbon fibers. Heating elements cover the leading edge area of the blade. The ice detector and blade surface temperature are used to control the operation of the heating system. Additional temperature sensors are installed to control the operation of the heating system. From permanent damage induced by over-heating. Heating foil can be applied to most turbines. A system of 15 kW per blade has been used for a 600 kW wind turbine, corresponding to 1%–4% of annual production, depending on climate conditions. The minimum time to keep the heating on, after the icing event has passed, is usually about 15–30 min. Heating demand is almost linearly dependent on the temperature difference between the air and the blade surface. More energy is needed to de-ice the tip’s leading edge than that of the hub’s (3.5–3.9 times more). More energy is also needed to de-ice the tip’s trailing edge than that of the hub’s (2.6–2.9 times more) and to de-ice the lower surface rather than the upper (1.3–1.5 times more).

This simple method has been used successfully in the aerospace industry for many years. It has also been used in the wind industry since 1990. Heating power seems to be adequate except in the case of super cooled rain. Thermal efficiency is close to 100% because of direct heating. Energy demand does not increase with blade size. As an inconvenience, there are many commercially available products but none are mass produced. The technology is still at the prototype level because of the limited market. If one heater fails, it will cause major imbalance on the whole system. In some extreme icing cases, blade heating power was found to be insufficient. Icing of the run-back water at the edges of the heating elements occurs quite often. When the running water from the heating element area reaches a cold blade surface, it re-freezes and forms a barrier at the edges of the heating element. The edge barriers may grow towards the leading edge as ‘horns’ without a contact with the heating element. This could explain why in some blade icing cases, the thermostat of the ice prevention system indicates a temperature higher than 0°C on the surface of the heating element during icing. Heating elements can attract lightning but lightning protection is efficient and no damage was detected in the ice prevention system studied by Marjaniemi and Peltola [9].
Advantages:

• Comparatively simple and widely spread.
• If considering the profitability of wind energy production the needed energy is small.
• Thermal efficiency is close to 100% due to direct heating.
• Energy demand does not increase with the turbine capacity increase.
• Comparatively low energy consumption.

Disadvantages:

• Despite the product availability there is no mass production.
• The technology prototype level because of the limited market.
• Even if only one heating element fail, the whole system may come into imbalance.
• Run-back water should be managed. If not it can reach the cold area of the blade and refreeze. Further, it can lead to the ‘horn’ appearance on the blade.

4.2.2.2 Electro impulsive/repulsive devices. This consists in very rapid electromagnetically induced vibration pulses in cycles that flex a metal abrasion shield and crack the ice. A spiral coil is placed near the surface of the blade. When a current is applied to the coil, a magnetic field is created between the coil and the thickness of the blade. The result is a rapid movement of the surface and the expulsion of the accumulated ice. The method has been recently certified for use on Raytheons Premier I business jet. It is used by Hydro-Quebec for transmission lines and Goodrich is currently developing this method for aeronautical applications.

Advantages:

• The system is efficient.
• Environmental friendly.
• Low-energy consumption.
• No interference with Hertz transmission.
• Easily automated.

Disadvantages:

• New technology that has not been tested on wind turbines.
• Ice expulsion is a potential problem.

4.2.2.3 Flexible pneumatic boots. Flexible pneumatic boots remove ice from the blade surface by breaking after surface inflation. After the buildup of about 6–13 mm of ice on the surface of the aerofoil, de-icers are inflated with compressed air. The inflation cycle lasts for a few seconds to achieve optimal ice shed and prevent additional ice formation on the inflated surface. After the ice has cracked, its bond to the surface is broken and it is removed through centrifugal and aerodynamic forces. Deicers are then allowed to deflate. Vacuum is then applied to ensure that
there is no lifting of the surface on the low-pressure side of the aerofoil. De-icers for wind turbine applications have equivalent ice shedding and residual ice performance as conventional aircraft de-icers. Working at higher pressures for wind turbine applications, tests indicated satisfactory icing shedding on glaze ice at temperatures above −10°C and residual ice at temperatures between −10°C and −20°C.

