Numerical procedure for electro-thermal anti-icing system simulation coupling internal thermal analysis and external multi-physic code

A. Carozza 1, F. Petrosino 2 and G. Mingione 3
CIRA Italian Aerospace Research Center, Capua (CE), Italy

Abstract. The present work has the aim of coupling two codes, one able to perform icing simulations and another one capable to simulate the performance of an electro–thermal anti-icing system in an integrated fashion. In fact, the classical tool chain of icing simulation (aerodynamics, water catch and impact, mass and energy surface balance) is coupled to the thermal analysis through the surface substrate and the ice thickness. In general, the substrate consists of a multi-layered composite with different properties for each layer and embedded heaters (resistors) at interfaces between layers. In the present approach, the ice protection simulation is not decoupled from the ice accretion simulation, but a single computational workflow is considered. Validation results obtained on benchmark test cases from NASA database will be detailed as well as comparison with numerical results from other authors.

1. Introduction
The formation of ice on aircraft components caused several problems for in-flight safety. Liquid water droplets may exist in supercooled conditions up to -40°C, remaining in an unstable state until they meet an external disturbance, e.g. the impact with an aircraft surface. Depending on the environment and surface substrate conditions, the supercooled droplets may freeze immediately upon contact, partially stick and partially being ejected over the body (splashing, rebounding), deposit and flow along the surface (runback). In case of severe ice accretion, the aerodynamics of the aircraft surface can be severely deteriorated, leading to a decrease in lift and controllability and an increase in drag. Ice protection systems (IPS) are usually designed to prevent ice accretion (anti-icing systems) or to restore clean conditions (de-icing systems). Anti-icing systems act to increase the surface temperature above the freezing point, allowing the caught water mass to flow downstream (running-wet anti-icing) or to evaporate (evaporative anti-icing). De-icing systems, instead, are used when a limited amount of ice has already accreted on the aircraft surface, decreasing the adhesion forces by de-bonding the inner ice layers and letting the aerodynamic forces remove the detached ice fragments. The heat required by the anti-icing systems is usually provided by electrical heaters embedded within the surface metal skin (electro-thermal anti-icing) or by hot air coming from the engine bleed system and impinging on the internal surface of the metal skin (hot-air anti-icing). De-icing systems

1 Researcher, Mechanic of Fluid department
2 Researcher, Mechanic of Fluid department
3 Head, Mechanic of Fluid department
may be of different kind: mechanical (pneumatic boots), electro-thermal or electro-mechanical. Numerical simulation represents a fundamental step inside the design process of an anti-icing system and for the reduction of the experimental testing burden. This paper presents a novel coupling procedure to connect two different phenomena: the aero-thermodynamics on the airfoil surface and the heat conduction through the airfoil skin where some heaters are allocated.

2. Numerical Methodology

2.1. Termico

Termico [10] is an ice protection simulation code developed by CIRA, the Italian Aerospace Research Centre, and validated to perform the design of aircraft de-icing and anti-icing systems using electrical devices. It has been written in FORTRAN and includes the possibility of thermal sources and different boundary conditions. Furthermore, it requires as an input a file containing the grid points related to the distribution of different materials and including their density, conductivity and specific heat.

2.2. Multi-Ice

MULTI-ICE code [6] is a scientific software package for the evaluation of the ice accretion on 2D airfoils, developed by CIRA in a user-friendly environment. The aim is to provide a powerful tool for the prediction of the ice shape. The code can evaluate the ice accretion on single or multi-element airfoils (airfoils with slat or flat) and on 2D nacelles, performing the aerodynamic analysis using a potential panel method (symmetric singularities); otherwise, it can be interfaced with more complex aerodynamics solvers. The droplet trajectories and the impingement are calculated using a 4th order Runge-Kutta integration, while the ice accretion evaluation is based on the classical Messinger model [2, 9].

2.3. Coupling between Termico and Multi-Ice

The coupling procedure is conceived to balance the total heat lost due to the external flow phenomena (evaporation, convective cooling, impingement, freezing) and the heat flux provided by the internal anti-icing system. The convergence metric is the effective heat transfer coefficient which is exchanged between the two zonal solutions. This reflects the physical principle that the external solution is influenced by the conduction heat transfer at the surface, as the ice protection system provides a heat flux to increase the local temperature, and simultaneously the solution of the heat conduction problem depends on the overall heat transfer which takes place on the surface. A procedure for coupling Termico and Multi-Ice codes has been written and validated. It is based on the following steps:

(i) Initialization step: the anti-icing heat source is initialized to null and the effective heat transfer is assumed as purely convective

\[ Q_{ai,m} = 0 \text{ and } h_{eff,m} = h_c \]

(ii) First step in Multi-Ice: Messinger model solution

(iii) Exchange parameter evaluation: the effective heat transfer coefficient is estimated by considering the total heat lost on the surface as

\[ h_{eff,c} = \frac{(Q_c(T_{s,m}) + Q_{evs}(T_{s,m}) + Q_f + Q_{sh}(T_{s,m}) + Q_{kin})/(T_{s,m} - T_\infty)}{Q_{w,hc}} = h_{eff,c}(T_{s,c} - T_\infty) = -k_w \delta T_{hc}/\delta n \]

where \( T_{s,c} \) is the new value of the surface temperature.
(v) Convergence check: if the value $\|h_{\text{eff},c} - h_{\text{eff},m}\|^2 < \epsilon$, convergence is assumed and the solution of the coupled problem is found; otherwise $h_{\text{eff},m} = h_{\text{eff},c}$ and $Q_{\text{ai},m} = q_{w,c} \cdot St$ and one more iterative step is performed going back to point 2.

