DE-ICING PHENOMENA MODELLED BY FINITE ELEMENT MODELS

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Abstract

The main purpose of this paper is to present an ice release numerical model on a heated surface to validate with respect to experimental results. Developed on the basis of the standard finite element method implemented in ANSYS software, two different test-cases have been taken into account. The test article is an Aluminum alloy plate fitted with an array of discrete heater elements and thermocouples chamfered and mounted to present a flat surface to the icing flow. The tests differ to each other in terms of heating power taken into account. Numerical model predicts the ice-release time instant.

1 Introduction

Ice adhesion and deposition is considered a main threat to aviation. During ascent and descent phases, aircrafts may have to pass through clouds of water droplets at temperatures below the freezing point. Water droplets can impinge on different vehicle components causing ice accretion. This phenomenon generates changing in the aero-shape of the lifting surfaces and propulsive components, resulting in a very dramatic reduction of the corresponding performances and in the rise of accident risks. For these reasons it is mandatory to deeply study this topic, in order to design reliable and certifiable anti-icing and de-icing systems. Certification tests are never simple because icing phenomena are very complex and designers have usually access to a very low level of prediction capability compared to other fields, mainly relying on a very fragmented knowledge based on empirical past experience.

This paper aims at presenting a numerical model for the simulation of a de-icing system on a heated surface. This model has been validated by comparison with respect to experimental results.

2 State of the art

Ice protection systems (IPS) have a remarkable importance for the improvement of safety in all flight condition. Ice generated on the various aircrafts components can result in degraded performance and an increased risk of accidents or crashes.

In the relevant bibliography one can find a lot of papers and reports describing the methodology of ice formation, accretion and release with results obtained from measurements and numerical simulation.

In [1] numerical FEM simulations are illustrated to evaluate the strength adhesion between ice and aluminum using cohesive zone model (CZM) and also considering the roughness and bubbles; the FE model coupled to CZM proposed are indeed effective in predicting the strength adhesion between ice and substrate.

Concerning the ice release phenomena, it is important to make a distinction between heated and not heated surfaces in order to choose the most suitable IPS.

As to the heated surface, e.g. wings or rotor blade, it is possible to use thermal anti-ice systems; in [2] a numerical simulation on electro-thermal de-icing of a helicopter rotor blade is performed, aimed at calculating the temperature actually reached and the time required to reach the melting ice condition.

As to not heated surfaces, like an engine rotating component, an alternative solution must be followed [3] shows an experimental test in order to measure the strength adhesion between ice and substrate by applying a pulse vibration.

In [4] an experimental test is illustrated. It aims at evaluating the ice strength adhesion to bare aluminum substrates with different values of surface roughness. The strength adhesion between ice and metal samples is measured by means of a permanent magnet shaker.

In [5] is compared the ice adhesion to solid substrates with different surface properties; experimental measurements are implemented on an iced cantilever beam to evaluate the maximum interfacial shear stress to vary of water contact angle with substrate by applying a sine pulse .

In [6] an iced cantilever beam (structurally representative of an engine rotating component) excited by applying a vibrating impulse able to generate ice fracture has been studied.

3 Numerical Approach

CIRA developed a numerical model for the simulation of a de-icing system on a heated surface.

The main objective of the implemented numerical models is to simulate an electro-thermal de-icing system able of heating the ice up to leading to zero the forces of adhesion with the substrate. A 3D numerical model, based on the standard finite element method implemented in ANSYS software, has been developed in order to evaluate the time required for the ice at the interface to change phase and become liquid thanks to the heat flow coming from the heaters.

The numerical model simulates the behavior of a system substrate-ice in the presence of a de-icing electro-thermal system placed on the free bottom surface of the substrate.

A transient thermal analysis has been performed in order to evaluate the time required for a layer of ice at the interface to get completely melted. The model has been designed so that the analysis stops automatically when at the interface there is no more ice but water.

Three issues have to be assessed:

- phase change;
- the implementation of a temperature control of the ice at the interface during the run;
- a routine implementation allowing the analysis to be repeated up until the complete melting of ice interface at the is occurred.

