Analytical model based on experimental data of centrifuge ice adhesion tests with different substrates

Frederic Guerin *, Caroline Laforte, Marie-Isabelle Farinas, Jean Perron

Anti-Icing Materials International Laboratory, University of Quebec at Chicoutimi, 555 blv. Université, Chicoutimi, QC G7H 2B1, Canada

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ABSTRACT

This paper proposes an analytical model of the adhesion shear stress of non-confined accreted ice on different substrates. The model is based on the existence of an amorphous liquid-like layer (LLL) at the substrate/accreted–ice interface adhering by capillary forces. This analytical model includes both substrate properties and icing parameters but is limited to rigid substrates. For the preliminary validation of this model, 54 centrifuge adhesion tests (CAT) were performed to measure ice adhesion of accreted ice on three different substrates at different temperatures. The validation strategy uses the proposed model to calculate the nucleation time of water droplets upon impact with the substrate to fit with experimental results. These nucleation times were calculated and found to be in accordance with theory and available literature data, showing that this new approach involving the LLL seems promising.

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1. Introduction

Industry is always seeking new and innovative solutions to icing problems encountered in cold climates. Over the years, various deicing methods, active or passive, mechanical or thermal, have been developed so as to ensure maximum reliability of various transport networks: electricity, aerospace, telecommunication, maritime, etc. (Laforte et al., 1998). Despite the numerous efforts made up to now, a simple, effective, and inexpensive deicing technique has yet to be found. The ideal solution would probably be a material that can prevent ice accumulation on all types of surfaces, and some icephobic substrates may reduce ice adhesion (Anderson and Reich, 1997; Laforte and Laforte, 2002; Laforte et al., 2014; Susoff et al., 2013). At present, the reduction obtained in a few cases is sufficient to prevent ice from accumulating, or to cause natural shedding. Unfortunately, for the best ice adhesion reducers, the icephobic effect is not permanent. It is still sought to develop tools that could assist researchers in the overall improvement of coating performances. To this end, an analytical model depicting the relation between coating parameters and ice adhesion would be a useful tool.

1.1. Ice adhesion

The mechanical properties of ice, including the strength of its adhesion to surfaces, depend on numerous factors, including the environmental parameters that determine grain size and porosity (temperature, wind velocity, liquid water content, droplet size, the nature of ice, cold box, or atmospheric). Regarding ice adhesion, parameters related to the substrate need to be considered: surface characteristics (roughness, water superficial tension or contact angle, cleanness) and substrate properties (stiffness, geometry, etc.). Moreover, the measuring method itself or the way that the ice is mechanically solicited influence the strength of the adhesion (Laforte and Laforte, 2012). In fact, at − 10 °C, ice adhesion strength values on metallic surface vary considerably, depending on methodology and type of ice, ranging between 0 and 2 MPa (Laforte and Laforte, 2002; Makkonen, 2012).

1.2. Mechanisms of adhesion

The literature identifies two main mechanisms that may explain ice adhesion: mechanical and electrostatic.

1.2.1. Mechanical

Ice adheres to surfaces by anchoring to the surface asperities of the substrate. Thereby, adhesion increases with surface roughness. Indeed, the increase in roughness increases the number of possible anchoring sites. This is the conclusion reached by Saito et al. (1997). However, he states that high levels of roughness will lead to a decrease in ice adhesion. This reduction is in fact caused by the increase in the number of air bubbles present at the ice/coating interface. The viscoelastic properties of the substrate may also affect the mechanical adherence of ice (Andrews et al., 1984), which can be reduced on a flexible substrate (Landy, 1967).

1.2.2. Electrostatic

For this mechanism, ice adhesion strength would be caused by inter-molecular bonds, mainly van der Waals bonds. To study the effect of intermolecular bonds at the ice/substrate interface, the surface tension of the substrate is calculated from the measured contact angle of water. As the water contact angle increases, its wettability and chemical affinity with water decrease, causing ice adhesion to decrease (Andersson et al., 1994; Dotan et al., 2009; Yoshida et al., 1991). This model would explain the dependence of adhesion on ice temperature (Ryzhkin and Petrenko, 1997).

These two mechanisms partly describe the ice adhesion phenomena because they are limited to one aspect of ice adhesion phenomena and are not related each other. The new approach proposed in this paper would be an integration of those two mechanisms.

1.3. Liquid-like layer (LLL)

The mechanism proposed for the understanding of ice adhesion is the presence of a liquid-like layer at the ice/substrate interface, consisting of an amorphous layer of water molecules. In 1859, Michael Faraday, British physicist and chemist, postulated that ice surfaces are covered with a thin water film (Faraday, 1859). The presence of this film is due to the reduced number of chemical bonds at the surface of the ice crystal lattice, where they form an amorphous layer in order to minimize the surface energy (Rosenberg, 2005). This layer of amorphous molecules, called liquid-like layer, is present both at the free ice surface and between ice and substrate. Several experiments have been performed to verify and confirm this assumption (Dash et al., 1995; Döppenschmidt and Butt, 2000; Dosch et al., 1995; Engemann et al., 2004; Gilpin, 1980; Hobbs, 1974; Kouchi et al., 1987; Mezger et al., 2008). Döppenschmidt and Butt (2000) have measured the LLL thickness at the ice free surface using an atomic force microscopy and obtains thickness in the nanometer range. Gilpin (1980) and Engemann et al. (2004) have measured values in the same order of magnitude for thicknesses at the ice/substrate interface using wire regelation and high-energy x-ray transmission reflection, respectively. This paper proposes a new approach to explain the adhesion of accreted ice, on the basis of which an analytical ice adhesion model using the liquid-like layer theory is elaborated, taking into consideration the surface property of the substrate. The model is validated experimentally using centrifuge ice adhesion tests with non-confined accreted ice samples solicited by shearing on three different substrates, at different temperatures.

