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Pulse electro-thermal de-icer (PETD)

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ABSTRACT

De-icing is a process in which interfacial ice attached to a structure is either broken or melted and then the ice is removed by some sort of external force (e.g. gravity or wind-drag). Conventional thermal de-icing is effective but requires too much energy. Mechanical de-icing requires less energy but is less effective, often leaving significant amounts of ice behind, and may also damage structures and accelerate wear. We have invented, developed, and tested a pulse electro-thermal de-icer (PETD) that reduces the energy needed for de-icing by up to a factor of one hundred. PETD achieves this by melting only a thin layer of interfacial ice, leaving the temperature of the environment unchanged.

In conventional de-icers, the heater is thermally connected to the ice, the structure, and the outside environment. This makes heat losses through conduction and convection inevitable to the point where the losses exceed by orders of magnitude the amount of "useful" heat needed to melt the interfacial ice. PETD cuts these losses by using a short heating pulse – approximately 1 ms to 5s long – to heat a minimal layer of interfacial ice. This short heating time limits the heat penetration depth into both the ice and the structure. A PETD pulse heats the ice-structure interface just above the melting point causing the ice to slide off on the resulting thin water film.

PETD was successfully tested for a variety of applications including the de-icing of airplanes, car windshields, bridge over-structures, glass roofs, commercial and residential icemakers, and windmill rotors. The tests demonstrated almost instant action along with up to 99% savings of the electricity required by conventional thermal de-icers.

This paper presents the PETD method, its theory, results of computer simulations, and extensive data from laboratory tests as well as several large-scale implementations of PETD on an airplane, a bridge, a building roof (>10,000 m^2), a car windshield, and a commercial ice maker.

1. Introduction

Ice adhering to engineering structures such as bridges, wind turbines, airplanes, and power lines causes dangerous and costly problems. Two comprehensive reviews of known de-icing methods were recently published by Ryerson (2008) and by Farzaneh et al. (2008). There are three major physical mechanisms of ice adhesion: electrostatic interactions, hydrogen bonding, and Van der Waals interaction (Petrenko and Whitworth, 1999). While the first two mechanisms can be significantly reduced or even eliminated, the third one – Van der Waals interaction – is strong enough to keep ice in place and cannot be cancelled. Numerous attempts to develop a durable ice-phobic coating have all failed to decrease ice adhesion to where ice can be easily removed from the coating.

The variety of previously attempted de-icing methods fall into three main categories: mechanical, chemical, and thermal. Of those three, only the thermal methods could clean well enough without either damaging the structure or polluting the environment. However, the serious disadvantage of thermal de-icing remained: its high energy requirement. For instance, the computer modeling described in Section 2.2 below shows that the minimum energy required to melt an ice-concrete interface in still air with ice thickness of 1 cm and concrete thickness of ≥10 cm is 2 MJ/m^2 when a heating power of density 1 kW/m^2 is applied to the interface. That energy would be even bigger under windy conditions or lower power density. The above exemplary power density was chosen as typical for deicing highways, locks and some bridges. A similar power density is applied to automotive windshield deicers: 0.6 kW/m^2 to 0.8 kW/m^2. Although only the interface needs to be heated in order to remove ice, one must inevitably heat substantial masses of the ice and substrate material as well.

When heat transfer by air-convection is involved, even more energy is needed for de-icing.

The recently invented Pulse Electro Thermal De-icer (PETD) (Petrenko, 2005) avoids the high-energy requirement by melting the ice-solid interface so quickly that only small amount of heat

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escapes from the interface into environment during that very short deicing process. When optimized, PETD requires only 1% of the energy used in conventional thermal de-icing and can complete the job in less than 1 s. This technology has been used to successfully de-ice airplanes, bridges, and car windshields, and to release ice from icemakers, and defrost refrigeration evaporator coils.

2. Theory

De-icing is a process in which ice adhesion at the interface is overcome mechanically, or reduced thermally by melting, and then the ice is removed by some sort of external force (e.g. gravity or wind-drag). Mechanical de-icing requires less energy but is less effective, often leaving significant amounts of ice in the form of fragments behind, and may also damage structures and accelerate wear. Conventional thermal de-icing is effective but requires too much energy due to heat loss that exceeds by orders of magnitude the amount of “useful” heat needed to melt the interfacial ice.