The main difficulty in modelling a thermal transfer problem with phase change lies in the management of the transformation between the phases and the concomitant absorption (or release) of the latent heat in the area. In fact, the temperature gradient in the transition phase is discontinuous and, moreover, the phase change can take place either in a wide temperature range or at a single temperature.

A general approach to the problems of the phase change is the so-called “Enthalpy method” which the phase change is not simultaneously monitored during calculations, but is done after the change of temperature [7].

This approach is possible because the condition of phase change is indirectly embedded in the definition of enthalpy.

Generally speaking, when a substance changes its phase the temperature keeps almost constant during the transformation. For example, the ice is ready to melt at 0°C; when heat is added the melting starts and ice becomes liquid. At the end of this process, the temperature is still 0°C. Indeed, during the phase change thermal energy absorbed is used for molecular structure changed and it is called residual heat. Therefore, an analysis of the phase change must take into account the material residual heat, which is necessary to define the material enthalpy as a temperature- dependent function. The relationship between enthalpy and temperature is not linear because the melting temperature keeps constant and equal to 0°C during the melting process (Fig.1). The non-linear behavior demands the use of an iterative solution to find an appropriate temperature at each node. Ansys software gives the opportunity to study the phase change performing a non-linear transient thermal analysis.

Relationship between enthalpy and temperature has been adequately modified in the present work. Indeed, the assumption that ice melts in a small temperature range has been done as shown in Fig. 2. This temperature range must be as small as possible to have good quality solution.

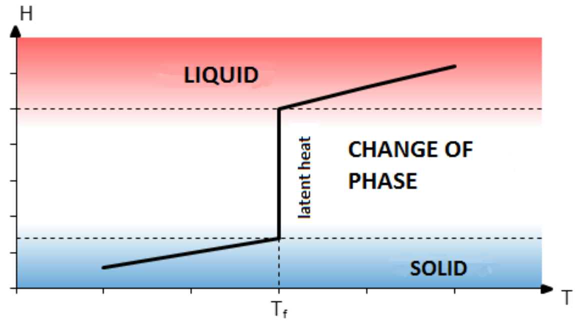

Fig.1: Relationship between enthalpy and standard temperature

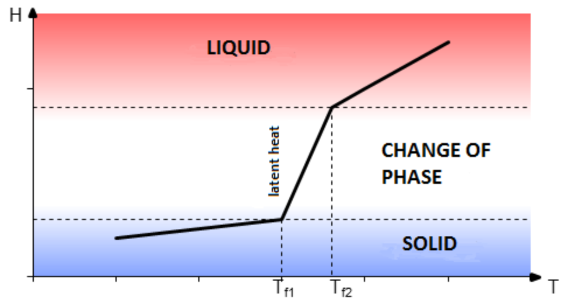

Fig. 2: Relationship between enthalpy and assumed temperature

Enthalpy has the dimensions of heat over volume and it is defined as:

$$H = \int \rho \cdot c(T)dT \qquad (1)$$

Where H is enthalpy, ρ is density and c is specific heat.
The following assumptions have been made in the development of the model:

- ambient temperature as well as heat transfer coefficient are constant;
- an ideally perfect thermal contact is realized between the different layers;
- ice is free of any impurity or bubbles;
- volume contraction effect during the melting phase is not taken into account;
- phase change happens in a small temperature range and not at a fixed melting temperature.

According to the technical norms, de-icing process, forced with a thermal device, is considered successfully completed when a 0.5 mm thicken ice is melted in water [8].
In order to force the analysis to continue until the interface ice is completely melted, a macro has been designed. A "do" cycle is implemented to split the analysis in a sufficient number of substeps leading to the desired solution. Fig. 3 shows the simulation process.

