Wind Turbine Performance under Icing Conditions

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The wind energy market is in full growth in Quebec but technical difficulties due to cold climate conditions have occurred for most of the existing projects. Thus, icing simulations were carried out on a 0.2 m NACA 63 415 blade profile in the refrigerated wind tunnel of the Anti-icing Materials International Laboratory (AMIL). The shapes and masses of the ice deposits were measured, as well as the lift and drag forces of the iced profiles. Scaling was carried out based on the 1.8 MW–Vestas V80 wind turbine technical data, for three different radial positions and two in-fog icing conditions measured at the Murdochville wind farm in the Gaspé Peninsula. For both icing events, the mass of ice accumulated on the blade profile increased with an increase in the radial position. In wet regime testing (first icing event), glaze formed mostly near the leading edge and on the pressure side. It also accumulated by run-off on the trailing edge of the outer half of the blade. In dry-regime testing (second icing event), rime mostly accreted on the leading edge and formed horns. For both icing events, when glaze or rime accreted on the blade profile, lift decreased and drag increased. A load calculation using the blade element theory shows that drag force on the entire blade becomes too large compared to lift, leading to a negative torque and the stop of the wind turbine. Torque reduction is more significant on the outer third of the blade. Setting up a de-icing system only on the outer part of the blade would enable significant decrease of heating energy costs. Copyright © 2007 John Wiley & Sons, Ltd.

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Introduction

Since 1995, wind energy has been in full growth worldwide. The 30% economic growth is mainly due to technological advancement in wind turbines, but also to awareness on the part of consumers, as well as government regulation to reduce greenhouse gas emissions by promoting or making compulsory the use of renewable energy. This is favourable to local wind energy markets, as in the province of Quebec, where the demand for wind energy comes principally from Hydro-Quebec with two invitations to tender, one for a 1000 MW wind farm in the Gaspé Peninsula in 2000, and another for a 2000 MW province-wide project in 2005. The Gaspé Peninsula has enormous wind potential, better than other exceptional sites in Germany, Denmark and Spain but, unfortunately, this northern location is often subjected to problems caused by freezing temperatures and atmospheric icing.

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During icing events, ice accumulates on the rotor blades, thus reducing the aerodynamic efficiency and torque, leading to power losses. A light icing event can produce enough surface roughness to considerably reduce aerodynamic efficiency.\textsuperscript{1} But when the icing event is more severe,\textsuperscript{2} torque drops to zero, the turbine stops and a complete loss of production ensues. Wind turbines can also stop rotating due to heavy vibrations under uneven ice cover.\textsuperscript{3} These vibrations can cause chunks of ice to detach and, during the accretion–expulsion process vibration intensity can increase, leading to the collapse of the wind turbine if it is not stopped. In some cases, when large chunks of ice are ejected, the wind turbine must be shut down to protect the other turbines on the farm, as well as nearby residents.\textsuperscript{4} The wind park operated by the 3Ci company near Murdochville, Quebec, is a good example of the severe effects of Nordic climate on wind turbines. The park comprises 60 Vestas 1.8 MW turbines\textsuperscript{5} (Figure 1) and is located between 850 and 950 m of elevation. During the 2004–2005 winter and spring, a meteorological station at 610 m of elevation, operated by the Wind Energy TechnoCentre, located near the wind park of Murdochville, recorded 13 icing events.\textsuperscript{6} Of those 13 events, five were considered severe and a hazard for the wind farm. Two events among the five were selected for wind-tunnel simulation to study their effects on the Vestas-V80 wind turbines, through a quantitative study of ice-accretion shape, lift reduction and drag increase.

The two icing events selected for the simulations were in-fog icing conditions as shown in Table I. They were characterized by their liquid water content (LWC), median volume diameter (MVD) of the supercooled droplets, air speed ($V_\infty$), air temperature ($T_\infty$) and duration of the event ($t$).

