Icing characteristics and mitigation strategies for wind turbines in cold climates, part 3: accumulation rate
Andrea G. Kraj and Eric L. Bibeau
Department of Mechanical and Manufacturing Engineering, University of Manitoba
Winnipeg, Manitoba, Canada R3T 5V6
1umkrajag@cc.umanitoba.ca

Abstract
Optimized power generation from available wind resources has gained substantial interest by many leaders in the wind power industry worldwide. One issue facing wind power generation in cold climates is ice accumulation on turbine blades, which is not only an energy production and efficiency concern, but also a safety issue. This paper explores various mitigation techniques for delaying and preventing ice accumulation on wind turbines blades. Firstly, a surface mitigation strategy has been applied to blade models involving hydrophobic and ice-phobic coatings. Secondly, a thermal mitigation strategy involving a new composite material has been developed. Subsequently these mitigation techniques are combined to form a third strategy, termed thermface mitigation. Stationary blade configurations have been experimentally tested in the University of Manitoba Icing Tunnel Facility. The results of the mitigation techniques depict icing profiles and aerodynamic changes along the blade leading edges during the icing event and quantify ice adhesion force, accumulation amount and rate of accumulation over a set period under simulated climatological Glaze and Rime icing conditions. Results are extended to wind turbine performance for estimation of energy production.

Introduction
Wind, as an energy resource, contains the potential to become an important contributor to utility and non-utility power generation in many regions in Canada and in cold climates throughout the world. However, due to extreme climatological factors, many Canadian wind turbine sites are affected by icing problems that impact power generation. Thus, the potential to harness an abundant source of wind for power generation is greatly disadvantaged. Icing is an issue of interest to many groups—from private energy companies, to public utilities and landowners. This paper discusses the experiments performed in the University of Manitoba’s Icing Tunnel Facility, (UMITF), for the investigation of icing mitigation strategies for wind turbines in cold climates. Experiments are performed on aerofoils representative of blades currently used in the wind turbine industry, under simulated climatological conditions for severe icing events found in cold climates where wind turbines are commonly employed. Of particular interest is the 99.9 MW wind farm in St. Leon, Manitoba, which has been developed in a region very well-known for icing events.

Wind turbines are subjected to rime, glaze or mixed ice accretion conditions [1]. In the UMITF, glaze ice forms at temperatures just below freezing in air with high liquid water content, characteristically between 0°C and -6°C. Rime ice forms in colder environmental conditions, traditionally below -10°C, in air of low liquid water content, but also forms when surface temperatures are below -6°C. In rime icing, supercooled water droplets freeze immediately upon impact and form a low-density ice, white and feathery in appearance. In glaze icing, part of the water droplets freeze upon impact and the remaining water runs along the surface before freezing, forming a smooth lumpy profile shape of high-density clear ice.
**Icing Mitigation Strategy**

Current techniques for ice shedding from airfoil blades are commonly found in literature related to aerospace and aircraft applications. As Fitt and Pope [2] indicate these methods include anti-icing and de-icing techniques ranging from freezing point depressants and surface deformation, to thermal melting. Reducing the force of ice adhesion from a surface is a key point to improving the ability to shed ice with ease. As explained by Loughborough [3] of the B.F. Goodrich Company, the force of adhesion is approximated to be linear with temperature, increasing 8.5 lbs per sq. in (5976.09 kg/m$^2$) for each degree centigrade decrease in temperature. The significance of this value indicates that a reduction in the adhesion force of the ice would greatly improve ice shedding and the resulting performance of the turbine. Therefore, a method that reduces the adhesion force of ice on the surface would ideally aid in preventing and delaying the onset of ice accretion.

Since environmental conscientiousness is a key factor in the wind turbines systems, hot oil, chemicals and their derivative are not viable mitigation strategies. Furthermore, the use of electrical energy may contradict the purpose of generating electricity, and must be cautiously implemented. Therefore, the initial preference for an icing mitigation strategy is to implement a passive mitigation technique, such as a surface mitigation to improve the resistance of ice accretion and adhesion to the aerofoil surface. The correlation between a high contact angle for droplets on a surface and their enhanced ability to shed from the surface is highly influenced by the ability of a coating to be hydrophobic or ice-phobic [4]. Thus, the following have been selected for experimentation, for their favourable characteristics in icing conditions: Wearlon Super-Icephobic and Super-Hydrophobic. The icephobic coating is designed to perform best in icing conditions, whereas the hydrophobic coating is catered more towards repelling water droplets [5, 6].