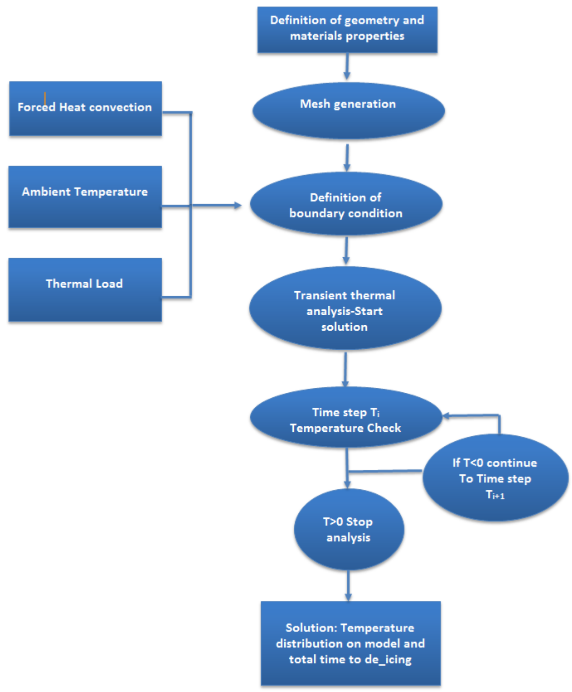

Fig. 3: Simulation process

3.1 Numerical Model

Following the numerical approach described in section 3, a numerical model have been set-up to rebuild the de-icing phenomena. In particular, 50W electrical heaters have been simulated as heat flux [W/m^2], acting on the substrate inferior surface. On the other hand, the ice upper surface exchanges via free convection with the external ambient. This thermal convective flux q between surface and fluid is compute by Newton formulation as follows:

$$q = h(T_w - T_\infty) \qquad (2)$$

where:

- h is the local convection heat transfer coefficient [W/(m^2*K)];
- T_w is the surface temperature;

- T_∞ is the ambient temperature;
- The heat convective coefficient has been calculated by using MULTI-ICE[1] code developed by CIRA. An example of the local convection heat transfer coefficient considered is depicted in Fig4.

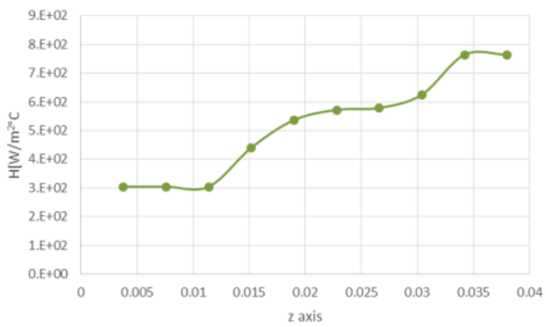

Fig. 4: Heat convective coefficient along z axis (flow direction)

Adiabatic boundary conditions are considered on the other side as shown in Fig.5.

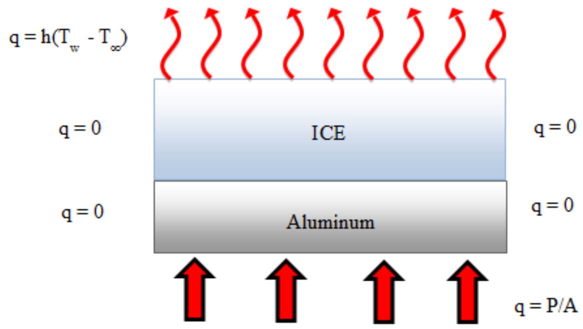

Fig. 5: Boundary conditions

The numerical model developed has been used for the simulation of three experimental tests case carried out by the Cranfield University in the framework of STORM EC –funded project [9].
The test article is an Aluminum alloy plate fitted with an array of discrete heater elements and thermocouples chamfered and mounted to present a flat surface to the icing flow.

The geometry has been designed in Ansys workbench in accordance with the dimensions provided by the experimental tests as shown in Fig.6. According with experimental Cranfield test case, six heaters, situated on the free surface of the aluminum plate, are simulated. A thermal load of 0.55 MW/m^2 is locally applied in correspondence of each heater (Fig. 6).