This workflow is inspired to [7], this paper describes a new procedure for coupling a heat conduction opensource code and a Messinger code developed by CIRA in unsteady way. Such a procedure is able to consider not only more cycles of heating but also different laws of heating. So, it can be useful in a design approach.

3. Results and Discussion
In order to validate this interface, two test cases are considered and presented in the following paragraphs, the first one related to a running wet condition and the second one related to a fully evaporative condition [4].

3.1. Running wet condition 67B
An heating simulation has been done considering the multilayer properties of paper by Al-Khalil et al. [4], shown in figure 1. The heaters location inside the airfoil skin is presented in the same figure. The physical time of simulation was of 6 min or 360 s and was subdivided in 10 time steps of 36 s. A free stream velocity of 89 m/s, an angle of attack of 0 degrees, a free stream temperature of 251.4 K, a LWC of 0.00055 kg/m$^3$ and a mean diameter of 20 µm are the icing conditions for this test case. Material properties and heaters power densities can be seen in tables 1 and 2.

Two preliminary CFD runs have been carried out on the NACA0012 airfoil in order to have the heat transfer coefficient distribution on the external surface, using the commercial code ANSYS Fluent R18 [5]. The Multi-Ice code use a semi-empirical correlation to compute that coefficient, but comparing the results with experimental data, it can be stated that CFD procedure is more accurate than Multi-Ice inner one because the agreement between numerical results and experiments are really good, as shown in figure 2.

The final distribution of temperatures has been compared with the experimental results and with the temperatures computed by ANTI-ICE code, as shown in 3. In that figure, the temperatures computed by TERMICE, after 360 s, without considering more time steps are shown. Furthermore, the distribution of the heaters power densities on table 2 (67B) has been
Table 1. Layer material properties.

| Item | Material                        | Thermal conductivity, $\kappa$ (W/m/K) | Density, $\rho$ (kg/m$^3$) | Specific heat, $c_p$ (J/kg/K) | Thickness (mm) |
|------|---------------------------------|----------------------------------------|-----------------------------|------------------------------|----------------|
| 1    | Heating Element (Alloy 90)     | 41.02                                   | 8906                        | 385.2                        | 0.0127         |
| 2    | Erosion Shield (SS 301 H)      | 16.27                                   | 8025                        | 502.4                        | 0.20302        |
| 3    | Elastomer (Cox 4300)           | 0.26                                    | 1384                        | 1256                         | 0.559          |
| 4    | Fiberglass/Epoxy Composite     | 0.29                                    | 1794                        | 1570                         | 0.889          |
| 5    | Silicone Foam insulation        | 0.12                                    | 649                         | 1130.4                       | 3.429          |

Table 2. Heaters Setup.

| Heater ID | Non dimensional streamwise distance s/c | Anti-icing heat flux [kW/m$^2$] |
|-----------|------------------------------------------|---------------------------------|
|           | Start | 67A | 67B | End |
| F         | 0.9178 | 0.9588 | 20.15 | 8.37 |
| D         | 0.9588 | 0.9868 | 21.70 | 11.94 |
| B         | 0.9868 | 1.0148 | 32.35 | 10.85 |
| A         | 1.0148 | 1.0358 | 46.40 | 15.19 |
| C         | 1.0358 | 1.0628 | 26.35 | 9.92 |
| E         | 1.0698 | 1.0908 | 18.60 | 12.87 |
| G         | 1.0908 | 1.1328 | 18.60 | 8.68 |

Figure 2. Heat transfer coefficients of CIRA Multi-Ice [6], ANSYS Fluent R16 [5] and by Al Khalil et al.[4].

The temperatures achieved on the airfoil skin are really close to the experimental ones and the use of a coupled approach gives a better agreement because the coupling is on the whole arc of time simulation and so the two codes communicate between them not only at regime but in each time step. In the same figure, temperatures predicted by the numerical code ANTICE are added. The coupling procedure wants that the temperatures predicted by the single codes are compared for each time step and to assure a good rate of communication between them a residual based on the second order norm of the heat transfer coefficient difference $||h_{eff,c} - h_{eff,m}||^2$ has been monitored as shown in 4. For each time step, the residuals achieved a convergence rate established ahead. In particular, in the first time step the number of iterations is higher because
it was about 30 and this is due to the fact that the starting assumption of pseudo–steady state for each time step is more strong in the first time steps. More interactions between the two codes are so necessary to reach the equilibrium for the heat transfer.

