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THE ACCRETION OF MIXED ICE ON AN AIRCRAFT WING DUE TO THE PARTIAL FREEZING OF IMPINGING SUPERCOOLED DROPLETS

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INTRODUCTION

Ice accretion is a problematic natural phenomenon that affects a wide range of engineering applications including power cables, radio masts and wind turbines. Accretion on aircraft wings occurs when supercooled water droplets freeze instantaneously on impact to form rime ice or runback along the wing to form glaze ice. This ice formation dramatically alters the friction characteristics of the surface, leading to variations in drag over short time scales. Icing models to date have replicated accretion rates with varying amounts of success [[5],[1],[2]] but the formation of mixed ice, which is a combination of rime and glaze, is yet to be explained although it is frequently viewed in nature under suitable atmospheric conditions. An improvement to the previous commercial icing codes such as LEWICE, TRAJICE and ONERA, the ICECREMO code has been developed over a number of years to include the effect of the dynamic behaviour of the runback water film on the accretion rate and will form the basis for our numerical analysis.

We hypothesise that the formation of mixed ice on an aerofoil occurs due to the partial freezing of impinging supercooled droplets that deposit onto the growing interface as rime particles within a mushy layer [3]. The mushy layer acts as a porous medium containing solid rime particles saturated by water. Underneath this, at the water-ice interface, the solidifying liquid then entrains the rime particles into a glaze matrix to form mixed ice. The purpose of pursuing this research is to determine more accurately the growth rate of ice and also the correct type of ice formation based on parametric conditions to ensure more efficient energy use from electro-thermal mats near the leading edge of the wing. Models that do not include the mushy layer typically over-estimate ice accretion. We envisage the mushy layer behaves as a insulating region regarding the growth of the ice layer.

MASS AND ENERGY BALANCE

The solid mass balance of the system is given by

$$\lambda \dot{M} = \phi \rho_w \frac{\partial h}{\partial t} + \phi \rho_i \frac{\partial b}{\partial t}, \tag{1}$$

where λ is a dimensionless term defined as the fraction of a supercooled droplet that freezes on impact with the interface, ϕ is the solid fraction of the water layer, h and b are the heights of the liquid and ice layer respectively, ρ_i and ρ_w are the densities of ice and water respectively and $\dot{M}$ is the mass flux of impinging supercooled droplets. For simplicity we start by considering a one-dimensional system. Conversely, the liquid mass balance is given by

$$(1-\lambda)\dot{M} = (1-\phi)\rho_w \frac{\partial h}{\partial t} + (1-\phi)\rho_i \frac{\partial b}{\partial t}. \tag{2}$$

The growth of the mushy layer is thus

$$\phi \rho_w \frac{\partial h}{\partial t} = \rho_r \frac{\partial m}{\partial t}, \tag{3}$$

where ρ_r is the density of rime ice and m is the height of the mushy interface. m is essentially determined by the rate of deposition of rime particles versus the rate of entrainment of rime particles into the solidifying matrix. An expression for the solid fraction of the mushy layer ϕ_m can be given by the difference in densities of rime and water in the water continuum

$$\phi_m = \lambda \frac{\rho_w - \rho_r}{\rho_w - \lambda \rho_r}. \tag{4}$$

This assumes water only comes from the droplets though. A modified Stefan condition [3] is imposed at the solidifying interface to account for the presence of a mushy layer which forms the solid fraction of the water layer,

$$\rho_i L_f \frac{\partial b}{\partial t} = k_i \frac{\partial T}{\partial z} - k_t \frac{\partial \theta}{\partial z} \tag{5}$$

there L_f is the latent heat of fusion, k_i is the thermal conductivity of ice, T and θ are the temperatures in the ice and

