



A novel electro-thermal anti-icing system for fiber-reinforced polymer composite airfoils

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ABSTRACT

For the first time, the concept of embedded thermal elements as an anti-icing system for polymer composite airfoils used in wind turbine blades and aircraft wing structures is proposed, and developed experimentally and numerically. A manufacturing technique was developed to implement the electro-thermal anti-icing system in the form of discrete constantan thermal elements with a specific pattern inside the composite airfoil. Thermography was used to understand the surface temperature distribution of the composite airfoil surface in cold (dry) and icing (wet) condition tests. Two composite airfoil samples with two different thermal elements' patterns were made to study the effect of wires' spacing on the airfoils' surface temperature distribution, and the effectiveness of the thermal elements' pattern for icing mitigation. Thermal elements of the anti-icing systems were energized by using two different power schemes to determine and adjust the required power to have an ice free composite airfoil, and adjust the amount of power consumption. A numerical thermal analysis was performed to determine the power threshold in the anti-icing system to prevent thermal degradation of the polymer composite. Thermal modeling was also used to explain some of the experimental observations. Experimental data and thermal analysis are in a good agreement, indicating the feasibility of using thermal elements as anti-icing system for surface heating in order to prevent ice accretion on polymer composite airfoils.

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1. Introduction

Composite materials are versatile and customizable, hence used widely in wind turbine blades and aircraft structures. The most important properties of polymer composite materials are their high specific stiffness and strength in comparison to metals. Icing of the polymer composite aerodynamic structures, such as airplanes' wing and wind turbine blades, can be a serious problem. Icing changes the dynamic behavior of the whole structure, changes the airfoils' shape, increase surface roughness, and can increase the weight, increase drag, and decrease lift (Civil Aviation Authority, 2000; Thomas and Cassoni, 1996). In wind turbines, icing affects the turbine's power production efficiency; and even a light icing event can roughen the turbine blades' surface to decrease the aerodynamic efficiency (Fortin and Perron, 2009; Seifert, 2004).

Anti-icing systems are mainly categorized into two types: passive and active. Passive anti-icing systems such as black paint and so-called "ice-phobic" coatings have their own drawbacks on composite materials. Since the polymer composite materials are sensitive to high temperatures, black paint on the wind turbine blade may increase the surface temperature which leads to thermal degradation of the composite material in summer time (Parent and Ilinca, 2011; Seifert, 2004). Most of the time the passive anti-icing systems are

not sufficient to prevent icing, and they should be combined with an active anti-icing systems (Antonini et al., 2011; Parent and Ilinca, 2011).

Active anti-icing systems mainly require an energy supply, which can be thermal, chemical or pneumatic. Traditional thermal anti-icing systems such as hot-air systems for polymer composite airfoils can be challenging due to maximum operating temperature, and high thermal resistance of the polymer composites which pose a temperature limit for the hot air (Hung et al., 1987; Lubin and Peters, 1998; Parent and Ilinca, 2011; Seifert, 2004).

A few hot-air and electro-thermal anti-icing systems (Ciardullo et al., 1987; Hung et al., 1987; Talhaug et al., 2005) were developed for polymer composite materials, e.g., by using surface heating. But these studies did not consider energy consumption of these systems, and the effect of surface roughness as a result of installing surface mounted heating systems on aerodynamic efficiency. Also wind tunnel icing experiments were not conducted. Besides, electro-thermal anti-icing systems which are used in the form of thermal pads, electrically heated foils, and metal or carbon fiber electrical heating elements on the composite blades' surface, have serious drawbacks (Dalili et al., 2009; Fortin et al., 2008; Seifert, 2004). For example, thermal pads and electrically heated foils which are mostly mounted on the surface of the blade, change the aerodynamic performance of the airfoil, and disturb the air flow around the blade. Also, metal and carbon heating elements can attract lightning strikes to the surface of the blade. Carbon fibers as the thermal elements, which are

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positioned at the leading edge can also cause additional problems for the polymer composite blade, since they bear a large portion of the load which leads to cracks in the heating elements (Dalili et al., 2009; Parent and Ilinca, 2011; Seifert, 2004).

Currently, there are relatively few experimental studies in the icing conditions examining the performance of the anti-icing systems developed for composite airfoils; and most of the studies are numerical analysis to model the heat transfer in the icing conditions or simulate the icing behavior of the airfoils (Elangovan and Olsen, 2008; Fortin and Perron, 2009; Wang, 2008). To the best of our knowledge this is the first experimental study on the developed anti-icing system for polymer composite airfoils in icing conditions.

Given the trend towards expanded use of composites for wind turbine blades and aircrafts, it is important to develop icing mitigation systems that are compatible with composite materials. In this study embedded thermal elements as an anti-icing system for polymer composite airfoils were investigated. The concept involves embedding thermal elements in the form of constantan wires inside a glass-fiber-reinforced/epoxy composite airfoil and heating the composite structure through these elements. The main goal of this study was to develop a new concept for anti-icing system for polymer composite airfoils which potentially may be used for, e.g., wind turbine blade. However, the intention is not as much on a specific application, but to investigate the feasibility of the new concept in a condition where ice can be formed. The idea is not to focus on icing conditions which lead to formation of the ice, or physics of ice formation. The intention is to study the functionality of the concept for using embedded thermal elements in a composite aerodynamic structure to prevent ice formation without thermal degradation of the composite material. The focus of this study is thermal behavior of the concept; and issues related to possible effects of embedding thermal elements on mechanical performance of composite test samples are not considered. As such, the study is focused on conceptual design aspects of the proposed anti-icing system, the energized airfoils' surface temperature profiles, and energy consumption; experimental as well as numerical methods are used.