Advantages:

- Low-energy consumption.
- Good results in laboratory tests.
- Low-energy consumption.

Disadvantages:

- Field-landed tests have to be made.
- Aerodynamic characteristics can be affected because the drag coefficient is increasing.
- Maintenance requirements during lifelong period can be expensive.
- High centrifugal loads at the outer radius of the pneumatic system will inflate itself or has to be divided into short sections.
- Detached ice fragments hazard should be taken into account.

4.2.2.4 Warm air and radiators. The main idea is to create a water film between the ice and the surface like a heating resistance, but instead of using an electrical resistance warm air is blown inside the blade. The blowers are located in the blade root; the internal blade volume is divided into two sections. These sections are used to guide a re-circulating hot air stream passing through the rotor blade. From the blower, the heated air flows directly along the blade’s leading edge profile to the blade tip and then back to the blade flange. The returning air is then reheated and passed into the rotor blade. This closed circuit reduces the needed energy, because the initial air temperature is higher than the outside one. The process efficiency can be improved by using hot waste air from the machinery.

The ENERCON company has tried this method in its WEC. An evaluation of the efficiency of the rotor blade de-icing system was performed during the winter 2009/2010 at a wind farm site in northern Sweden (Dragaliden) and in Czech Republic (Krystofovy-Hamry). On each site, two ENERCON E-82 2.0 MW wind energy converters with hub heights of 108 m (Dragaliden) and 78 m (Krystofovy-Hamry) were used for the evaluation. Each WEC was equipped with the ENERCON rotor blade de-icing system, while only one turbine on each site operated with the system activated. The installed rotor blade de-icing systems had a power consumption of 23.8 kW per blade.

On both sites, the WEC with the rotor blade de-icing system in operation produced significantly more energy than the corresponding WEC. The mean deviation in the production amounts to about 50% and 46% of the production of the WEC without blade de-icing system in case of the test sites Dragaliden and Krystofovy-Hamry, respectively.
After having described the theoretical aspects of ice accretion in wind turbines, this section will focus on the computational analysis of an icing event. All the simulations are performed by using the software called LEWINT, from American Kestrel Company. For this analysis, the input variables of an icing event are needed. Simulations are carried out for the relevant ranges of the variables.

It will be presented how a profile of an aerofoil for wind turbines reacts in an icing event. How ice is formed, the heat necessary to melt it and how much time is needed for the ice to be formed will be presented. This information is necessary to determine as a de-ice system has to be activated.

In this chapter, the effect of the rotational speed of the blades is not taken into account.

The output data extracted from the simulations are compared with some experimental data provided from other references. It has been found that the order of magnitude is similar to the experimental data. The difference between the simulations and the experimental data might be due to the effect of the blade’s rotational speed and the consideration of the variable MVD.

### 5.1 Icing conditions

A simulation of an icing event needs all the input data relevant for such situations. In this chapter, the aerofoil profile considered is a NACA 63-415 because it is difficult to obtain industrial profiles as companies keep this kind of information secret. This profile is used in the industry of wind turbines. Figure 6 shows the profile of the NACA aerofoil.

The other variables being considered are relative humidity, air temperature, angle of attack, wind speed, median volume diameter (MVD) of the water droplets (MVD), LWC in the air, chord length and time of the icing event.

The AOA is the angle between the chord line of the aerofoil and the vector representing the relative motion between the body and the fluid flux, in this case the air, the unit is degree (°).
The LWC is a measure of the mass of the water in a cloud for a specified amount of dry air. It is typically measured in grams per volume of air (g/m$^3$).

The MVD refers to the midpoint droplet size, where half of the volume of the spray is in droplets smaller and half of the volume is in droplets larger than the median. This variable is used instead of multiple drop size distributions. The difference in ice shape and icing limits is very slight for single body simulations.