The following example illustrates the above statement: Consider the de-icing of an icemaker evaporator. A typical commercial icemaker with an ice-production rate of 400 lb/24 h typically has an evaporator/ice interface area of about 0.7 m^2 and uses a compressor power of about 1 kW power for $t = 2.5$ min to 3 min to compress and adiabatically heat gaseous refrigerant that is then directed to the evaporator to perform so-called “hot-gas” deicing. The heating power density of such thermal deicing is equal to:

$$W = 1\text{kW} / 0.7\,\text{m}^2 = 1.43\text{kW} / \text{m}^2. \tag{1}$$

Sustaining such power for 2.5 min requires an energy density of:

$$Q = W \cdot t = 214.5 \cdot \frac{\text{kJ}}{\text{m}^2}. \tag{2}$$

In contrast, the “absolute minimum energy density” required to remove ice thermally from a surface is the energy needed to melt a layer of ice of thickness d that is comparable with the surface roughness:

$$Q_{\text{min}} = d \cdot q \cdot \rho_i = 3\frac{\text{kJ}}{\text{m}^2} \tag{3}$$

where $d = 10$ μm, ρ_i is ice density = 920 kg/m^3, and $q = 333$ kJ/kg is the ice latent heat of fusion. Eq. (3) is based on assuming no losses of heat into the environment, into the substrate, or into the portion of the ice that is not melted. The energy of Eq. (3) is 71.5 times less than that in Eq. (2). The high deicing energy density shown in Eq. (2) is required because the heat diffuses into the ice and the metal parts of the icemaker used in the example.

In contrast with conventional ice-melters, PETD (as well as pulse electro-thermal brake (PETB), Petrenko, 2006) melts only a thin layer of interfacial ice while limiting the above-mentioned heat-drainage mechanisms by applying the heat as a short pulse, rather than continuously. Shortening the heating-pulse duration minimizes the thickness of heated layers in both ice and substrate, thus decreasing the heat penetration/diffusion length and, hence, the thermal mass of those layers. Short pulsing also reduces heat loss into the environment. Section 5 below illustrates an advantage of PETD use to harvest ice from commercial icemakers.

Fig. 1 schematically depicts an ice/substrate interface that has a thin-film heater placed on top of the substrate. A thin layer of ice melted by the heater is also shown in the figure. Fig. 2 schematically depicts temperature distribution near the interface shown in Fig. 1 after a thin layer of interfacial ice has been melted.

With pulse de-icing the heat diffusion length is typically much shorter than the thickness of the ice and the substrate. The result, therefore, would not depend at all on the thickness of the materials.

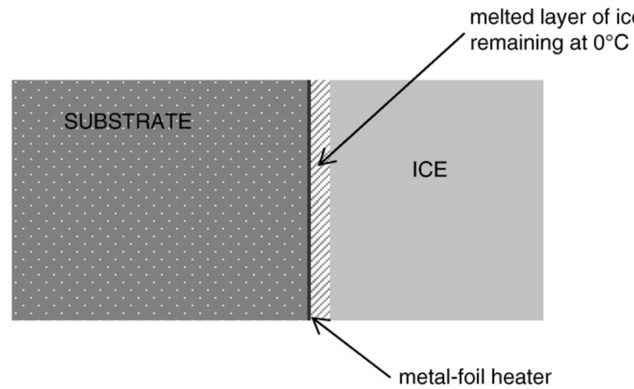

Fig. 1. Ice/heating film/substrate schematics.

To simplify boundary conditions, we can consider infinitely thick layers of the materials, and we can also break the mathematical problem into two halves:

1) Heating the ice/heater interface from an initial temperature, T_0, to the ice-melting point, $T_\text{m} = 0$ °C.
2) Melting interfacial ice. In this case, due to the large latent heat of ice melting, q, we can assume that the interfacial temperature remains almost constant at $T = 0$ °C, as shown in Fig. 2.

Mathematically, the problem in #2 is similar to the problem of a “constant surface temperature” time-dependent heat-conduction problem, but with a different set of initial conditions. After the heating power is “off,” the melted layer refreezes.

2.1. Analytical method

Consider a simpler problem of a semi-infinite layer of ice, $0 \leq x < +\infty$. The surface at $x = 0$ is heated with a power density W (W/m^2) starting at time $t = 0$. Let us first neglect the small heat capacity of a thin-film heater. The temperature in the ice is $T(x,t)$ and it obeys the heat diffusion equation:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha_i}\frac{\partial T}{\partial T}, \qquad x > 0 \tag{4}$$

where α_i is the thermal diffusivity coefficient of ice:

$$\alpha_i = \frac{k_i}{\rho_i C_i} \tag{5}$$

where k_i is the ice's thermal conductivity, ρ_i is ice density, and C_i is the specific heat capacity of ice.

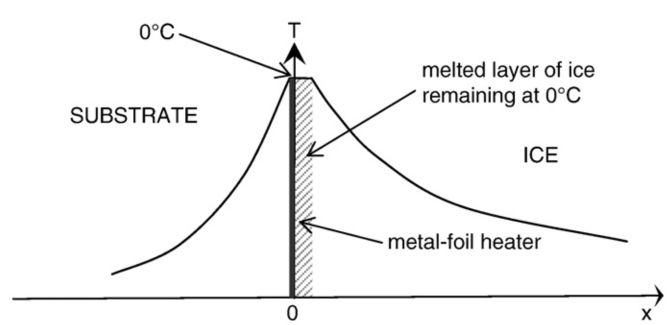

Fig. 2. Temperature distribution near an ice/substrate interface during formation of a melted layer. This picture implies constant temperature in the metal and in a thin water film. T is the temperature and x is the distance from the interface.