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The influence of freezing and ambient temperature on the adhesion strength of ice

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ABSTRACT

Glaze ice adhesion on transmission lines and aerofoils causes structural and economic damage. The effects of surface roughness, contact angle parameters, liquid water content and the size and rate of adhering droplets affect the adhesion strength of ice, which is typically considered to be both mechanical and electrostatic in nature. Using a spinning centrifuge, we determine adhesion strength for three different metals while altering "freezing temperature", the temperature at which glaze ice forms; and "ambient temperature", the temperature of the surrounding during the test. Results indicate that the effect of the ambient temperature is much greater than the freezing temperature on the adhesion strength of ice. The reason for this is the presence of an amorphous liquid-like layer at the ice-substrate interface, whose bond with the substrate is strengthened at lower ambient temperatures when the substrate conducts heat much faster than the ice and acts as a heat sink. Future tests envisaged focus on thermally non-conducting substrates and their influence on adhesion strength.

1. Introduction

Ice formation on telecommunications, power lines and aircraft wings affects transmission characteristics, aerodynamic control and results in economic loss due to infrastructure damage or enhanced fuel usage in flight. Glaze ice tends to have a greater effect on these factors than rime ice in most circumstances. The former can occur when supercooled droplets impact a surface and flow back before freezing. Alternatively, glaze ice can form due to the freezing of left over water on the surface. It is hard, sticky and has an absence of air pockets within the ice matrix (Politovich, 2003).

Literature refers to several techniques to measure ice adhesion (Kasaai and Farzaneh, 2004; Anderson and Reich, 1997; Susoff et al., 2013; Gohardani and Hammond, 2013; Kraj and Bibeau, 2010), but the centrifuge technique has been found most suitable due to rapid adhesion strength calculation, low variability (18%) (Laforte and Beisswenger, 2005) and easy design. Using the centrifuge technique, several researchers (Laforte and Beisswenger, 2005; Kulinich and Farzaneh, 2009; Bharathidasan et al., 2014) were able to obtain the influence of contact angle and surface roughness parameters on the adhesion strength of glaze ice. The findings indicate that low contact angle hysteresis and surface roughness contribute towards reducing ice adhesion. Saito et al. (1997) mentioned that beyond a limit, high surface roughness contributes to lowering ice adhesion strength due to the incorporation of air bubbles at ice-surface interface. Momen et al. (2015) also studied the effect of atmospheric icing conditions such as liquid water content and droplet size on adhesion strength. They found that lower liquid water content and smaller droplet size reduced adhesion strength. However, the quantified influence of altering temperature conditions on the adhesion strength of ice has yet to be fully understood.

In this regard, we define two separate temperature conditions involved in the adhesion testing of ice: "freezing temperature" and "ambient temperature". The freezing temperature refers to the temperature of the surroundings during the freezing process of the glaze ice. Ambient temperature on the other hand, refers to temperature of the surroundings at the time of centrifugal detachment. The temperature of the rotor or the "beam temperature" was assumed to be the same as the environmental chamber. The aim of this paper is to quantify the effect if any, of these two temperature conditions on the adhesion strength of ice using four different freezing/ambient temperature combinations on three different types of substrates. Contact angle hysteresis (CAH) and surface roughness have been measured prior to testing to permit correlation with previous work.

2. Experimental procedure

Fig. 1 exhibits the top view of the centrifuge schematic for the adhesion tests. The stainless steel cylindrical drum is 300 mm deep and has a diameter of 500 mm. A motor is located underneath the drum floor, 150 mm below its top rim, and the shaft passes through the floor (see Fig. 2). This device was placed in a temperature-controlled

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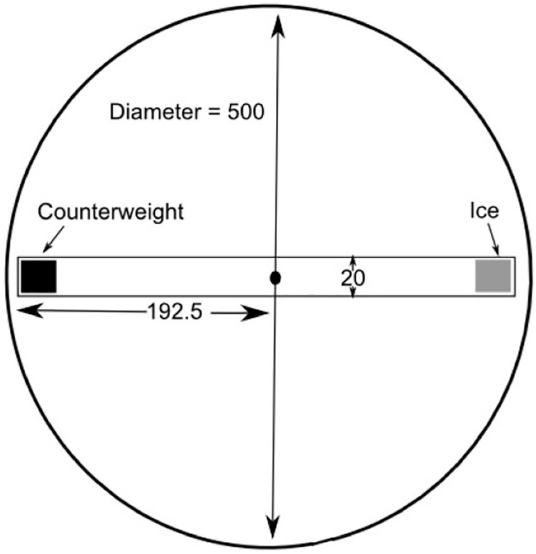

Fig. 1. Schematic of top view of centrifuge setup for adhesion tests. All values are in mm.

