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Flame-sprayed coatings as de-icing elements for fiber-reinforced polymer composite structures: Modeling and experimentation

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ABSTRACT

The development of embedded de-icing elements for polymer-based composite materials, coupled with mathematical models that describe their performance, is of interest to the aerospace, communications, and energy industries. Nickel–chromium–aluminum–yttrium (NiCrAlY) coatings were deposited on to fiber-reinforced polymer composite (FRPC) plates by using a flame spraying process. Electric current was supplied to the metal alloy coatings to generate energy by way of Joule heating (or resistive heating) and to enable the coatings to act as heating elements for the FRPC structures. De-icing tests were performed at ambient temperatures of −5 °C, −15 °C, and −25 °C, after liquid water was sprayed on the samples. Heat transfer models were developed to predict the heating and melting times of the ice during the de-icing process with the flame-sprayed coatings. The models were based on the separation of variables method for a finite length-scale melting problem and Stefan's problem applied to a semi-infinite medium. It was found that a coating that was on the order of 100 μm thick was effective for melting accumulated ice on polymer composite structures that were exposed to cold environments. The results of the finite length-scale model and its agreement with experimental data suggest that a heat conduction model based on the separation of variables method may be applied to free boundary problems to predict phase change phenomena induced by thermal-sprayed coatings.

1. Introduction

Ice accretion (or icing) is the formation and accumulation of ice on structures that are exposed to cold and humid ambient environments. It is a common problem in structures in the transport and energy industries, among others [1–6]. Particularly, ice growth affects the airfoils of airplanes (the wings) and wind turbines (the blades) by decreasing their performance, safety, and durability for over as much as 6 months of a year [1–4,6–8]. On planes, ice accretion during flights produces a significant threat to safety, representing around 9% of large-scale safety accidents of aircraft during flight [7,8]. On wind turbines, ice accretion has been found to produce mechanical and electrical failures, errors in the measurement of temperature, humidity, and wind velocity, overproduction, and power losses of up to 50% [1,2,4,6]. Therefore, developing methods to reduce the effects of ice accretion is of interest to the aerospace, marine transport, telecommunications, and energy industries since it would increase overall safety, the integrity of structures, and performance of equipment [1–3].

In low-temperature climates, wind turbines will produce increased power output due to the cold, dense air, since power output is proportional to air density [2,5]. However, formation and accumulation of ice on the blades of wind turbines will adversely affect the performance, longevity, and safe operation of the turbine. Ice accretion on wind turbine blades have caused full shutdown of turbine operation, overloading that adversely affects structural components and the generator that is connected to the rotor, and degradation in the mechanical health of the blades [1,2,9]. Furthermore, Antikainen and Peuranen [10] have shown that mass and aerodynamic imbalance of the turbine blades will occur, even in the early stages of ice growth. These imbalances will cause higher fatigue and dynamic loads and increase the excitation of edgewise vibrations [1,3,5]. Given that these serious problems will occur due to ice formation on wind turbine blades, novel heating systems are urgently needed to mitigate or completely eliminate the issues generated by ice accretion.

Active de-icing systems, that mitigate the adverse consequences of ice accretion on the surface of wind turbine blades, have been developed [2,8,11]. Some of the systems have used warm air that is blown from the rotor into each blade [1,12]. The heat that is transferred from the air to the structure of the blades keeps them warm and devoid of ice. Warm air has been successfully used in an

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Nomenclature

A	surface area (m^2)
Bi	Biot number, $Bi = \frac{h\delta}{k_s}$
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
$\dot{E}$	energy rate (W)
Fo	Fourier number, $Fo = \frac{\alpha_L t}{\delta^2}$
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
I	electric current (A)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
l	substrate length (m)
P	electrical power (W), $P = VI$
Pr	Prandtl number, $\frac{c_p \mu}{k}$
q''_g	heat flux due to Joule heating ($W\ m^{-2}$)
r	coefficient of determination
R	electrical resistance (Ω)
Re	Reynolds's number, $Re = \frac{ul}{v}$
T	temperature (°C)
t	time (s)
u	free stream air velocity ($m\ s^{-1}$)
V	voltage (V)
x	position (m)
x_i	location of liquid–solid interface (m)