![Figure 1. Vestas 1·8 MW wind turbines in Murdochville](image)

<table>
<thead>
<tr>
<th>Fog</th>
<th>LWC (g m$^{-3}$)</th>
<th>MVD (µm)</th>
<th>$V_\infty$ (m s$^{-1}$)</th>
<th>$T_\infty$ (ºC)</th>
<th>$t$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.218</td>
<td>38.3</td>
<td>8.8</td>
<td>−1.4</td>
<td>6.0</td>
</tr>
<tr>
<td>2</td>
<td>0.242</td>
<td>40.5</td>
<td>4.2</td>
<td>−5.7</td>
<td>4.4</td>
</tr>
</tbody>
</table>
A load calculation based on the blade element theory was used to estimate the effects of icing on the driving and bending forces, as well as torque. The resulting data were used as a basis to determine the best position for a heating-element de-icing system for wind turbine blades.

Generally, the shapes of ice deposits used in wind-tunnel aerodynamic simulations are measured directly on blades during icing events, or calculated by ice-accretion simulation software. An artificial deposit is then moulded and glued along the blade profile to simulate the 2D run-off on an iced blade profile. Seifert and Richert presented experimental measurements of lift and drag on a blade profile, the leading edge of which was covered with artificial ice deposits shaped from actual deposits collected from a small, horizontal-axis wind turbine during different icing periods. Jasinski et al. made the same measurements, but used artificial ice shapes created with the LEWICE ice-accretion simulation software at NASA. The special feature of the experiments described in this paper resides in the way the ice deposits on the blade profile were derived, that is to say by simulating in a wind tunnel the meteorological and operating conditions of the wind turbine during in-fog icing. The simulations were carried out in two phases: one phase of ice accretion on the blade profile and one phase of aerodynamic efficiency tests on the iced blade profile.

**Experimental Method**

The simulations were carried out in the Anti-icing Materials International Laboratory (AMIL) refrigerated wind tunnel (Figure 2) at the University of Quebec in Chicoutimi (UQAC). The tunnel operates as a closed-loop, recirculation system. The test section is 1.5 m long, 0.5 m wide and 0.6 m high.

In-fog icing is produced using an oscillating spray-nozzle assembly located upwind from the convergent. The spray nozzles are set to produce water droplets with a diameter of 27.6 μm. The lift and drag forces are measured using an aerodynamic scale made up of two aluminium arms linked together by a bearing. A load cell is placed at the end of each arm to record the lift and drag forces created by the aerodynamic blade profile in the test section.

The Vestas-V80 wind turbine blade is composed of a NACA 63 XXX blade profile between the blade tip and its centre, and an FFA W3 XXX blade profile between the centre of the blade and the hub. Because the exact blade profile configuration was unknown, a 0.2 m (chord) × 0.5 m (width) NACA 63 415 blade profile....

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![Figure 2. The AMIL refrigerated wind tunnel](image_url)
was arbitrarily chosen (Figure 3). It was cut from a block of 6061-T6 aluminium, has a 200 μm surface finish and was horizontally mounted, suction side upwards, in the test section.

**Simulations**

The simulations were performed at three radial positions, 12, 23.5 and 35 m, of a 40 m blade. Each simulation included two major parameters, the relative wind speed ($V_{rel}$) and the angle of attack ($\alpha$). As shown in Figure 4, these parameters were calculated from the wind speed at the rotor disc entrance ($V_{vent}$), the tangential speed ($V_{tang}$) and the pitch angle ($\phi$). The relative wind speed was

$$V_{rel} = \sqrt{V_{vent}^2 + V_{tang}^2}$$  

(1)
and the angle of attack ($\alpha$) was

$$\alpha = \arctan \left( \frac{V_{\text{vent}}}{V_{\text{tang}}} \right) - \phi$$

(2)

The wind speed at the rotor disc entrance ($V_{\text{vent}}$) was calculated using the actuator disc concept,$^7$

$$V_{\text{vent}} = V_w (1 - a)$$

(3)

and the tangential speed ($V_{\text{tang}}$) of the blade section was derived from the rotor disk theory.$^7$

$$V_{\text{tang}} = \omega r (1 + a')$$

(4)