The developed system can simply be incorporated during the manufacturing of a polymer composite structure such as airfoils. The embedded thermal elements will leave the exterior surface of the airfoil smooth unlike prior systems. In principle, this system can be customized; so that the temperature of different locations on the surface can be controlled to reach a specific anti-icing temperature to reduce energy consumption.

2. Experimental methods

2.1. Manufacturing process of the composite airfoils with the anti-icing system

Polymer composite airfoils with embedded thermal elements as the anti-icing system were manufactured from a commercially available aerospace-grade fiberglass/epoxy prepreg, i.e., Necote E-765 epoxy/fiberglass prepreg from Park Electrochemical Corporation Advanced Material Technologies. Constantan wire, i.e., SPCC-010-50 with 0.25 mm diameter, was used as the thermal element in the anti-icing system, from Omega Engineering Inc.

The polymer composite laminates were fabricated by dry hand lay-up of six prepreg layers with a total thickness of 1.4 mm. The anti-icing system is comprised of separate thermal elements (wires) embedded inside the composite airfoil. The thermal elements with equal lengths were sandwiched in between the composite laminate with desired spacing. Three layers of the prepreg were laid first, and then the thermal elements were aligned straight on them (perpendicular to the airfoil chord line), by using a specially designed jig. Another three layers of the prepreg were laminated on top of the elements.

Fig. 1(a) shows the designed jig with wires laid on the third layer (middle) of the composite laminate. As shown in Fig. 1(a), the screws

are placed at a specific distance from each other on the jig plate; and the wires can be kept straight with a specific spacing, by using the screws.

After fabricating the composite laminates with embedded thermal elements, the laminates were formed into the airfoil profile, by using a mold. By using the vacuum bag molding, the airfoil was cured in an oven for 1 h at 82 °C, followed by a 2-hour cure at 135 °C, applying a minimum vacuum pressure of 82 kPa. The vacuum bag molding is used for improving the consolidation of the fibers, and removing excess resin, air and volatile compounds from the composite laminate. Fig. 1(b) and (c) shows the two-part aluminum NACA 0021 airfoil's mold and the polymer composite inset. The final dimension of the composite airfoil inset is: 148 mm (L) × 84 mm (W) × 1.4 mm (H).

In this study, two composite airfoil samples with two different thermal element patterns were made to study the effect of wire spacing on the airfoils' surface temperature distribution, and the effectiveness of the thermal elements' pattern for icing mitigation. First, the composite airfoil labeled as: (I) had 11 equally spaced thermal elements with an equal length of 120 mm; five thermal elements were placed on the top side, five on the bottom side, and one thermal element at the leading edge of the airfoil, as shown in Fig. 2(a). The spacing of the thermal elements in this pattern was 10 mm.

The anti-icing system in the second fabricated airfoil, named airfoil (II), had 19 thermal elements with different wire spacings, but each wire had an equal length of 130 mm. Fig. 2(b) shows the position of thermal elements inside the composite flat plate before shaping to an airfoil. As can be seen from Fig. 2(b), one thermal element was embedded on the leading edge (wire 1), and the next four thermal elements till wires 2 and 2' on the top and bottom sides of the airfoil (II), respectively, were placed with a 2.5 mm spacing. This area, which considered as the leading edge region, is 3.42% chord length of the airfoil. The wires at the leading edge region were embedded closer than that of the area beyond the leading edge region to increase the heat flux for the expected maximum convective heat transfer coefficient at this region.

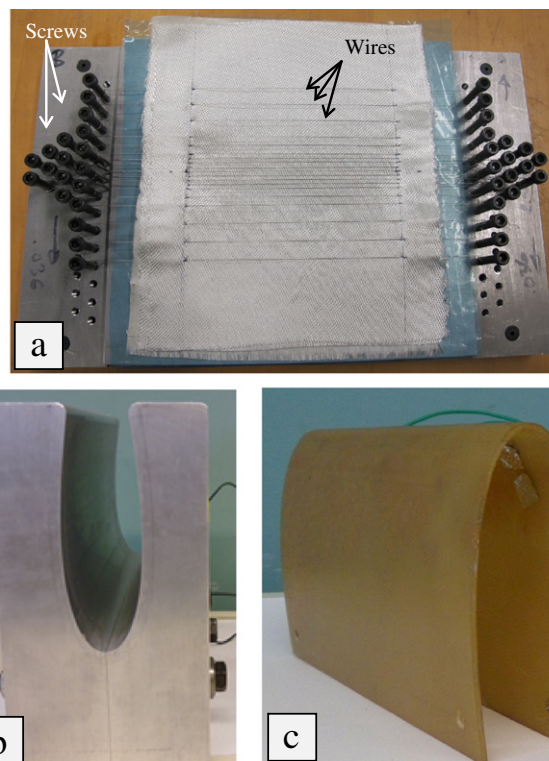


Fig. 1. (a) The designed jig to lay the wires inside the composite laminate, (b) aluminum airfoil's mold, and (c) the cured polymer composite airfoil inset.

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