Fig. 2. Photograph of the centrifuge ice adhesion measurement system. The left end of the rotor shows the counterweight attached while the right end is the substrate on which ice is to be grown.

chamber - Design Environmental ALPHA 1550-40H (see Fig. 3). The spinning arm has a radius of 192.5 mm and width of 20 mm with a thickness of 3 mm. A counter weight is attached to one end of the arm (to prevent vibrations during spinning) while the other end of the arm has glaze ice grown on the substrate. When the arm is spun with increasing rotation rate, the centripetal acceleration on the ice sample overcomes the adhesion strength of the ice to the substrate, and the ice shears off the substrate. The adhesion strength of ice can be calculated as $F = m\,r\,\omega^2$ where m is the mass of ice, r is the rotor length and ω is the speed of rotation at detachment in rpm·s^{-1}. As a shear stress, the adhesion stress $\tau = F/A$, where A is the ice/substrate contact area. The substrate dimensions are 50 × 20 × 3 mm with counter sunk holes to take M4 thread 12 mm screws (see Fig. 4).

A servo motor (MOOG G403-2053A) drove the rotor from 0 to 4500 rpm at 30 rpm/s acceleration. The motor was chosen because of its efficient performance at low temperatures and the ability to prevent condensation from affecting its functioning. Attached to the drum floor was an accelerometer (RS-online 759-1994 70 g accelerometer 22 kHz iMEMs CLCC8) which along with a microphone was used to measure the time of detachment. The voltage output is viewed via an NI USB6212 DAQ system. Glaze ice was uniformly created by freezing de-ionised 18 MΩ UltraPore UV (ultraviolet) filtered water in a cuboid silicone (with dimensions 25 × 15 × 10 mm) as the substrate plate was

Fig. 3. Photograph of environmental chamber.

placed upside down on it for 24 h at a fixed temperature in an insulated box inside the environmental chamber. Fig. 5 shows the schematic description of glaze ice formation on the substrates. The substrates were transferred to the rotor inside the same environmental chamber at the "freezing temperature" after 24 h. If the freezing and ambient temperature differed, the temperature value on the environmental chamber was adjusted. The change in temperature occurred at a rate of 0.1 °C per 5 s; hence the effective settling time between the attachment to the rotor and the start of the test was 250 s or 4 min 10 s. Latex gloves were used to attach the substrates to the rotor and the remaining substrates were placed inside an insulated box to prevent the changes in environmental chamber from affecting adhesion strength. It is extremely important to ensure that upmost care is taken while handling the substrates with ice attached to prevent any unwarranted heat transfer; thereby affecting adhesion characteristics. Each substrate was tested once for each of the four freezing-ambient temperature conditions.

3. Substrate characterisation

A total of thirty substrates were prepared with identical dimensions from the following three materials for the test purposes (ten each): stainless steel (SS) 304, aluminium (Al) 6082 with temper T651 and aluminium 1050A with temper H14. Ice was grown on the ten stainless steel 304 substrates at both − 5 °C and − 10 °C for 24 h to measure m. At − 5 °C, the average ice weight was found to be 3.47 ± 0.05 g and at − 10 °C, the average ice weight was found to be 3.43 ± 0.06 g. Since both values are within error limits of the other because we are creating freezer ice, the sample ice mass can be assumed to be independent of freezing temperature and the overall ice weight m was taken as an average of twenty samples i.e. 3.45 ± 0.06 g. The r (perpendicular distance of the rotor axle to the ice sample centre of mass) is 175 mm and A (the contact area) is 375 mm^2 (25 × 15 mm). To calculate adhesion strength τ, we only need ω at the point of detachment measured in rpm/s.

Surface roughness was measured using a Taylor and Hobson Form Talysurf50 profilometer at 20.2 °C room temperature and relative humidity 57.7%. The least squares line method was employed with a critical wavelength λ_c of 0.8 mm, cut off wavelength λ_s of 0.0025 mm and a bandwidth of 300:1 (ISO 4288-1996). For each substrate, a single 15 mm assessment length along the cross-sectional width (7.5 mm either side of the centre point) was chosen. The sessile drop technique