The axial induction factor, noted $a$, was assumed to be 1/3. This is an optimal value for the wind turbine power coefficient ($C_p$), according to the actuator disc concept. The tangential induction factor was assumed to be very weak ($a' \ll 1$) and tip corrections were not included. The twist angle was calculated for an optimal lift to drag ratio along the blade with a free stream speed ($V_\infty$) of 8 m s$^{-1}$. These assumptions, as explained in the blade element theory,$^7$ are usually good approximations for fairly well-designed wind turbines in normal conditions (without ice). Therefore, they were considered acceptable to the aim of this work, which is not to accurately calculate airflow or aerodynamic forces along the blade but only to emphasize the difference between iced and non-iced situations.

The meteorological conditions for the two in-fog icing conditions selected were scaled down to wind-tunnel dimensions. The method described by Anderson$^10$ was used. The fixed variables for scaling were the model chord, 0.2 m, and the MWD of the water droplets, 27.6 $\mu$m. The imposed variable was the air speed in the wind tunnel, which corresponds to the relative air speed at the radial position tested. The free variables were the LWC, air temperature and duration of the event. The simulation parameters for the six tests are shown in Table II. They are the radial position ($r$), angle of attack ($\alpha$), LWC, MWD of the supercooled water droplets, relative air speed ($V_{\text{rel}}$), experimental Reynolds numbers ($Re$), wind-tunnel temperature ($T_\infty$), and duration of the event ($t$).

The LWC was calibrated using the rotating cylinder method,$^{11}$ which consists in accreting ice on a rotating cylinder 5 cm in diameter for 1 h. The spray nozzles were adjusted to yield, at a given speed, the desired LWC.

The experimental method for the simulations consisted in positioning the blade profile at the desired angle of attack; setting the speed, temperature and LWC in the test section; accreting ice on the blade profile for a specified duration; measuring the lift and drag coefficients; weighing the blade profile to determine the mass of accreted ice; and noting the ice deposit shape at the centre of the blade profile. Each simulation was repeated once to ensure conformity of results.

### Results

The results of the six simulations for ice mass, ice-deposit shape, lift reduction and drag increase are described in this section.

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**Table II. Wind-tunnel simulation parameters**

<table>
<thead>
<tr>
<th>Test</th>
<th>Fog</th>
<th>$r$ (m)</th>
<th>$\alpha$ (°)</th>
<th>LWC (g m$^{-3}$)</th>
<th>MVD ($\mu$m)</th>
<th>$V_{\text{rel}}$ (m s$^{-1}$)</th>
<th>$Re$</th>
<th>$T_\infty$ (°C)</th>
<th>$t$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>11.9</td>
<td>13</td>
<td>0.37</td>
<td>27.6</td>
<td>19.9</td>
<td>$2.65 \times 10^5$</td>
<td>$-1.4$</td>
<td>14.8</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>23.4</td>
<td>13</td>
<td>0.48</td>
<td>27.6</td>
<td>38.0</td>
<td>$5.07 \times 10^5$</td>
<td>$-1.4$</td>
<td>15.1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>34.8</td>
<td>13</td>
<td>0.48</td>
<td>27.6</td>
<td>56.0</td>
<td>$7.47 \times 10^5$</td>
<td>$-1.4$</td>
<td>24.8</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>11.8</td>
<td>3</td>
<td>0.37</td>
<td>27.6</td>
<td>18.7</td>
<td>$2.49 \times 10^5$</td>
<td>$-5.7$</td>
<td>10.6</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>23.3</td>
<td>7</td>
<td>0.48</td>
<td>27.6</td>
<td>36.7</td>
<td>$4.89 \times 10^5$</td>
<td>$-5.7$</td>
<td>11.8</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>35.0</td>
<td>9</td>
<td>0.48</td>
<td>27.6</td>
<td>55.0</td>
<td>$7.33 \times 10^5$</td>
<td>$-5.7$</td>
<td>19.6</td>
</tr>
</tbody>
</table>
In-fog Icing Event 1