Greek symbols

α	thermal diffusivity ($m^2\ s^{-1}$)
δ	thickness of ice (m)
Γ	function dependent on t, only
Δ	time rate of change
θ	non-dimensional temperature, $\theta = \frac{T_f - T_\infty}{T_f}$
λ	separation constant (m^{-1})
$\hat{\lambda}$	non-dimensional constant
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
v	kinematic viscosity ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
Φ	function dependent on x, only
X	function dependent on x, only
Ψ	function dependent on x and t
$\hbar$	latent heat of fusion ($J\ kg^{-1}$)
∞	ambient

Subscripts

A	air
f	fusion
F	FRPC substrate
h	heating
i	initial
in	in
L	liquid phase
n	number
o	out
s	solid phase

850 kW wind turbine, consuming approximately 1% of the total electricity produced to heat and circulate the air [1,13]. However, this method consumes a significant amount of energy during operation of the blades at high speed winds and low temperatures. In addition, given that polymer-based composites, which are widely used to fabricate wind turbine blades, are good insulators, air at higher temperatures is required in order to increase the temperature across the composite material, resulting in high power consumption. Other de-icing methods include the use of electrical heating wires embedded within the blade or structure [14] and microwave heating [9]. These methodologies have inherent problems, which include positioning of the heating wires in the blade to avoid potential structural issues, the generation of high dynamic loads, and the creation of concentrated localized "hot spots" on the surface, which leads to high-temperature degradation of the blade. Also, microwave heating has never been successfully implemented. In some cases, surface modification work, with the use of superhydrophobic coatings, have been explored to improve the efficacy of anti-icing features of the material surfaces [15].

While fiber-reinforced polymer composites (FRPCs) provide several mechanical benefits to wind turbine structures, their thermal properties typically do not allow them to conduct heat rapidly. Novel heating methods for FRPCs that are exposed to cold ambient conditions are usually required. Some of the methods that are used as de-icing systems to mitigate ice accretion on FRPC surfaces are based on using heating elements that are embedded or laminated in the FRPC structure [1,14]. The heating elements may be wires or plates that are located at the leading edge of the blades. Depending on the power production of the turbine, the heating elements can consume between 1% and 15% of the energy produced by the turbine [1,6]. This consumption is usually lower than the power losses generated by ice accretion, which can be up to 50% [1,2,4,6]. However, the heating elements for wind turbines are not widely produced and have been found to be an inefficient method since they do not produce homogeneous or uniform heating of the surface, and localized ice accretion occurs in colder zones on the blades [14]. The goal of these methods, and those previously cited, is to create a layer of liquid water between the ice and the blade. After the layer of water is formed, the centrifugal force that is generated due to the rotation of the turbine rotor will propel the ice from the blade surface [16].

The use of thermal spray processes may provide an alternate method to fabricate heating systems for FRPC structures that are exposed to cold climates. Various studies have proposed the use of thermal spray processes in the fabrication of heating elements (usually referred to as resistive heaters) [17–19]. Lamarre et al. [18] have assessed and modeled the performance of FeCrAl wire-fed flame-sprayed coatings as heating elements on titanium substrates. However, the application of thermal spray processes to fabricate coatings on FRPC structures has only been recently initiated. Some investigators have deposited aluminum coatings by flame spraying on to FRPC plates that have been used in structural health monitoring systems [20]. Lopera et al. [19] have tested the performance of flame-sprayed NiCr and NiCrAlY coatings on FRPC plates as heating elements for anti-icing proposes. The study found that the metallic coatings were able to produce surface temperatures above 0 °C even at ambient room temperatures below −20 °C. However, this work did not explore the performance of the coatings as de-icing elements. Given that the coating heat source is close to or in direct contact with the substrate, burning and degradation may occur in the fiber-reinforced polymer composite substrates [20–22]. Previous studies have shown that it is possible to deposit aluminum–12 wt.% silicon (Al–12Si), with a melting point of 577 °C [22,23], on FRPCs, without significant damage to the underlying substrate. However, with the exception of Lopera et al. [19], no studies have focused on the deposition of high melting point alloys such as nickel–chromium–aluminum–yttrium (NiCrAlY), with melting points on the order of 1400 °C [24], on