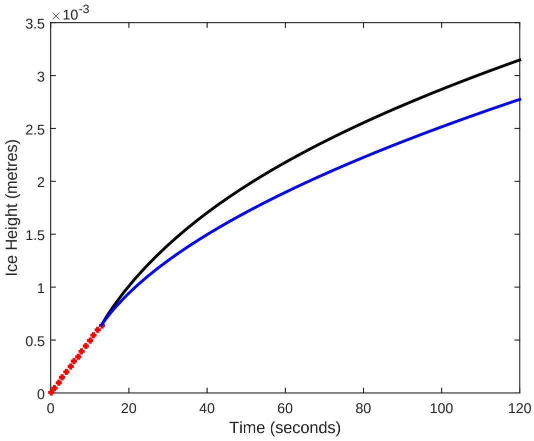

Figure 1: Ice growth vs. time for one-dimensional accretion of Myers and Charpin (2004)'s model [5] [black line] and authors' model [blue line] for air temperature -5°C and freezing fraction $\lambda = 0.3$.

water layers respectively and k_t is the bulk thermal conductivity of water at the Stefan interface and is a function of ϕ and k_w (thermal conductivity of water). The individual equations for calculating T, θ and λ along with the respective boundary conditions will be detailed in a future paper. When $\lambda = 1$, we have rime ice growth; and when $\lambda = 0$, we revert back to the original mass and thermal balances in the ICECREMO code [5].

RESULTS

The MATLAB Runge Kutta ode45 was used to solve equations 1, 2 and 5 to determine the ice growth with respect to time. λ was assumed constant to simplify the solution but in reality, it will be dependent upon a variety of parameters including the temperature and size of the supercooled droplet, the water-air interface temperature and the free stream (i.e. aircraft) velocity. Figures 1 and 2 compare the ice growth rate for Myers and Charpin (2004)'s model [5], the basis of ICECREMO assuming runback glaze ice accretion, with this mixed ice model. For accretion on an aircraft wing, even at warmer temperatures, initially only rime ice will form which is represented by the red dots. This region is characterised by solid crystal growth directly on the surface, with the liquid water as either runback or otherwise present in the matrix. At a particular time, a transition will occur from rime to glaze/mixed ice.

ANALYSIS

From figures 1 and 2, it is apparent that the proposed mixed ice model predicts lower ice accretion rates than previous descriptions. We conjecture that the mixed ice in a 'mushy layer' has an insulating influence on heat transfer from the freezing front. This is because the ice growth rate is essentially determined by the heat flux across the Stefan interface. A higher value of λ, which will occur for either very cold ambient conditions or small supercooled droplets, will ensure a larger amount of latent heat is lost before the droplet reaches the Stefan interface, thus over predicting the growth rate of ice. In a thesis on a multi-stepping scheme of the ICECREMO code, one of the problems mentioned with current icing codes was listed as the over prediction of ice growth during the accretion process [4].

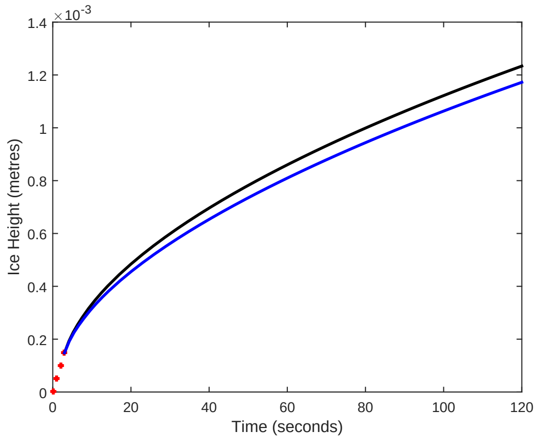

Figure 2: Ice growth vs. time for one-dimensional accretion of Myers and Charpin (2004)'s model [5] [black line] and authors' model [blue line] for air temperature -1°C and freezing fraction $\lambda = 0.1$.

CONCLUSION AND FUTURE WORKS

A simple-one dimensional ice accretion model has been developed. A dimensionless parameter λ has been introduced to account for the accretion of mixed ice on an aerofoil in nature. The model predicts lower ice accretion rates than the ICECREMO code, in line with observations on real aircraft.

Future work will include a detailed study of the energy balance of the freezing process that governs λ, to include the effects of atmospheric conditions. The model will be expanded to account for two-dimensional accretion on an aircraft wing. Eventually, a detailed model will reduce energy requirements for de-icing electro-thermal mats by determining the correct type of ice formation under a given set of parameters.

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