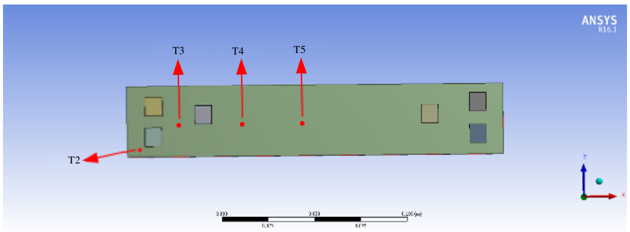

Fig. 6: Geometrical layout and heater positions

A 3D 90000 hexahedral finite elements model has been finally set-up (Fig.7).
A transient thermal analysis has been carried out for the different test cases.
A convective heat flux with the air is considered on free ice surface varying its values for each model according with experimental conditions. The heat convective coefficient has been calculated by using MULTI-ICE code developed by CIRA.
Adiabatic boundary conditions are imposed on lateral free surface of aluminum and ice.
The analysis conducted on the three test cases are described in the following subsections.

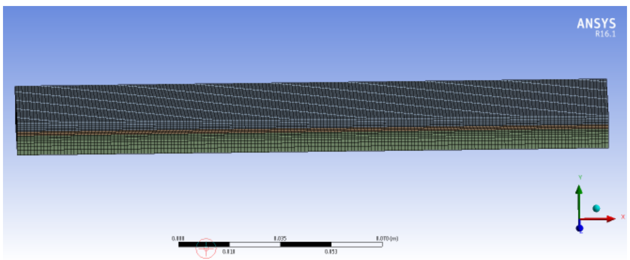

Fig. 7 Computational 3D mesh

1 MULTI-ICE code is a scientific software package for the evaluation of the ice accretion on 2D airfoils, developed by CIRA, the Italian Aerospace Research Centre, 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 at) 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 and use a RANS solution. The droplet trajectories and the impingement are calculated using a 4th order Runge-Kutta integration with SLD model, while the ice accretion evaluation is based on the classical Messenger model. The MULTI-ICE code is now available with a graphical Windows-based interface for PC platform, to provide an easy access and fast tool to perform the ice simulation, simplifying the program usage also for not-skilled users.

3.2 Numerical Results

Two different test cases are presented in the paper. They are the so-called test case 15 and the test case 16.

In the test case 15 the following boundary conditions are considered:

- Ambient temperature=-15 °C.
- A convective flux on free ice surface. The heat transfer convection coefficient has been calculated taking into account test conditions (Tunnel speed 75m/s, Temperature -15°C, plate angle 33 deg) and its spatial trend on ice surface as showed in Fig. 8 and Fig.9.
- An imposed value of 0.55 MW/m^2 heat flux in correspondence of each of the sixth heaters.

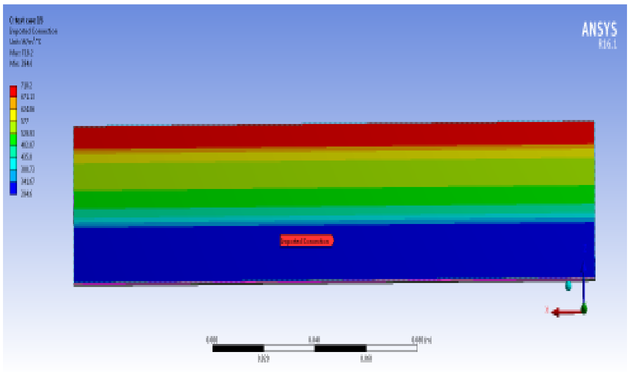

Fig. 8: Convective heat coefficient spatial distribution

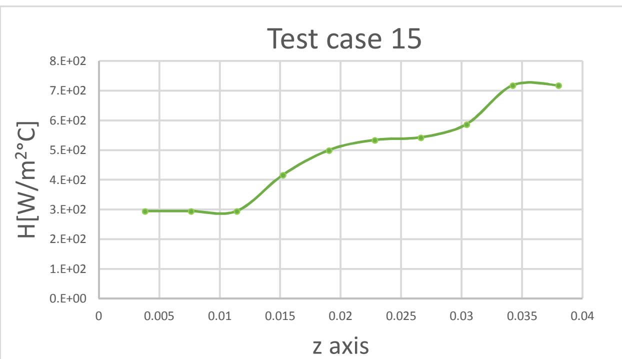

Fig. 9: Convective heat coefficient value vs z-axis

The run stops automatically when a layer of 0.5 mm of ice at the interface melts in water. Indeed, in this case, the bonds with the substrate are considered broken and the dynamic pressure is able to sweep away the ice remaining.