Tests 1 to 3 simulated the effects of in-fog icing event 1 on three positions of a Vestas 1.8 MW wind turbine blade. The icing event characteristics were as follows: LWC of 0.218 g m\(^{-3}\); temperature of \(-1.4\) °C; wind speed of 8.8 m s\(^{-1}\); duration of 6 h. For this wind speed, the angle of attack was calculated to 13° for all simulations. Simulations 1, 2 and 3 were carried out 11.9, 23.4 and 34.8 m from the hub, respectively.

Figure 5 shows the masses and shapes of the ice deposits for simulations 1 to 3 of in-fog icing 1. For the three simulations, the deposits on the blade profile were glaze, a transparent ice of high-density (917 kg m\(^{-3}\)) characteristic of wet-regime accretions. A fraction of the water striking the leading edge of the blade profile froze upon impact while the rest ran along the pressure surface and, at very high speeds, along the suction surface as well. All or some of the running water may freeze on the pressure and suction surfaces of the blade profile. The unfrozen water flowed to the trailing edge where some of it froze and the rest sprayed off into the air. Moreover, because of the sharp incidence angle, some droplets struck the pressure surface, thus increasing the water flow. In the ice accretion simulation near the hub (Figure 6(a)), the glaze on the leading edge followed the contour of the blade profile. In the ice accretion simulation near the middle of the blade (Figure 6(b),(c)), the glaze on the leading edge and that on the pressure surface followed the contour of the blade profile. In the ice accretion simulation near the blade tip (Figure 6(d)), the glaze on the leading edge was horn shaped, on the pressure side followed the contour of the blade profile, while on the suction side formed rivulets. The glaze on both sides of the airfoil was the result of run-off water that froze nearly completely for the simulation near the hub, and partially for the simulations near the mid and tip positions. For these last two positions, a fraction of the run-off water froze on the trailing edge. The quantities of captured water and glaze increased with an increase in the relative air velocity seen by the blade section. The ice masses experimentally accreted on the blade section in the tunnel were 48, 130 and 354 g for the simulations corresponding to radial positions 11.9, 23.4 and 34.8 m, respectively.

Figure 7 shows the lift coefficient reduction and the drag coefficient increase for wet-regime simulations 1, 2 and 3. The lift coefficients measured on the iced profiles were 0.697, 0.685 and 0.553 for the simulations.
Figure 6. Iced blade profiles at the end of the simulations: (a) simulation 1, view from below; (b) simulation 2, view from above; (c) simulation 2, view from below; (d) simulation 3, view from below

Figure 7. Lift and drag coefficients for icing event 1
corresponding to radial position 11.9, 23.4 and 34.8 m, respectively. The drag coefficients measured for the same simulations were 0.068, 0.090 and 0.195, respectively.

**In-fog Icing Event 2**

Tests 4 to 6 simulated the effects of in-fog icing event 2 on three positions of a Vestas 1.8 MW wind turbine blade. The icing event characteristics were as follows: LWC of 0.242 g m\(^{-3}\); temperature of \(-5.7\) °C; wind speed of 4.2 m s\(^{-1}\); duration of 4 h and 24 min. Simulation 4 was carried out 11.8 m from the hub at an angle of attack of 3º, simulation 5, 23.3 m at 7º, and simulation 6, 34.8 m at 9º.