The chord length is the length of the chord line and is the characteristic dimension of the aerofoil section. Of course, the chord length depends on the position of the aerofoil from the centre of the wind turbine.

The relative humidity (RH) normally is assumed to be 100%, unless these data are known. In this case, there are no data provided so it will be assumed to be 100%.

---

Table 1: Ranges for input data [2].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA airfoil profile</td>
<td>63415</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>100</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>–20 to 0</td>
</tr>
<tr>
<td>Wind velocity (m/s)</td>
<td>10–30</td>
</tr>
<tr>
<td>MVD (µm)</td>
<td>10–100</td>
</tr>
<tr>
<td>LWC (g/m$^3$)</td>
<td>0–2</td>
</tr>
<tr>
<td>Chord length (m)</td>
<td>1.435</td>
</tr>
<tr>
<td>AOA (deg.)</td>
<td>0–25</td>
</tr>
<tr>
<td>Time of icing (h)</td>
<td>0.5–5</td>
</tr>
</tbody>
</table>

Table 2: Values for input data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>NACA airfoil profile</td>
<td>63415</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>100</td>
</tr>
<tr>
<td>Air temperature (°C)</td>
<td>–2, v10, –20, –30</td>
</tr>
<tr>
<td>Wind velocity (m/s)</td>
<td>10, 30</td>
</tr>
<tr>
<td>MVD (µm)</td>
<td>15, 50, 90</td>
</tr>
<tr>
<td>LWC (g/m$^3$)</td>
<td>0.5, 2</td>
</tr>
<tr>
<td>Chord length (m)</td>
<td>1.435</td>
</tr>
<tr>
<td>AOA (deg.)</td>
<td>0, 5, 7</td>
</tr>
<tr>
<td>Time of icing (h)</td>
<td>4</td>
</tr>
</tbody>
</table>
The analysis will take into account a total of nine input parameters. However, humidity and chord length will have just a single value and a specific NACA profile will be studied.

The other variables have different values depending on which icing event being evaluated.

- Chord length for an airfoil of 2 MW of power should be 1.435 m [11].
- The range of atmospheric temperatures will be from –30°C to 0°C.
- RH of 100%.
- The wind speed is from 10 to 30 m/s.
- The AOA is from 0°C to 25°C.
- The MVD has values from 10 to 100 μm.
- The LWC is from 0 to 2 g/m³.
- The time of the simulated icing event should be no less than 30 min, because it is enough for the ice to form and to find out how it grows. As described the icing events can take hours, so an appropriate time simulation can be 4 h.

Figure 7 shows different aspects of an aerofoil profile and Table 1 shows the range of the input data being analysed.

Taking into account the number of variables involved, it is necessary to restrict them to limited values representing all parts of the ranges. Due to the limitations of the software the AOA can not be higher than 7, because there are no data available in the program to simulate such conditions. Also MVD can not be higher than 500 μm for the same reason.

Finally, the values of the variables considered for the general analysis are shown in Table 2.

The time for general simulations is 4 h because this is sufficient to detect the evolution of ice accretion. Of course, in many studied cases the de-icing systems that melt the ice must act before this time because the final thickness is far from the acceptable maximum.

For the general analysis, the range of MVD is between 10 and 100 μm, although it can have higher values. However, for the dependence of ice thickness on MVD, the full range is taken into account.

5.2 Case studies

The simulations in this study provide the input data required to calculate the power loss occurring in each icing event. Also, by the ice thickness versus the time relation, the data necessary to decide when the de-icing systems have to start are provided.

The icing conditions calculated are based on weather prediction models. Then, the corresponding ice accretion rate and the amount of ice on wind turbine rotor blades are calculated using the icing simulation software LEWINT.