The time necessary for the ice shedding and the temperature distribution of the plate-ice system are shown in Fig. 10 and Fig. 11.

A temperature probe at each thermocouple has been used and results have been compared with respect to measured tendencies at thermocouples 2, 4 and 5. Fig.12, Fig. 13 and Fig. 14 show the results.

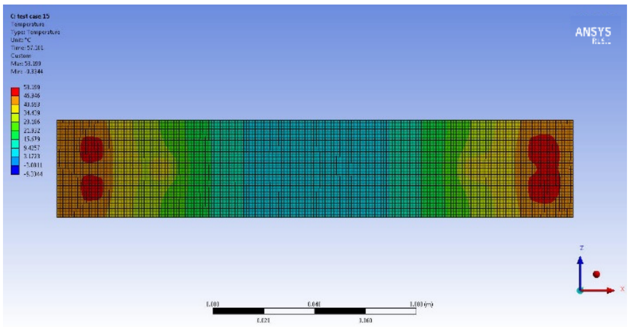

Fig. 10: Temperature distribution at de-icing time (a)

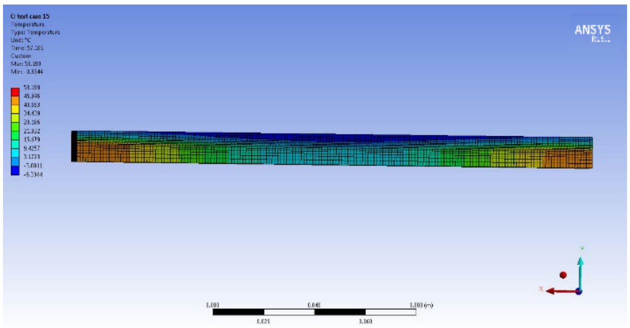

Fig. 11: Temperature distribution at de-icing time (b)

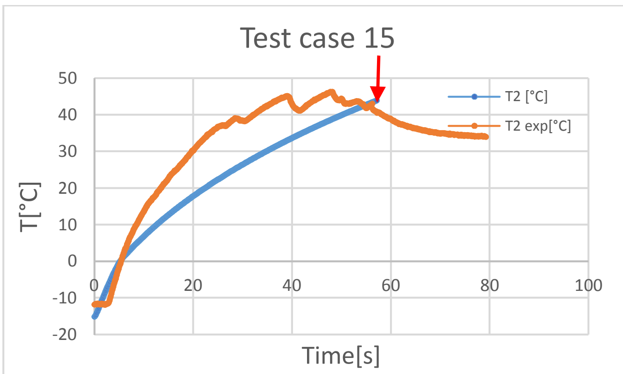

Fig. 12: Temperature comparison between experimental and numerical data corresponding to thermocouple 2

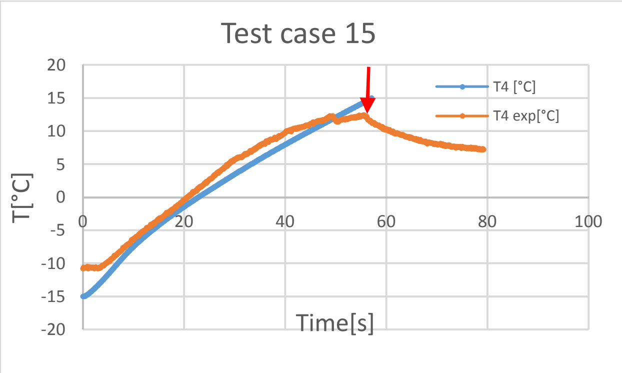

Fig.13: Temperature comparison between experimental and numerical data corresponding to thermocouple 4