To further confirm the convergence of the coupling procedure, also the temperatures at the surface in correspondence of the heaters positions are shown for each iteration and for all time steps, see 5.

The agreement with surface temperature experimental data is quite satisfactory, especially around stagnation and in the outer regions, while some overshoots in the numerical prediction are observed in the middle. However, it can be noticed that such a feature is shared with both ANTICE code [4] by NASA and reference data by da Silva and Bu [3, 1], especially for case 67B. The temperature range is between the freezing point at 273.15 K and 285 K for case 67B. Furthermore, an overestimation of the runback mass flow rate is evident with respect to ANTICE [4] predictions: indeed, for a given impingement mass flow rate, having more water...
flowing on the surface implies that less water has evaporated, which in turn implies a higher value of the local surface temperature (evaporative cooling is lower) and a lower effective heat transfer coefficient (see 2). The evaporating mass is just a limited portion of the incoming mass due to relatively low surface temperature values; even a small runback ice formation is observed near the impingement limits, as also highlighted experimentally by Al-Khalil et al. [4].

3.2. Fully evaporative condition 67A
The same considerations can be done in fully evaporative condition, see table 2 (67A) for the heaters power distribution. As shown in figures 6, 7, and 8, a good agreement between the temperatures predicted by the use of the two codes Termico and Multi Ice (label TERMICE) has also been achieved when the experiments of Al Khlalil et al. [4] are considered as a reference. A free stream velocity of 89 m/s, an angle of attack of 0 degrees, a free stream temperature of 251.4 K, a LWC of 0.00055 kg/m$^3$ and a mean diameter of 20 $\mu$m are the icing conditions for this test case.

The residuals reach a good convergence rate, see figure 7, and the temperatures predicted by Termico and MultiIce are in agreement, for each time step, see figure 8. Respect to the overshoots observed in running wet conditions, in the evaporative condition a satisfactory agreement has been reached with experimental data and numerical results. A consistent trend has been observed in underestimating the total heat transfer coefficient and overestimating the runback mass flux with respect to ANTICE code [4] by NASA: this can be probably due to the differences outlined in the impinging mass flux more than in the estimation of the evaporative rate. Further investigations will be devoted to extend the coupled code validation and to make comparative studies about the evaporative cooling law as applied to aircraft icing, as also recommended by Al-Khalil [4, 8]. Electrothermal de-icing cases will be also considered even if no coupling with the external solution is needed.

4. Conclusion
A coupling procedure between an ice protection code Termico and an ice accretion code Multi-Ice has been presented here. The work is based on the exchange of information regarding wall temperature and heat fluxes between the mentioned codes. The result is a numerical interface
Figure 6. Temperatures in proximity of leading edge (67A)

Figure 7. Residuals history in Termice

written in Fortran 90 programming language which has been validated using two literature test cases, a running wet one and a fully evaporative one. Some comparisons have been done with other numerical codes and experiments. The agreement between experiments and numerical results has been good. The procedure has clear limits because the ice accretion code has been run in a single step mode but a possible future development could be using Multi-Ice in multistep mode.

References
[1] Xueqin Bu et al. “Numerical simulation of an airfoil electrothermal anti-icing system”. In: Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering (2013).
Figure 8. Termico External Temperatures

[2] E. Iuliano et al. “Water impingement prediction on multi-element airfoils by means of eulerian and lagrangian approach with viscous and inviscid air flow”. In: 44th AIAA Aerospace Sciences Meeting and Exhibit (2006).

[3] G. Silva et al. “Differential boundary-layer analysis and runback water ow model applied to ow around airfoils with thermal anti-ice”. In: 1st AIAA Atmospheric and Space Environments Conference (2009).

[4] K. Al-Khalil et al. “Validation of NASA thermal ice protection computer codes. III - the validation of ANTICE”. In: 35th Aerospace Sciences Meeting and Exhibit AIAA 97-0051 (Jan 1997).

[5] ANSYS Fluent R16, User Guide. 2014. URL: http://www.ansys.com.

[6] V. Brandi and G. Zanazzi. Multi-Ice code user’s guide: an user-friendly interface for the evaluation of ice accretion on multi-element airfoils. CIRA-TR-05-0037.

[7] E. Iuliano and M. Ferrainuolo. “Coupled Numerical Simulation of Anti-Icing Problems”. In: VII International Conference on Coupled Problems in Science and Engineering, Rhodes Island, Greece (12-14 June 2017).

[8] Konstanty C. Masiulaniec and William B. Wright. User’s manual for the nasa lewice accretion/heat transfer prediction code with electrothermal deicer input. Tech. rep. NASA, 1994.

[9] Bernard L Messenger. “Equilibrium temperature of an unheated icing surface as a function of air speed”. In: Journal of the Aeronautical Sciences (1953).

[10] TERMICO code, User Guide. CIARA Internal Report.