2. The model

2.1. General equations

The model is based on the presence of an amorphous ice layer, called liquid-like layer, between ice crystals and substrate surface. Fig. 1 illustrates the LLL between ice and substrate.
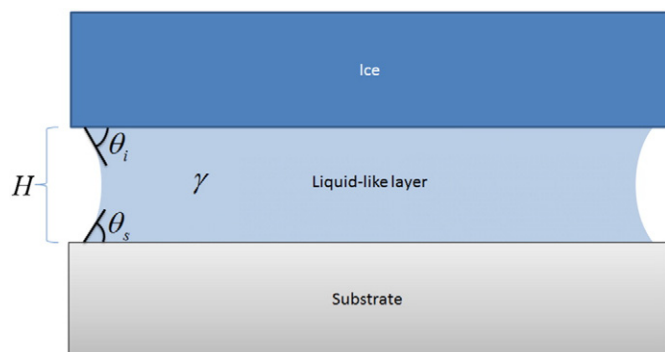

Fig. 1. Representation of a liquid-like layer between ice and substrate.

A thin liquid layer between two solid plates can work as an adhesive. The adhesion of accreted ice on a substrate is then supposed to be mainly due by the capillary forces created by this LLL. The capillary force being simply the result of the pressure difference, ΔP, across the curved liquid/air interface:

$$\Delta P = \frac{\gamma}{r_{\mathrm{m}}} \tag{1}$$

where γ is the surface tension of the water (N/m) and r_{m} is the meniscus radius (m). When the contact is heterogeneous, involving two different plates, the pressure difference is calculated as follows (Cai and Bhushan, 2008; Jellinek, 1962):

$$\sigma_{\mathrm{ad}} = \Delta P = \frac{2\gamma(\mathrm{Cos}\,\theta_i + \mathrm{Cos}\,\theta_s)}{H} \tag{2}$$

where θ_i, θ_s, and H are the contact angle between ice crystals and the LLL, the contact angle between the LLL and the substrate, and the thickness of the LLL, respectively.

When ice is mechanically solicited in shear, the separation of the ice from the substrate surface produces both meniscus and viscous forces, which operate inside the LLL. The implication of this viscosity in the ice adhesion phenomena is already demonstrated by its sensitivity to deformation rates (Jellinek, 1959). However, at the strain rate prevailing in the centrifuge test used to determine adhesion stress, ice behavior is considered fragile, thus independent to the rate. Because of this, the viscosity of the LLL was simplified to a friction phenomenon. To obtain the adhesion shear stress, τ_{ad}, the normal stress, σ_{ad}, is considered to be the normal force acting on the substrate, related to shear by coefficient α, and acting like a friction coefficient according to the following relation:

$$\tau_{\mathrm{ad}} = \alpha\sigma_{\mathrm{ad}} \tag{3}$$

A definition of the dimensionless coefficient, α, is proposed in Eq. (4), involving two parameters:

- Substrate-related parameters: R_{Sm} (m) is the mean spacing of profile irregularities, and R_a (m), the average roughness.
- Icing-related parameters: t_n (s) is the average nucleation time of droplets upon impact with the substrate, MVD (m), their median volume diameter, and U (m/s), their impact velocity.

$$\alpha = \frac{R_{\mathrm{Sm}} \cdot R_a}{\mathrm{MVD} \cdot U \cdot t_n} \tag{4}$$

The final equation (Eq. (5)) is derived from the definition of the critical shear stress needed to break the interfacial adhesion of accreted ice for different icing conditions and substrates.

$$\tau_{\mathrm{ad}} = \frac{2 \cdot R_{\mathrm{Sm}} \cdot R_a \cdot \gamma \cdot (\mathrm{Cos}\,\theta_i + \mathrm{Cos}\,\theta_s)}{\mathrm{MVD} \cdot U \cdot t_n \cdot H} \tag{5}$$

In this equation, the water surface tension, γ (Hacker and U.S.N.A.C.f., 1951), meniscus angle between LLL/bulk ice, θ_i (Makkonen, 1997), and LLL thicknesses, H (Döppenschmidt and Butt, 2000), are evaluated from literature values, while the meniscus angle between LLL and substrate, θ_s, mean spacing, R_{Sm}, average roughness, R_a, droplet median volume diameter, MVD, droplet impact velocity, U, and finally critical shear stress, τ_{ad}, are experimentally measured. Moreover, only the nucleation time, t_n, remains unknown.

In order to initially validate the model, inverse calculations are used where ice adhesion strength is first measured at different temperatures on different substrates, from which the value of one average nucleation time per substrate is calculated for all temperatures, according to Eq. (5). This paper discusses the validity of these time results based on available experimental data in literature with regard to the general behavior of the model.