Figure 8 shows the masses and shapes of the ice deposits for simulations 4 to 6 of in-fog icing event 2. For the three simulations, the deposits on the blade profile were rime, opaque ice of lower density than glaze due to the air bubbles trapped in the ice. This is characteristic of dry-regime accretions. Ice density was estimated to be between 850 and 900 kg m\(^{-3}\). All the water striking the leading edge and the blade profile froze upon impact. For the simulation corresponding to the cross section closest to the hub (Figure 9(a)), the rime on the leading edge, pressure surface, and suction surface partially followed the contour of the blade profile and formed slight protrusions. For the cross section near the middle of the blade (Figure 9(b)) and closest to the tip (Figure 9(c),(d)), the rime on the leading edge had a double-horn shape, and that on the pressure and suction side partially followed the contour of the blade profile and exhibited protrusions. The rime was oriented in the direction of the water droplets incidence angle, creating zones of shadow with little accretion, leading to the formation of protrusions. The quantity of accreted rime increased with an increase in the relative air velocity seen by the blade section, due to the proportional increase of captured water, as follows: 24, 91 and 220 g for the simulations at radial positions 11.8, 23.3 and 35 m, respectively.

Figure 10 shows the lift coefficient reduction and the drag coefficient increase for wet-regime simulations 4, 5 and 6. The lift coefficient measured on the iced blade profile was 0.227 for the cross section nearest to the hub (radial position of 11.8 m and angle of attack of 9º), it was 0.491 for the cross section near the middle of
Figure 9. Iced blade profiles at the end of the simulations: (a) simulation 4, view from below; (b) simulation 5, side view and from below; (c) simulation 6, view from above; (d) simulation 6, view from below

Figure 10. Lift and drag coefficients for icing event 2
the blade (radial position of 23.3 m and angle of attack of 7º) and 0.506 for the cross section near the blade tip (radial position of 35 m and angle of attack of 9º). The drag coefficients for the same simulations were 0.033, 0.063 and 0.130, respectively.

**Analysis**

The dry-regime simulations (icing event 2) were easier to carry out than those in wet regime (icing event 1) because they have better reproducibility. Each simulation was repeated once. Tables III, IV and V show the mean values and the standard deviations of ice mass, lift coefficient and drag coefficient for the two simulations carried for each regime. Standard deviations are based on the two average values measured during the experiments and not on the signals in time.

As shown in Figures 5 and 8, in both wet (icing event 1) and dry (icing event 2) regimes, because of local cinematic conditions, the ice mass accreted on the profile increases as the cross section moves from the hub to the blade tip. In order to show dimensionless results (Table VI), the accreted ice masses on the experimental blade profile have been reevaluated for the six simulations considering a standard 1 m (chord) × 1 m (width)

<table>
<thead>
<tr>
<th>Icing event</th>
<th>Wet regime (event 1)</th>
<th>Dry regime (event 2)</th>
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</thead>
<tbody>
<tr>
<td>Radial position (m)</td>
<td>11.9</td>
<td>23.4</td>
</tr>
<tr>
<td>Average mass of ice (g)</td>
<td>48</td>
<td>130</td>
</tr>
<tr>
<td>Standard deviation (g)</td>
<td>0.25</td>
<td>9.25</td>
</tr>
<tr>
<td>Standard deviation (%)</td>
<td>0.52</td>
<td>7.07</td>
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</table>

<table>
<thead>
<tr>
<th>Icing event</th>
<th>Wet regime (event 1)</th>
<th>Dry regime (event 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial position (m)</td>
<td>11.9</td>
<td>23.4</td>
</tr>
<tr>
<td>Average lift coefficient</td>
<td>0.697</td>
<td>0.685</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.021</td>
<td>0.011</td>
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<tr>
<td>Standard deviation (%)</td>
<td>3.04</td>
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<th>Wet regime (event 1)</th>
<th>Dry regime (event 2)</th>
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</thead>
<tbody>
<tr>
<td>Radial position (m)</td>
<td>11.9</td>
<td>23.4</td>
</tr>
<tr>
<td>Average drag coefficient</td>
<td>0.068</td>
<td>0.09</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.01</td>
<td>0.017</td>
</tr>
<tr>
<td>Standard deviation (%)</td>
<td>14.7</td>
<td>18.4</td>
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<table>
<thead>
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<th>Icing event</th>
<th>Wet regime (event 1)</th>
<th>Dry regime (event 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial position (m)</td>
<td>11.9</td>
<td>23.4</td>
</tr>
<tr>
<td>Average mass of ice (g)</td>
<td>2,400</td>
<td>6,500</td>
</tr>
</tbody>
</table>
NACA 63 415 blade profile and the six ice shapes of Figures 5 and 8. In the real case, the blade chord length decreases with the radial position from the hub to the blade tip. Considering this chord size variation, it is in the median zone of the full-size blade that the largest quantity of ice accretes, as shown in Figure 11. The total mass of accreted ice is estimated to 709 kg for event 1 (11% of the blade initial mass, which is 6500 kg) and 434 kg for event 2 (6.7% of the blade initial mass).