Subsequently, a less-passive mitigation strategy can be explored. For this experiment, a thermal technique is selected. A highly controllable, lightweight system, compatible with modern composite materials has been adapted as an electro-thermal ice protection system where heat is generated at the point of use. Thermion® heaters are made from finely dispersed metal coated carbon fibre elements that may be integrated into composite or polymer material structures and are ideally suited for leading edge blade ice protection applications due to their lightweight and uniform heat distribution capability, contrary to traditional wire heaters [7]. The heat generated by this method is conducted into the ice-substrate interface, where a thin film of water is formed. This breaks the adhesive bond between the ice and the outer surface so that the ice can be swept away by aerodynamic forces. Furthermore, cycling of the heater power helps to control and reduce energy requirements [8], suggesting the use of various thermal regimes to further enhance the effectiveness of the mitigation strategy. By controlling the duration and timing of heat application both anti-icing and various de-icing regimes can be explored.

Finally, the combination of the surface mitigation with the thermal mitigation, termed thermface, is explored as means of more controlled-passive deicing technique, providing insight to the combined effectiveness of these mitigation strategies. The cycling of power for the electro-thermal heaters allows integration with other techniques to optimize mitigation efforts.
**Experiment Description**

Icing experimentation is performed in the Icing Tunnel Facility located in the Engineering Complex at the University of Manitoba. The UMITF consists of a spray system to emit droplets into the flow and a refrigeration system for cooling of the air as shown in Figure 1 [9].

![Figure 1: Top view of spray flow and icing tunnel](image)

Experiments are conducted using stationary aerofoils placed within an inner duct ($1\text{m}^2$) of the wind tunnel. Scaled test specimens are subjected to cooled airflows containing water droplets that are released into the flow stream from a customized spray bar located upstream of the aerofoil test piece. Air atomizing nozzles can produce a reliable spray pattern with water mean droplet diameters ranging from $10^{-3}$ to $10^{-5}$ meters. The droplets travel in a trajectory towards the test specimen, are cooled along the way and freeze upon impact with the test specimen forming different icing characteristics and shapes, according to the climatological conditions set for the conducted experiment.

The test specimen is in the forms of a NACA 634421 profile aerofoil with aluminum frame and fiberglass sheeting. For this experimental series, six test pieces with various mitigation strategies were required to investigate the surface, thermal and thermface mitigation strategies. The specimen without a heater or coating was used as a datum. The selected coatings were applied to the aerofoil test specimens using specialized paint application equipment and procedures. The icephobic coated specimen is black, whereas the hydrophobic coated specimen is white, and the plain, uncoated specimen is the original fiberglass composite colour, yellow. All thermally mitigated specimens had two $0.508 \times 0.127 \text{ m}$, 12 V / 5 W heaters, mounted on each of the upper and lower leading edge surfaces. All thermface specimens contained both coatings and heaters. The specimens are shown in Figure 2 as mounted for testing.

![Figure 2: Aerofoil test sections: (L-R) Hydrophobic; Icephobic; Plain](image)

The aerofoil test specimens were mounted at zero angle of attack downstream of the spray bar. Firstly, the surface mitigation technique was performed for the plain, hydrophobic and icephobic samples under both glaze and rime icing conditions. Subsequently, the thermal mitigation strategy was applied. For the thermal and thermface mitigation both anti-icing and de-icing regimes were employed in both rime and glaze icing conditions. The anti-icing regime consisted of applying heat for the complete duration of the 20 minute test, whereas for the de-icing regime, heat was applied for only the second half of the test. The thermface strategy consisted of implementing the thermal strategy with the coated specimens.

**Experimental Parameters**

A cooled air-water system was used in these experiments. Table 1 indicates the experimental conditions for the wind tunnel and spray bar equipment; the dimensions of the test specimens; and summarizes the implemented climatological conditions. The diameter of the water droplets and the Liquid Water Content (LWC) are approximated.
### Table 1: Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental equipment conditions</strong></td>
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</tr>
<tr>
<td>Spray bar water flow (kg/s)</td>
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<tr>
<td>Spray bar water temperature (°C)</td>
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<td>Spray bar air pressure (Pa)</td>
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<td>Wind tunnel set velocity, $v_t$ (Hz)</td>
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<td><strong>Test specimen parameters</strong></td>
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<td>Chord length (m)</td>
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<tr>
<td>Aerofoil specimen width (m)</td>
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<tr>
<td>Angle of attack (degrees)</td>
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<tr>
<td><strong>Weather conditions for glaze icing</strong></td>
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</tr>
<tr>
<td>Liquid water content, LWC (kg/m³)</td>
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</tr>
<tr>
<td>Diameter of droplet, d (m)</td>
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<tr>
<td>Freestream temperature, $T_i$ (K)</td>
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</tr>
<tr>
<td>Freestream pressure, $P_o$ (MPa)</td>
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<tr>
<td>Measured local wind velocity, $V_w$ (m/s)</td>
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<tr>
<td><strong>Weather conditions for rime icing</strong></td>
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<td>Liquid water content, LWC (kg/m³)</td>
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#### Experimental Analysis