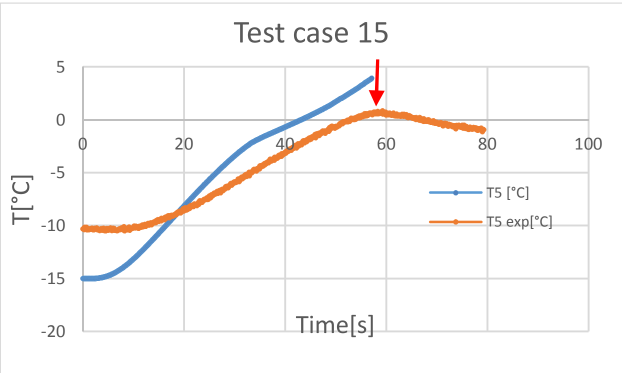

Fig. 14: Temperature comparison between experimental and numerical data corresponding to thermocouple 5

In the test case 16 the following boundary conditions have been considered:

- Ambient temperature T=-20°C.
- A convective flux on free ice surface. The heat transfer convection coefficient has been calculated taking into account test conditions (Tunnel speed 50m/s, Temperature -20°C, plate angle 33 deg) and its spatial trend on ice surface as showed in Fig. 15 and Fig. 16.

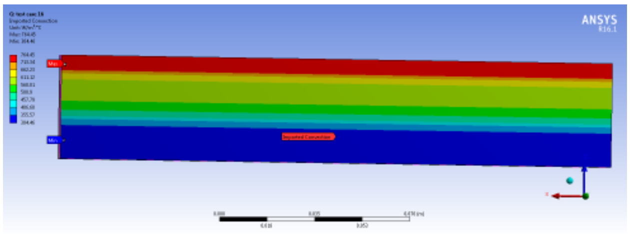

Fig. 15: Convective heat coefficient spatial distribution

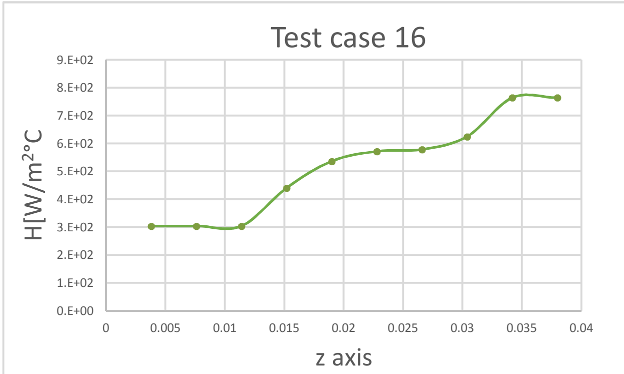

Fig. 16: Convective heat coefficient values vs z-axis

- An imposed value of 0.55MW/m^2 heat flux in correspondence of each of the six heaters.

Temperature distribution at time necessary for the de-icing of the plate-ice system are shown in Fig. 17 and Fig. 18.

The temperature comparison between numerical and experimental results at thermocouple 2, 3 and 5 is showed in Fig. 19 to Fig.21.

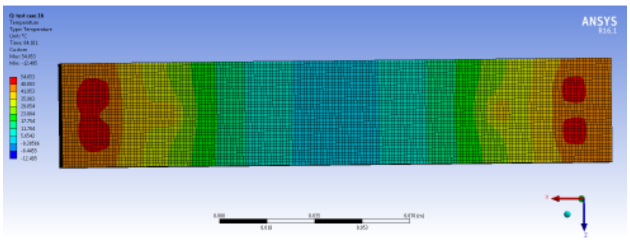

Fig. 17: Temperature distribution at de-icing time (c)