In both dry and wet regimes, the lift and drag coefficients are more affected as we move from the hub to the blade tip. In Figures 7 and 10 it is illustrated how the lift coefficient decreases and drag coefficient increases with the radial position on the blade. The drag coefficient variation with radius follows approximately a power law. Especially between the middle and the blade tip, drag coefficient increased considerably and, combined with lift decreases, lead to a significant reduction of lift to drag ratio. In wet regime (icing event 1), we estimated that drag coefficient increased 7.7% at 11.9 m, 45.7% at 23.4 m and 220% at 34.8 m, according to the test results corresponding to the respective positions on the real blade. Using the same assumptions, the lift coefficient decreased 11.2% at 11.9 m, 6.8% at 23.4 m and 27.2% at 34.8 m. The drag coefficient increase at the blade tip (40 m) is estimated to 365% and the lift coefficient reduction to 37%.

In order to assess the effect of ice on the aerodynamic forces on the full-size rotor, a load calculation based on the blade element theory has been used. The orthoradial force component, which generates rotor torque, is called driving force and noted as $F_q$. The force component perpendicular to $F_q$, noted as $F_Z$, is oriented in the direction of the rotor axis and serves to estimate the bending force applied to the blade. The formulas for $dF_q$ and $dF_Z$ are

$$dF_q(r) = \left( \frac{1}{2} \rho c(r) \sqrt{V_{vent}^2 + r^2 \omega^2} \right) \left( C_l(r)V_{vent} - C_D(r)\omega r \right) dr$$

$$dF_Z(r) = \left( \frac{1}{2} \rho c(r) \sqrt{V_{vent}^2 + r^2 \omega^2} \right) \left( C_l(r)\omega r + C_D(r)V_{vent} \right) dr$$

Here, $r$ is the radial position in metres, $\rho$ the air density in kg m$^{-3}$, $c$ the blade profile chord in metres, $\omega r$ the tangential speed in m s$^{-1}$, and $V_{vent}$ the wind speed in m s$^{-1}$ at the rotor disc entrance. The driving ($dF_q$) and bending force ($dF_Z$) variations along the blade span are shown on Figures 12 and 13.

![Figure 11. Mass of ice accumulated along the full-size rotor blade](image-url)
Figure 14 shows the torque distribution ($r \times dF_\theta$) along the blade which has been linearly interpolated over the entire blade length in order to estimate the total torque. During both wet and dry accretion regimes, the driving and bending forces acting on the blade decrease, leading to a drastic torque reduction. In both cases, the drag force becomes so large compared to lift, that a negative torque occurs leading to rotor deceleration and possible stop.
Torque reduction is more significant on the outer third of the blade so that the efficiency of a de-icing system would be increased in that region. In Figure 15 we illustrate the variation of the total torque produced by the blade with the length of the de-icing system. The de-icing system is installed over a given length starting from the blade tip, and the lift and drag coefficients of the clean airfoil are used where the de-icing system is operational. We notice again that the most efficient zone to be de-iced is near the blade tip as approximately 90% of the torque penalty compared to the clean blade is recuperated with only 30% length de-iced.
Conclusion

