JOURNAL OF AIRCRAFT
Vol. 46, No. 5, September–October 2009

# Multistep Results in ICECREMO2

P. Verdin*
*Cranfield University, Cranfield, Bedfordshire MK43 0AL, United Kingdom*
J. P. F. Charpin†
*University of Limerick, Limerick, Ireland*
and
C. P. Thompson‡
*Cranfield University, Cranfield, Bedfordshire MK43 0AL, United Kingdom*

DOI: 10.2514/1.41451

**Multistep versions of the aircraft icing code ICECREMO2 are investigated. Several multistep algorithms are presented and tested on a NACA0012 wing in rime and glaze ice conditions. The resulting ice layers are compared with experimental results and the efficiency of each algorithm is discussed. The step-by-step algorithm with an ice height criterion provided the most time-efficient solution in glaze ice conditions.**

## Nomenclature

$b$ = ice layer thickness, m
$c$ = chord length, m
$c_a$ = specific heat capacity of air, $\mathrm{J\,kg^{-1}K^{-1}}$
$c_i$ = specific heat capacity of ice, $\mathrm{J\,kg^{-1}K^{-1}}$
$d_d$ = droplet diameter, m
$E$ = heat balance coefficient, $\mathrm{K\,m^{-1}}$
$e_0$ = vapour pressure constant, $\mathrm{Pa\,K^{-1}}$
$e_*$ = unit vector in the $x$, $y$, and $z$ directions, ND
$F$ = heat balance coefficients, $\mathrm{m^{-1}}$
$g$ = acceleration due to gravity, $\mathrm{m\,s^{-2}}$
$H$ = heat transfer coefficient at the ice air interface, $\mathrm{W\,m^{-2}\,K^{-1}}$
$h$ = water layer thickness, m
$L_f$ = latent heat of fusion, $\mathrm{J\ kg^{-1}}$
ND = nondimensional
$n_{\mathrm{step}}$ = number of multi time steps
$Q_x$ = $x$ component of the water flux, $\mathrm{m^2\ s^{-1}}$
$Q_y$ = $y$ component of the water flux, $\mathrm{m^2\ s^{-1}}$
$r$ = local recovery factor, ND
$T$ = temperature in the ice layer, K
$T_f$ = freezing temperature, K
$T_s$ = substrate temperature, K
$T_\infty$ = freestream temperature, K
$t$ = time, s
$t_{\mathrm{exp}}$ = exposure time, s
$V_\infty$ = freestream velocity, $\mathrm{m\,s^{-1}}$
$X$ = ice height to chord length ratio, ND
x,y = Cartesian coordinates, m
$\beta$ = collection efficiency, ND
$\theta$ = temperature in the water layer, K
$\kappa_i$ = thermal conductivity of the ice, $\mathrm{W\,m^{-1}\ K^{-1}}$
$\kappa_w$ = thermal conductivity of the water, $\mathrm{W\,m^{-1}\ K^{-1}}$
$\mu$ = dynamic viscosity, $\mathrm{kg\,m^{-1}\ s^{-1}}$
$\rho$ = cloud liquid water content of air, $\mathrm{kg\,m^{-3}}$
$\rho_i$ = density of the ice, $\mathrm{kg\,m^{-3}}$
$\rho_w$ = density of the water, $\mathrm{kg\,m^{-3}}$
$\tau_x$ = $x$ component of the shear stress, Pa
$\tau_y$ = $y$ component of the shear stress, Pa
$\chi$ = evaporation coefficient, $\mathrm{m\,s^{-1}}$

## I. Introduction

ICE accretion is a major concern for aircraft manufacturers. Over the years, numerous incidents or accidents have occurred because of ice growing on key parts of the plane [1,2]. To limit the consequences of ice accretion and guarantee safety, manufacturers are required to test all aircraft for icing and equip them with adequate anti-icing or deicing systems. Computer codes are used to assist manufacturers with design and certification work required by the aircraft industry. The first aircraft icing codes to appear were NASA Lewis Ice Accretion Prediction Code (LEWICE) developed by NASA in the United States, Trajectory and Ice Accretion Code (TRAJICE) in the United Kingdom, engineered by what has now become QinetiQ, and Office National d'Etudes et de Recherches Aérospatiales (ONERA) in France [3–5]. Italian and Canadian codes, among others, appeared later [6–9]. At first, all the codes were based on the work of Messinger [10]. This model, developed in the fifties, proved quite successful. However, weaknesses have been found [11]: the Messinger model overestimates the ice growth and the error increases with the ambient temperature. With this original model, the ice formation is not affected by the existing ice layer, the ice growth rate is constant throughout the simulation and the fluid flow depends on the size of the mesh chosen for the simulation. Some of these difficulties were partially addressed by the various development teams. All these problems could only be solved simultaneously with a new model detailed in [12,13]. This improved model is used in the icing code called ICECREMO2, developed by a number of companies in the United Kingdom (see acknowledgments).

Icing occurs in cold and wet conditions. In this situation, the cloud droplets can be in a liquid state, although their temperature is below freezing. When droplets hit the aircraft wing, they turn to ice almost instantaneously and form what is known as rime ice. In mild conditions and once the rime ice layer is thick enough, part of the impinging droplet may remain liquid and form a thin film that runs back over the ice layer [14]. The ice formed in these conditions is known as glaze ice. Icing codes reflect these two different possibilities and flow parameters necessary for each phase must be calculated.

When simulating an ice shape, physical parameters influencing the accretion (shear stress, heat transfer coefficient, and water droplet trajectories) are first evaluated on the clean uniced airfoil at the beginning of the calculation and are held constant during the entire

---

Received 8 October 2008; revision received 2 April 2009; accepted for publication 2 April 2009. Copyright © 2009 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0021-8669/09 and $10.00 in correspondence with the CCC.

*Lecturer/Research Fellow, Applied Mathematics and Computing, School of Engineering.

†Senior Research Fellow, Mathematics Applications Consortium for Science and Industry, Department of Mathematics and Statistics.

‡Professor, Applied Mathematics and Computing, School of Engineering.