Leading edge (LE) profiles were compared among all resulting test samples from which ice shape, symmetry and consistency were observed. A high resolution black-and-white digital camera and data acquisition system was used to collect images of the side-view aerofoil profile and the ice accretion for test duration of 20 minutes. Collected image data was processed using graphics software to determine changes in ice profile shape and accumulation rate. Following this test, the shear-adhesion force test was performed on the LE curved surface of the aerofoil to determine the required force to remove the ice from the surface. The iced LE specimens were collected and their geometry was measured. The specimens were melted for a liquid volume measurement to gauge the amount of water that had accumulated along the leading edge.

#### Results & Discussion

##### Ice Profile Changes

A visual profile of ice formation on the LE surface, illustrates the varying amounts of ice accumulation and profile shapes between surfaces in glaze icing conditions. The resulting icing profiles are displayed in Figure 3.

![Image](a) Plain  (b) Icophobic  (c) Hydrophobic

Figure 3: Experimental icing pictures of leading edge of airfoil for different coatings

#### Adhesion Force & Accumulation

The experimental results collected for ice adhesion force and the amount of water accumulation along the leading edge of the aerofoil for the various mitigation techniques are contained in Figures 4 and 5.

##### Adhesion Force

Comparing glaze and rime icing results indicate that on an uncoated plain surface, the adhesion force of glaze ice is 60% less adhesive than rime ice. The most effective surface mitigation in glaze conditions is the hydrophobic coating which reduces adhesion force by 70%. In rime condition, the icophobic coating is more effective, reducing adhesion by 26%. Evidently, in surface mitigation, the hydrophobic coating is most effective in glaze conditions while the icophobic coating is most effective in rime conditions. This can be attributed to the physical properties of the coatings: the hydrophobic coating is designed to be effective by repelling water as in glaze ice forms, while the icophobic coating is designed to repel solid-ice, as in rime conditions. Thus, the results identify the differences in the surface strategies and indicate that this distinction is related to the applied climatological conditions. This validates the significance and effectiveness of applying the proper coating in their designed-for conditions.
For thermal mitigation, anti-icing is more effective than the deicing regime, in both glaze and rime icing conditions, reducing adhesion 71% and 47% respectively. Furthermore, the results indicate that the glaze responds more effectively than rime to this thermal mitigation strategy.

For the thermface mitigation, in both icing conditions, the de-icing regime is more effective than the anti-icing regime. In glaze conditions it performs equally well among the icephobic and hydrophobic coatings, reducing adhesion by 80%; whereas in rime conditions, it is best paired with the icephobic coating, reducing adhesion by 63%. Furthermore, the deicing regime also consumes less energy, which is ideal for energy production systems. Isolating the thermal variable indicates that for glaze icing, the thermal regimes are not solitarily effective at reducing adhesion force, and are thus most effective when paired with a secondary mitigation strategy. Furthermore, isolating the surface variable indicates that for glaze icing, there is no apparent adhesion reduction for either coating with the anti-icing regime, suggesting a supplementary result that the coatings may impede ice removal by preventing conductive heat transfer to the surface, as a result of their inherent thickness.

Thus, in both glaze and rime conditions the recommended strategy would be to employ the thermface mitigation technique with the icephobic coating in the deicing regime.

Accumulation Amount
In comparison of the amount of ice, in liquid state that accumulates along the LE of an aerofoil for both icing conditions, there is 14% less accumulation in glaze than in rime. The most effective surface mitigation in glaze icing is the icephobic coating, reducing accumulation by 29%, and in rime is the hydrophobic coating reducing accumulation 39%.

The most effective thermal mitigation strategy on a plain uncoated surface, in glaze conditions, is the anti-icing regime, reducing accumulation by 34%. In rime conditions, accumulation is not significantly reduced; in fact, only the anti-icing regime reduces accumulation by 8%, whereas for deicing, the amount of accumulation appears to supersede the effectiveness of the mitigation technique, suggesting that it does not have the capacity to be effective in the given conditions.

The most effective thermface regime for glaze conditions involves combining the de-icing regime with the icephobic coating, which reduces accumulation 63%. In rime conditions, the only effective solution is the icephobic coating with the anti-icing regime, reducing accumulation 48%. The inability of the mitigation strategy to be effective with the de-icing regime in rime conditions indicates that the thermal technique has nearly reached its max capacity of effectiveness, yet the combination with the surface mitigation remains more effective than the thermal technique alone. In light of energy
consumption, the deicing regime utilizes less energy, however it is limited in effectiveness of reducing accumulation in rime conditions, despite being the preferred regime.