The simulations allow to experimentally assess the impact of glaze (icing event 1, wet regime) and rime (icing event 2, dry regime) on a wind turbine blade. The LWC for glaze accretion was 0.218 kg m\(^{-3}\), at \(-1.4\ ^\circ\text{C}\) and 8.8 m s\(^{-1}\) wind speed, while the LWC for rime accretion was 0.242 kg m\(^{-3}\), at \(-5.7\ ^\circ\text{C}\) and 4.2 m s\(^{-1}\) wind speed. In wet regime (icing event 1), the angles of attack along the blade were 13\(^\circ\) in average and glaze formed mostly at the leading edge and on the pressure side. Some ice accreted by run-off on the trailing edge for cinematic conditions corresponding to the blade profiles located at the centre and blade tip. In dry regime (icing event 2), the angles of attack were below 9\(^\circ\) and rime accreted mostly on the leading edge and partially on the pressure side for cinematic conditions of the blade profiles located between the middle and the blade tip. The rime accreted on the leading edge was horn shaped, which considerably increased the surface roughness. The total mass of accumulated glaze on the blade was estimated to 709 kg (11% of the blade initial mass, which is 6500 kg) and the total mass of accumulated rime was estimated to 434 kg (6.7% of the blade initial mass). When glaze or rime accreted on the blade profile, lift decreased and drag increased. In both dry and wet regimes the lift reduction varied only slightly on the first two thirds of the blade, 9%, but increased to 25% on the last third, near the tip. The lift reduction at the blade tip was estimated to 40% for both events. Drag increased along the blade following approximately a power law. The increase at the blade tip was in the order of 365% for glaze and 250% for rime. The amount by which lift decreased or drag increased depended on the quality, shape and position of the ice. Finally, based on blade element model estimations, for both icing conditions the lift reduction and drag increase lead to a decrease in the bending and driving forces, and consequently a decrease in torque. The drag force becomes so important compared to lift that the torque is negative, resulting in rotor deceleration and stop. Torque reduction is more significant on the outer third of the blade. Setting up a de-icing system on the last third of the blade only, would enable to decrease equipment and heating energy costs while maintaining 90% of the aerodynamic performance of the clean blade.

Future Work

Based on the results of this study, a heating-element de-icing system will be fine tuned in order to maximize the ratio of lift and drag coefficients over the entire length of the blade, using a minimum of power to operate the de-icing system.

Acknowledgements

This study was completed thanks to the financial support of the Wind Energy TechnoCentre Gaspésie-Les Îles through a grant from Economic Development Canada, by the Wind Energy Group at Université du Québec à Rimouski, and the Anti-icing Materials International Laboratory at the Université du Québec à Chicoutimi. The authors kindly acknowledge the financial support from NSERC and FQRNT through research grants.

Appendix: Nomenclature

- \(a\) axial flow induction factor
- \(a'\) tangential flow induction factor
- \(C_D\) drag coefficient
- \(C_L\) lift coefficient
- \(D\) drag force
- \(F_Z\) bending force on the blade
- \(F_\theta\) driving force on the blade
- \(L\) lift force

LWC  liquid water content  kg m\(^{-3}\)
MVD  median volume diameter of water droplets  \(\mu m\)
r  radial position on the blade  m
\(t\)  duration of the icing event  s
\(V_{\text{rel}}\)  relative wind speed at profile  m s\(^{-1}\)
\(V_{\text{tang}}\)  tangential wind speed due to blade rotation  m s\(^{-1}\)
\(V_{\text{vent}}\)  wind speed at the rotor disc entrance  m s\(^{-1}\)
\(V_{\infty}\)  infinite wind speed (free stream speed)  m s\(^{-1}\)
\(\alpha\)  angle of attack  \(^\circ\)
\(\phi\)  pitch angle  \(^\circ\)
\(\omega\)  rotation speed of the rotor  rad s\(^{-1}\)
\(\rho_{\text{air}}\)  air density  kg m\(^{-3}\)
\(\tau_{\text{Ac}}\)  ice accumulation rate  s\(^{-1}\)

References