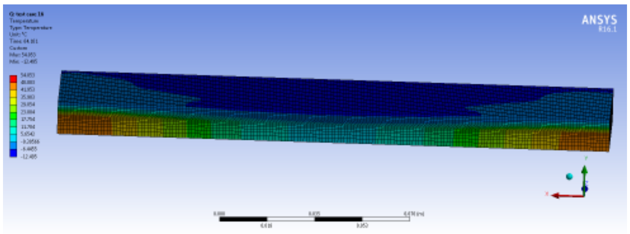

Fig. 18: Temperature distribution at de-icing time (d)

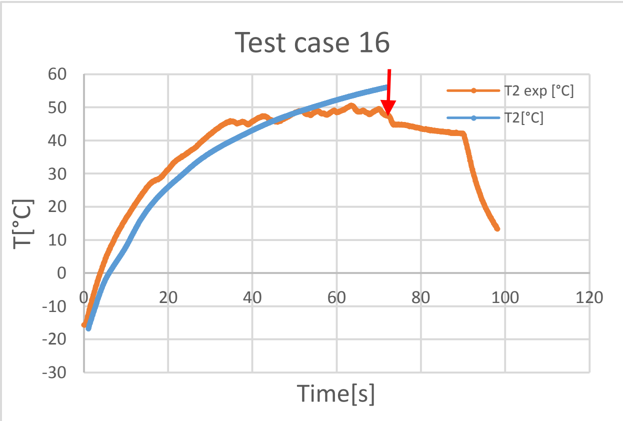

Fig.19: Temperature comparison between experimental and numerical data corresponding to thermocouple 2

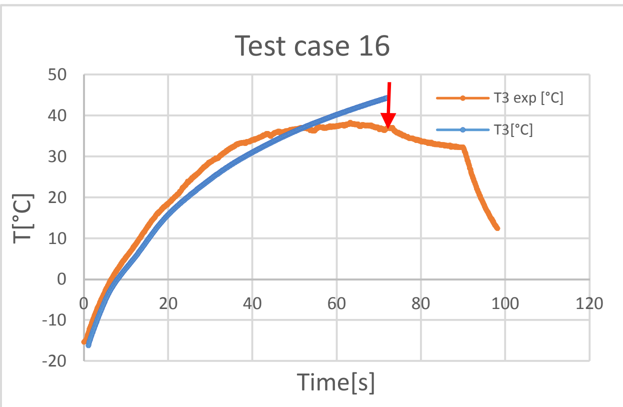

Fig. 20: Temperature comparison between experimental and numerical data corresponding to thermocouple 3

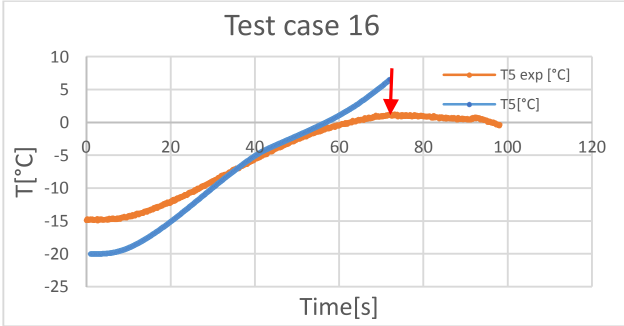

Fig. 21: Temperature comparison between experimental and numerical data corresponding to thermocouple 5

4 Conclusions

The comparison between experimental and numerical data show a partial agreement.
In particular, for the test case 16, it is possible to observe a similar temperature tendency, a perfect accordance with respect to time shedding (72s) and maximum temperature reached at the shedding.
For test 15, numerical model shows again a similar behavior with respect to temperature values and shape. On the other hand, at the numerical shed time (53s), experimental test showed that part of the ice is still glued on the substrate due to edge effects. This phenomenology is not predicted by the numerical model.
Therefore, the numerical model is quite predictive but it may be parametrized and generalized.
Aerodynamic phenomena like edge effect retention as well as ice growing again after melting should be taken into account. Mechanical air pressure effect have to be considered as well. This could lead to a fluid-structure strong coupling modelling.

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