Then CFD simulations are used to get the degraded aerodynamic properties of blades and finally power performance simulations are used to generate the power
curves. Measurement data are used to validate the power production simulations. The power production will be calculated based on wind data and representative power curves for the iced upwind turbine. For simplicity in the simulations, the icing is considered to be rime icing. Because of this, an additional degradation in power production has to be considered if the temperature on the site of interest is commonly in the range where glaze icing occurs, because it is known to have more deteriorating effects than rime icing. However, the focus is on the ice accretion rate and the amount of ice on wind turbine rotor blades.

A comparison on how different weather conditions generate different ice shapes is provided.

The aims of these simulations are:

- General analysis of the ice thickness and ice shape in different icing events and dependence on different variables.
- Comparison of the time required for different icing events to generate ice thickness.
- Analysis of the heat demand for some icing events.

### 5.3 Results

A general analysis of the ice thickness and ice shape for different icing events and dependence on the different variables is given in this section. The highest ice thicknesses of an icing event are compared. Also the dependence of ice thickness on the different variables is analysed.

1. Wind speed of 10 m/s, LWC of 0.5 g/m³ and MVD of 15 µm:

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>–10</td>
</tr>
<tr>
<td>5</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>0.2</td>
</tr>
</tbody>
</table>

It can be seen from Table 3 that ice accretion is higher for lower temperatures. Also it seems that the AOA does not affect the ice thickness.

2. Wind speed of 10 m/s, LWC of 0.5 g/m³ and MVD of 50 µm:

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.8</td>
</tr>
<tr>
<td>5</td>
<td>16.8</td>
</tr>
<tr>
<td>7</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Table 3: Ice thickness in millimetres.

Table 4: Ice thickness in millimetres.
3. Wind speed of 10 m/s, LWC of 0.5 g/m³ and MVD of 90 µm:

Table 5: Ice thickness in millimetres.

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>14.7</td>
</tr>
<tr>
<td>5</td>
<td>32.4</td>
</tr>
<tr>
<td>7</td>
<td>36.7</td>
</tr>
</tbody>
</table>

Tables 4 and 5 show much higher thickness than Table 3. This indicates that the ice thickness may have a great dependence on the MVD. However, 15 mm is a really small value, so maybe this value does not have a real significance.

4. Wind speed of 10 m/s, LWC of 2 g/m³ and MVD of 15 µm:

Table 6: Ice thickness in millimetres.

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16.4</td>
</tr>
<tr>
<td>5</td>
<td>1.2</td>
</tr>
<tr>
<td>7</td>
<td>0.4</td>
</tr>
</tbody>
</table>

5. Wind speed of 10 m/s, LWC of 2 g/m³ and MVD of 90 µm:

Table 7: Ice thickness in millimetres.

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>22.5</td>
</tr>
<tr>
<td>5</td>
<td>33.8</td>
</tr>
<tr>
<td>7</td>
<td>34.2</td>
</tr>
</tbody>
</table>

Tables 6 and 7 show a great difference between various MVDs. The first one is much lower than the second one. The values of the ice thickness in Table 7 are high, and in real situations the wind turbine would be losing a lot of power output.

6. Wind speed of 30 m/s, LWC of 0.5 g/m³ and MVD of 15 µm:

Table 8: Ice thickness in millimetres.

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>31.4</td>
</tr>
<tr>
<td>5</td>
<td>26.5</td>
</tr>
<tr>
<td>7</td>
<td>15.4</td>
</tr>
</tbody>
</table>
7. Wind speed of 30 m/s, LWC of 0.5 g/m$^3$ and MVD of 90 µm:

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
<th>Ice thickness in millimetres</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-2</td>
<td>54.5</td>
</tr>
<tr>
<td>0</td>
<td>-10</td>
<td>155.2</td>
</tr>
<tr>
<td>0</td>
<td>-20</td>
<td>161.1</td>
</tr>
<tr>
<td>0</td>
<td>-30</td>
<td>163.2</td>
</tr>
<tr>
<td>5</td>
<td>-2</td>
<td>84.5</td>
</tr>
<tr>
<td>5</td>
<td>-10</td>
<td>151.9</td>
</tr>
<tr>
<td>5</td>
<td>-20</td>
<td>158.7</td>
</tr>
<tr>
<td>5</td>
<td>-30</td>
<td>160.3</td>
</tr>
<tr>
<td>7</td>
<td>-2</td>
<td>82.8</td>
</tr>
<tr>
<td>7</td>
<td>-10</td>
<td>151.6</td>
</tr>
<tr>
<td>7</td>
<td>-20</td>
<td>158.6</td>
</tr>
<tr>
<td>7</td>
<td>-30</td>
<td>160.7</td>
</tr>
</tbody>
</table>

Tables 8 and 9 have a similar evolution as Tables 6 and 7. But for low temperatures, Tables 8 and 9 have larger ice thickness than those in Tables 6 and 7. For example, by comparing Tables 7 and 9 it can be seen that when the temperature is -2°C, the ice thickness is more than twice in Table 9 compared with that in Table 7,
but when the temperature is −20°C the values are more or less the same. This may indicate that the wind speed has a stronger effect when the temperatures are close to zero than they are very low.

8. Wind speed of 30 m/s, LWC of 2 g/m³ and MVD of 15 μm:

Table 10: Ice thickness in millimetres.

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
<th>Ice thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>−2</td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td>−10</td>
<td>106.1</td>
</tr>
<tr>
<td></td>
<td>−20</td>
<td>219.7</td>
</tr>
<tr>
<td></td>
<td>−30</td>
<td>206.0</td>
</tr>
<tr>
<td>5</td>
<td>−2</td>
<td>66.1</td>
</tr>
<tr>
<td></td>
<td>−10</td>
<td>105.3</td>
</tr>
<tr>
<td></td>
<td>−20</td>
<td>136.3</td>
</tr>
<tr>
<td></td>
<td>−30</td>
<td>152.5</td>
</tr>
<tr>
<td>7</td>
<td>−2</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>−10</td>
<td>115.1</td>
</tr>
<tr>
<td></td>
<td>−20</td>
<td>144.8</td>
</tr>
<tr>
<td></td>
<td>−30</td>
<td>142.6</td>
</tr>
</tbody>
</table>

Figure 10: Wind speed 30 m/s, MVD 15 μm and LWC 0.5 g/m³.

Figure 11: Wind speed 30 m/s, MVD 15 μm and LWC 2 g/m³.
9. Wind speed of 30 m/s, LWC of 2 g/m$^3$ and MVD of 90 µm:

Table 11: Ice thickness in millimetres.

<table>
<thead>
<tr>
<th>AOA</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>56.6</td>
</tr>
<tr>
<td>5</td>
<td>88.1</td>
</tr>
<tr>
<td>7</td>
<td>102.1</td>
</tr>
<tr>
<td></td>
<td>-2</td>
</tr>
<tr>
<td></td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>-20</td>
</tr>
<tr>
<td></td>
<td>-30</td>
</tr>
<tr>
<td>0</td>
<td>277.0</td>
</tr>
<tr>
<td>5</td>
<td>390.6</td>
</tr>
<tr>
<td>7</td>
<td>446.8</td>
</tr>
<tr>
<td>0</td>
<td>534.0</td>
</tr>
<tr>
<td>5</td>
<td>402.9</td>
</tr>
<tr>
<td>7</td>
<td>596.2</td>
</tr>
<tr>
<td>0</td>
<td>551.1</td>
</tr>
<tr>
<td>5</td>
<td>562.0</td>
</tr>
<tr>
<td>7</td>
<td>501.0</td>
</tr>
</tbody>
</table>

Figure 12: Wind speed 30 m/s, MVD 90 µm and LWC 2 g/m$^3$.

