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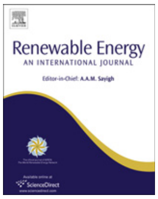

Measurement method and results of ice adhesion force on the curved surface of a wind turbine blade

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Experimental adhesion force measurements were conducted on accumulated ice on the leading edge of a scaled wind turbine blade in both glaze and rime icing regimes. An apparatus was first designed for specifically measuring the adhesion force of ice on a curved surface at climatic temperature where a vertical force was applied to the mounted structure in the test apparatus. Adhesion force measurements were measured and adhesion pressure calculated for plain and ice-mitigated test specimens. Results are presented for the increase in force of ice adhesion over a curved surface area in proportion to degree centigrade decrease in temperature.

1. Introduction ice adhesion

Ice accumulation typically occurs on surfaces exposed to atmospheric conditions in which liquid water content and near freezing temperatures or environments with high convective cooling rates exist, such as in cold damp windy weather or in typical cold climates that experience frost, snow and freezing rain.

The type of ice that forms in the atmosphere is dependent on several factors: air temperature, relative humidity, barometric pressure, wind speed, air density, and altitude; as well as the physical atmospheric processes that create the initial cloud formation. Furthermore, the ice that forms on the substrate of a wind turbine blade is also dependent on the temperature of the substrate surface.

Icing is problematic to the safe and efficient operation of wind turbine blades for several reasons which inhibit optimal power performance of the machine, limiting its effectiveness; thus, it is important to prevent and if not possible remove ice from the surface of turbine blades. Table 1 provides a summary of the potential problems that ice accretion may create for a wind turbine.

Reducing the force of ice adhesion from a surface is a key factor to improving the ability to shed ice with ease. As investigated by the B.F. Goodrich Company [1], the force of adhesion of ice on a *flat plate* is approximated to be linear with temperature, increasing 8.5 psi or 5976 Pa for each degree centigrade decrease in temperature, such that assuming a blade surface temperature of approximately −10 °C, corresponds to an ice adhesion force of 85 psi or 59,760 Pa. The significance of this value indicates that a reduction in the adhesion force of the ice would improve ice shedding and the resulting performance of the turbine.

Due to limited information regarding testing of ice adhesion force on a curved surface, an important aspect of research in icing of wind turbine blades is to develop a method to measure the adhesion force of ice on the curved aerofoil surface at the experimental temperature. In order to do this, a test apparatus and method was developed that enabled the measurement of ice adhesion force on a curved surface to be conducted in the University of Manitoba Icing Tunnel Facility, (UMITF), immediately after a simulated icing event at climatic conditions on an airfoil.

There are two distinct types of icing with different characteristics, namely glaze and rime. Tests are presented for these two distinct ice types. Often, there will be a "mixed" icing regime that is a combination of these two types. The characterization of mixed ice accretion is more involved due to the different proportions of either glaze or rime ice.

Glaze ice occurs at temperatures just below freezing, in atmospheric conditions of high liquid water content [2]; creating an ice that is clear and dense. Traditionally, glaze ice forms at temperatures between 0 °C and −4 °C. In the University of Manitoba Icing Tunnel Facility (UMITF), glaze ice has been simulated at a temperature of −5 °C. In glaze icing, part of the water droplets freeze upon impact and the remainder run along the surface before freezing,

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Table 1
Potential results of ice accretion on wind turbine performance.

1st Degree	2nd Degree	3rd Degree	4th Degree
Increased loads (static/dynamic)	Yaw angle declination	Ice throw/drop	Ice impact safety concerns
Reduced aerodynamic efficiency	Turbulence	Noise	Reduced power production
Vibrations	Blade material stress	Structure degradation	Structure Safety concerns
Untrue sensor signals	Plant stoppage	Restart problematic	Financial losses

forming a smooth lumpy profile shape of high-density clear ice. Glaze ice is expected to be more difficult to remove than rime ice due to its inherent physical properties. Fig. 1 depicts a typical experimental glaze ice formation. Rime ice occurs at colder temperatures of low liquid water content, freezing before contact with the substrate and accumulating in layers with mixed air pockets. Traditionally, rime ice forms at surface temperatures between $-12\,^{\circ}\mathrm{C}$ and $-4\,^{\circ}\mathrm{C}$ [2]. In the UMITF, rime ice has been simulated at a temperature of $-15\,^{\circ}\mathrm{C}$. In rime icing, supercooled water droplets freeze immediately upon impact and form a low-density ice, white and feathery in appearance, as shown in Fig. 2.

2. Icing tunnel facility

The University of Manitoba accommodates a unique experimental facility for aerodynamic icing research in the Faculty of Engineering complex. Since the basis of this research work is experimental, all collected data and results are produced within the limitations of the following experimental design apparatus.

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 Fig. 3 [3]. Experiments are conducted using stationary scaled-aerofoils placed within the inner duct (1 m^2) of the wind tunnel. Scaled test specimens are subjected to cooled airflows containing water droplets (filtered and distilled) that are released into the flow stream from a customized spray bar located upstream of the aerofoil test piece. The air atomizing nozzles produce a reliable spray pattern with water mean droplet diameters ranging from 10^{-3} to 10^{-5} m, per manufacturers specifications. The droplets travel in a trajectory towards the test specimen, are cooled along the way and freeze upon impact with the test specimen forming various ice shapes and characteristics, according to the climatological conditions of the conducted experiment.

3. Wind tunnel calibration

The calibration of the wind tunnel involved a series of tests to obtain data on the wind speeds at varying temperatures within the inner duct of the tunnel where the icing experiments would take place. Both a pitot tube-manometer and 3-cup anemometer are used for measurements and cross-referenced to validate tunnel configuration. The wind tunnel parameters set for this calibration involved a range of motor frequencies between 8 and 40 Hz, and a range of temperatures between $+25\,^{\circ}\mathrm{C}$ and $-30\,^{\circ}\mathrm{C}$ resulting in a range of calculated wind speeds between 3 and 24 m/s, depending on the motor setting and correlating tunnel temperature.

Fig. 1. Glaze ice with frozen rivulets formed in the icing tunnel.

Fig. 2. Rime ice with feathered texture formed on a rotating fan blade.

3.1. Experiment design

To understand the fundamental dynamics of the complex three-phase system that occurs during icing, the initial phase of the experiment is designed to minimize variables. Thus, blade specimens are held in a fixed stationary position and a single angle of attack of zero degrees is selected for testing. Only the two distinct glaze and rime icing types are generated.

The surface mitigation strategies were limited to three different surfaces; one remained a datum (untreated), while the two others were different type coatings: icephobic and hydrophobic. The thermal mitigation was limited to a single technique; however with two different heating regimes: anti-icing and deicing. The combinations of these techniques lead to the development of a third mitigation strategy, termed *Thermface* [4]. Due to the nature of the

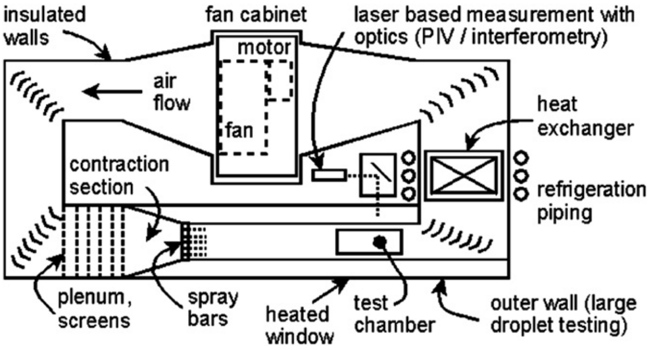

Fig. 3. Top view of spray flow and icing tunnel.