Evidently, both the thermal and surface mitigation strategies, independently, are significantly effective at reducing accumulation along the leading edge of an aerofoil. However, the combined mitigation of the thermface strategy provides the most substantial reduction in accumulation. Thus, the recommended mitigation strategy for reducing accumulation in either glaze or rime conditions would be to implement the icephobic coating in combination with a deicing regime, but with attention to enhanced thermal duration as needed in rime conditions due to the limitation of de-icing to effectively reduce accumulation. Furthermore, this strategy is effective at reducing adhesion force as well.

**Rate of Ice Accumulation**

The experimental results collected for ice accumulation rate for various mitigation techniques are contained in Figures 6.

Comparing the rate of accumulation between glaze and rime icing conditions, it has been found that on an uncoated plain surface, glaze ice accumulates at a rate of 5% less than rime. When surface mitigation is used, the rate of ice accumulations on a wind turbine blade is more effectively reduced. By employing the icephobic coating, icing accumulation rate (IAR) is 52% less in glaze than in rime, while using the hydrophobic coating IAR is 80% in glaze than in rime.

Comparing the surface mitigation techniques, in glaze conditions, the IAR is reduced by 12% with the icephobic coating and 18% by the hydrophobic coating. In rime conditions, surface mitigation does not effectively reduce IAR, suggesting that the mitigation strategy has reached its maximum capacity for the given climatological conditions.

In comparison of the thermal mitigation techniques, for glaze conditions, the anti-icing regime effectively reduces IAR by 24%, whereas the deicing regime is ineffective for reducing IAR. In rime conditions, neither thermal mitigation regime effectively reduces IAR suggesting that the technique has reached its maximum capacity to be effective in the given conditions.

The thermface strategy employing the hydrophobic coating with the deicing regime reduces IAR by 72% in glaze conditions and is the only thermface strategy to perform effectively. In rime conditions, not one mitigation strategy overall indicates a reduction in IAR. Isolating individual variables for further insight to these results indicates that the icephobic coating with anti-icing provides a reduction in IAR when compared to both surface and thermal mitigations individually. This thermface technique effectively reduces IAR by 20% over surface mitigation alone and 14% over anti-icing thermal mitigation alone; thereby suggesting that it would be the most effective mitigation strategy in rime conditions for controlling IAR.

Evidently, IAR is more easily mitigated in glaze than in rime conditions. The most effective mitigation strategy is the thermface technique, where in glaze the hydrophobic coating with the de-icing regime is employed, and in rime, the icephobic coating with the anti-icing regime is employed. These results are indicative of the correlation between the sensitivity of the behaviour of the ice to the employed mitigation strategy, i.e. rime icing being more severe and requiring a more intense mitigation technique to effectively control the icing accumulation rate.
Wind Turbine Performance Measures
Optimized wind turbine performance is dependent on the lift to drag ratio created by the blades. Ice accumulation changes the aerodynamic profile shape of the blade and directly affects the lift, as well as creates trigger points for non-laminar flow over the blade surface resulting in less-efficient energy capture; furthermore, ice adds weight to the aerofoil. With a less-effective lift-to-drag ratio the turbine is not capable of efficient wind energy production. As shown in the change in ice profile shapes and accumulation rate over the capture period, the transient change in chord length of the aerofoil can result in a significant extension in chord length after only a period of 10 minutes, for which the aerodynamic blades are not designed. Additionally, an effective mitigation strategy, must not consume more energy than the system produces. Therefore, an optimal mitigation strategy would best balance these performance measures.

Conclusion
Wind Energy production in adverse cold climates can be enhanced by implementing the presented mitigation strategies, which significantly control the ice profile shapes, reduce the accumulation rate, adhesion force and accumulation amount of ice on a blade surface and influence the formation of a more symmetric LE ice profile. It is shown that in glaze or rime conditions, the thermface strategy employing the de-icing thermal regime with the icephobic surface coating is the most effective mitigation for reducing adhesion force and accumulation amount, with the necessity to extend the duration of the thermal regime to best mitigate accumulation amount; while for controlling icing accumulation rate, glaze icing will be effectively mitigated with the minimalist strategy while rime icing requires the most intense strategy.

Furthermore, the combination of mitigation strategies must be carefully designed so that they are employed in the climatological conditions best suited for their use and within their scope of capability so that they do not adversely affect the capabilities of one another—specifically, in the case of coating thickness impeding heat transfer by conduction to the surface.

Acknowledgments
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References