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Comparison between experimental IR measurements and numerical prediction in hypersonic flows

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Abstract

Testing, in a flight environment, and numerical prediction of the behaviour of the technologies developed for the thermal protection of a re-entry vehicle is the key for a more reliable and robust Thermal Protection System (TPS) design. The improvement of the reliability of the experimental data acquired from ground tests is fundamental; moreover, the validation of numerical methodology with ground measurements necessarily asks for a correct rebuilding of the test.
In this work surface temperature measurements, carried out with IR thermography in CIRA Plasma Wind Tunnel on a Wing Leading Edge TPS demonstrator within the Advanced Structural Assembly (ASA) technological project, are performed and compared with the results of the test numerical rebuilding. For the present measurement campaign an IR mirror system has been developed to allow the view of the leading edge region. A software has been developed for the optical calibration of the camera and for the mapping of the IR images on the three-dimensional surface of the test article, thus providing an useful tool for the direct comparison of numerical and experimental data. An integrated procedure coupling the external aerodynamic field to the internal thermal state of the structure has been adopted for the numerical rebuilding of the test. Low temperature differences have been found between the experimental and numerical results.

1. Introduction

The extreme difficulties of testing, in a flight environment, technologies developed for the thermal protection of a re-entry vehicle put emphasis on the validation of numerical prediction tools. The ground testing in a Plasma Wind Tunnel facility entails a series of limitations in terms of cost and representativeness of the flight environment; therefore the research of improved CFD tools, both with flight and ground experimental data, is the key for a more reliable and robust Thermal Protection System (TPS) design. Existing database of in-flight measurements are extremely poor. On a parallel way it is also fundamental to improve the reliability of the experimental data acquired from ground tests. The validation of numerical methodology with ground measurements necessarily asks for a correct rebuilding of the test.

The Italian Aerospace Research Centre (CIRA) as prime together with several Research and Academic institutions all over Italy is involved in the research program CAST (Innovative Aerothermodynamic Configuration for Space Transportation Systems) founded by the Italian Space Agency that is aimed at improving the state of art of national simulation capabilities both in terms of basic phenomena modelling and numerical tools [1]. In the frame of this program, different experimental tests, covering a wide range of typical hypersonic flow phenomena, have been carried out with the aim to gather data to be used for code validation. Moreover, in order to maximize the synergy between different national programs, also a Plasma Wind Tunnel test carried out within the Advanced Structural Assembly (ASA) technological project, also funded by the Italian Space Agency, on a Wing Leading Edge TPS demonstrator has been used for the CAST purposes. The test article has been conceived in order to allow for the thermal qualification of two technologies developed for the leading edge, i.e. an Ultra High Temperature Ceramic (UHTC) and an actively cooled leading edge, and two technologies, i.e. an Hybrid C/C and a Metal Matrix Composite, developed for the windward and leeward section panels [2].

For the present work IR camera has been used for temperature measurements in "Scirocco" [3], the CIRA Plasma Wind Tunnel (PWT) and a mirror system that improve the field of view of the leading edge region has been adopted; moreover, a software has been developed for the mapping of the IR images on the three-dimensional surface of the test article thus providing a useful tool for the direct comparison between numerical and experimental data. IR images have been compared with data obtained with the numerical rebuilding of the test in order to validate an aero-thermal coupling procedure developed. In fact an integrated procedure coupling the external aerodynamic field to the internal thermal state of the structure has been adopted for the numerical rebuilding of the test.

Even if it has to be remarked that some uncertainties are associated to this type of numerical rebuilding, especially for what concerns the characteristics of the material, low temperature differences have been found between the experimental and the numerical results.

2. Model description

The main purpose of the Advanced Structural Assembly project was to qualify, in an high enthalpy ground facility, a certain number of new technologies potentially applicable as wing thermal protection system for a new generation of re-entry vehicles; to this aim it was proposed to realize an adequate test article to be tested in “Scirocco” facility, that should be representative of the wing of FTB-X vehicle. The test article has been conceived to be compatible with the facility itself in terms of dimensions, sustainable weights, auxiliary requested equipments, available measurement systems, etc., by guaranteeing the most valuable scientific feedback and, at the same time, an adequate safety level. As a matter of fact, it cannot be possible to test a real full-scale delta wing complete of the fuselage in the existing plasma facilities. The presence of chemical effects does not allow to simply scale the geometry to wind tunnel allowable dimensions; moreover, in the present case, the need to have a full scale test article is due to the necessity to test TPS technologies developed for flight. Moreover, it makes no sense to test only a portion of the delta wing because of the non-reproducibility of the real three-dimensional effects. For this reason it was decided to realize the test article by extruding a longitudinal section directly derived from FTB-X wing as described in Fig. 1.