Figure 13: Dependence of ice thickness on air temperature.
It has been found that among the variables that affect the ice accretion, the air temperature and wind velocity are the most important. Now some figures about the dependence of ice thickness on air temperature will be given. Also there are some aspects that it is not possible to show because of the limitations of the software. For example, the air density is a constant, but in reality it depends on air temperature. Also, the ice density is another limitation of the model, because it is assumed constant, but in reality it is not. These differences may change the ice thickness but not the evolution of it.

Figures 8–12 show the evolution of ice thickness with temperature by using the data from Tables 6, 5, 8, 10 and 11, respectively.

The data in Tables 3–11 and Figs. 8–12 provide a general view about the thickness of the ice that accretes on the aerfoil profile. It can be seen that with low temperatures the ice thickness becomes higher. Also for higher values of the wind speed, MVD or LWC the ice thickness seems to become bigger. Finally, the AOA does not affect the ice thickness to any significant amount.

Low temperatures have more energy potential due to higher air density. It is important that wind turbines can operate in such conditions, and then a de-icing system to melt the higher amount of ice is needed.

The ice thickness produces a power loss, also as the ice thickness causes the rotational speed to accelerate. This will damage the generator, as well as the electric equipment.

There are practical experiments, which show that with an ice thickness of 12.5 mm the power output is 15% of the regular one. Of course, it depends on the aerfoil, but it is an example of how power is affected by ice accretion [13].

After having presented a general view of the ice accretion, it is clear that the variable affecting most significantly is the air temperature, as is evident in Tables 3–11 and in Figs. 8–12. However, in the next subsections, the dependence of the ice thickness on all variables is analysed.
5.3.1 Dependence of ice thickness on air temperature

By comparing Tables 3–11, it is clear that the effect of air temperature is higher when the temperature is low. However, it can be seen that in most of the cases there are two different zones. The first zone is in the range between 0° and −10°. The characteristic of this zone is that the ice thickness grows rapidly. On the other hand, in the range between −10° and −30°, the ice thickness seems to be more stable and the growth is less. But this difference might be due to the combination of the different variables.

To make a more accurate study of the dependence of the ice thickness on temperature, all the other variables are fixed and the 16 different values of the air temperature are evaluated.

The values of the different variables are: wind speed 10 m/s, LWC 2 g/m³, MVD 90 µm and AOA 0° and time simulation 7200 s.

As can be seen in Fig. 13, despite the first impressions, the dependence of the ice thickness on the air temperature is quite regular in the whole ranges of the variables. However, the difference between the ice thickness from 0° to −10° is higher than the one between −10° and −20°, and the latter one is higher than the one between −20° and −30°. As shown in Fig. 13, the dependence of ice thickness on temperature is almost linear.

By comparing icing conditions, the ice thickness is greater at low temperatures. The significant difference in ice thickness is because of the different value of the collection coefficient. Low temperatures have higher collection coefficients.

5.3.2 Dependence of ice thickness on wind speed

In general, it seems that with higher velocities, the ice thickness is higher.

The values of the different variables are: MVD 100 µm, LWC 1 g/m³, temperature −10° and AOA 0° and simulation time is 7200 s.

The operational wind velocity of wind turbines ranges from 10 to 30 m/s, and, as it can be seen in Fig. 14 that the ice thickness is higher when the wind velocity is higher. The dependence seems to be linear as well.

5.3.3 Ice shape

The ice accretion events have been compared only by taking into account the greater thickness for each case. However, the shape of the aerofoil after icing events is also important because the aerodynamics are affected.

Aerodynamic characteristics of the wind turbine blades including lift and drag coefficients are affected by the ice accretion, and accordingly the power produced is different for each icing event.

The ice shape is also important. The de-icing systems focus on a certain part of the aerofoil. If it is known where ice forms the amount of heat produced to melt the ice will be less.
6 Conclusions

The topic of this chapter is really new and it is important nowadays because of the benefits of cold climates for wind turbines. This means that there is not much data available about icing events. Thus, it has been difficult to obtain the information needed. This chapter resumes part of the field of ice accretion in wind turbines. It shows different icing events, the weather variables of importance and the effects of ice accretion.

Also systems of anti-icing and de-icing are described. As it is a relatively new field not much work has been done on such systems. Accordingly, a lot of work is needed to optimise these processes. Most of these copy the systems installed in aircraft, because this field has more or less the similar problems, but in different situations. Warm air, a specific de-icing system, is described in details because there was information provided by the ENERCON company. It shows two different places with icing events and the difference of having a de-ice system and not having it is really important. The difference of having a de-ice system is a gain of 50.4% in power production.

There is a general physical model for ice accretion but it has some limitations that have to be corrected. One of them is that there are some coefficients in the formula that are based on cylinder shapes. Some programs transform these shapes to more complex structures like blades, but it would be better to reformulate the model.

The simulations show differences in the dependence on ice accretion of the different variables. The ambient temperature is the most important factor to take into account for icing events. The wind speed is the second most important variable. Also, if the rotational speed is added the relative wind speed in different parts of the blade would make this variable even more important. LWC is also important, but depending on the range of its value it does not really affect the ice accretion. The same is true for MVD, if the values of this variable are low the ice thicknesses of each case are really different, but after 100 μm the effect of it seems to be not important. Finally, the effect of AOA on ice thickness seems to be insignificant. However, AOA affects the ice shape, so it is a variable that must be taken into account depending on which kind of de-icing systems is installed in the blade turbine, for example heating resistance, that focus on a specified part of the blade surface.

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Nomenclature

\[ A \] Area the wind is passing perpendicular to the wind (m²)

\[ b \] Radiation linearisation constant (K³)

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$C_p$ Specific heat of air (J kg$^{-1}$ K$^{-1}$)
$C_{pw}$ Specific heat of water (J kg$^{-1}$ K$^{-1}$)
$C_p$ Constant efficiency for wind turbines
$D$ Cylinder diameter (m)
$d$ Droplet diameter (m)
$d_m$ Droplet median diameter (m)
$e_s$ Saturation water vapour pressure (Pa)
$e_a$ Ambient vapour pressure in the airstream (Pa)
$h$ Heat transfer coefficient (W m$^{-2}$ K$^{-1}$)
$L_e$ Latent heat of vaporisation (kJ kg$^{-1}$)
$L_f$ Latent heat of freezing (kJ kg$^{-1}$)
$P$ Power produced from wind turbines (W)
$P_w$ Power available in the wind (W)
$p$ Air pressure (Pa)
$R$ Radius of the rotor (m)
$Re_d$ Reynolds number
$t_s$ Surface temperature (K)
$V_{tip}$ Tip speed (m s$^{-1}$)
$w_r$ Rotational speed of the rotor (s$^{-1}$)
$v$ Free stream velocity (m s$^{-1}$)
$v_p$ Particle velocity relative to the object (m s$^{-1}$)
$v_o$ Droplet impact speed (m s$^{-1}$)
$v_w$ Wind velocity (m s$^{-1}$)
$\omega$ Mass concentration (kg m$^{-3}$)
$\lambda_{st}$ Tip speed ratio
$\mu$ Viscosity of air (Pa s)
$\rho_a$ Air density (kg m$^{-3}$)
$\rho_{ic}$ Ice density (kg m$^{-3}$)
$\rho_w$ Water density (kg m$^{-3}$)
$\sigma$ Stefan–Boltzmann constant (W m$^2$ K$^4$)

**Abbreviations**

ADIS Anti-icing and de-icing systems
AOA Angle of attack
CC Cold climate
CFD Computational fluid dynamics
IC Icing climate
LTC Low-temperature climate
LWC Liquid water content
MVD Median volume diameter
RH Relative humidity
WEC Wind energy converter
References