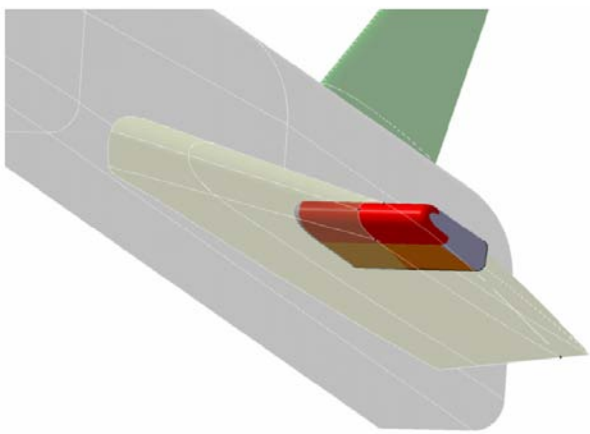

Fig. 1. *FTB-X wing and test article derivation*

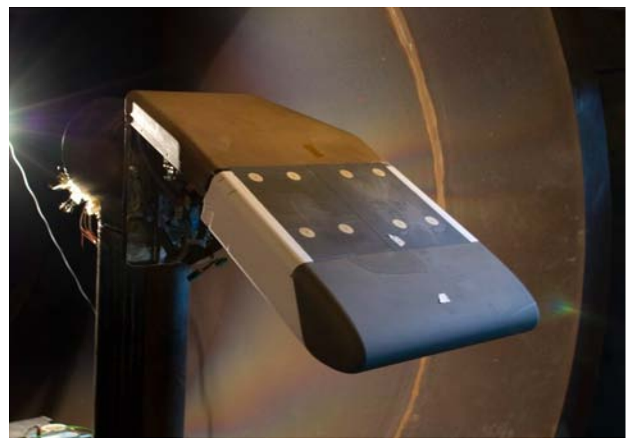

Fig. 2*. Test Article inside the Plasma Wind Tunnel*

Two lateral rounded fairings have been also defined in order to reduce as much as possible the overheating due to the finite span effects of the test article. Moreover some small modifications to the original wing section profile were necessary in order both to simplify the assembly and to allow the compatibility of the test article with the PWT.

The conceived test article has been used to test in the PWT facility the innovative manufacturing technologies and materials suitable for TPS and thermo-structural applications, developed in the frame of the same project, for the next generation of orbital re-entry vehicles. Different technologies were developed and tested within the ASA project but, for what concerns the aims of the present work, only the so-called FTB-1 configuration will be taken under consideration. In this case, the test article is equipped with an UHTC leading edge and two C/C SiC coated panels on the windward and leeward side, even though this analysis has been focused only on the leading edge.

As a matter of fact from the test design activity, that will be described hereinafter, it comes out that in order to reproduce as much as possible the in-flight heat flux distribution of the FTB-X delta wing over the designed test article with no-sweep angle it is necessary to perform the test at an angle of attack of at least 35 deg while the angle of attack along the flight trajectory was 25deg at its maximum. To this aim it was decided to have a mechanical incidence of 25deg provided by the model holder itself and to manage the remaining deflection angle by means of the facility Model Support System (MSS). In Fig. 2 the test article mounted on the MSS and ready to be tested is shown.

3. Plasma Wind Tunnel test

Hereinafter a brief description of the activities carried out to numerically design the PWT test are reported; more details can be found in [4]. The starting point for the design of a test to be performed in the Plasma Wind Tunnel “Scirocco”, is the definition of the requirement, generally in terms of heat flux and pressure to be realized on the model, that is necessary to achieve during the test itself. For the considered test, the requirements were extracted from the analysis of the loads foreseen during the re-entry trajectory of FTB-X vehicle and are summarized, for the different part of the model, in Table 1 in terms of heat flux. For each part of the model in the same table the wall boundary conditions are also shown, in terms of catalysis and temperature, to be considered. The test has been numerically designed, in terms of values of reservoir enthalpy

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and pressure and model positioning/attitude within the test chamber to be considered, through an extrapolation-from-flight methodology already used for previous test campaigns.

For what concerns the test on the model equipped with the UHTC-based leading edge, the requirement was to achieve a stagnation point heat flux over the model centreline equal to 410 kW/m^2 and the following operating conditions and model attitude have been determined: reservoir enthalpy equal to 15 MJ/kg, reservoir pressure equal to 3.9 bar, final model attitude equal to 35 deg (25 deg mechanical angle + 10 deg of MSS tilting), distance from nozzle exit equal to 950 mm.

Table 1. *Requirements for PWT test design.*

ID req.	TA part	Wall Conditions		q [kW/m^2]	Position
		Catalysis	*Temp*		
A	*LE UHTC*	FRC	Rad eq	**410**	Stagnation Point - x=0
B	*WINSIDE PANEL C-C / SiC*	FRC	Rad eq	**170**	Panel Apex - x=0.2
C	*LE AC*	FCW	Tfix	**410**	Stagnation Point - x=0
D	*LEESIDE PANEL MMC*	FCW	Rad eq	**90**	Panel Apex - x=0.1

In order to guarantee the safety of the test both in terms of flow blockage occurrence and test article integrity it was decided to consider some intermediate steps for the test procedure. These steps can be summarized as follow:

1. Insertion of the model with a mechanical angle of attack of 25 deg at a distance from the nozzle exit section equal to 200 mm;
2. Backward movement of the test article up to a distance from the nozzle exit section equal to 950 mm;
3. 10 deg tilting to reach the final attitude of 35 deg that assures the achievement of the requirements over the model.

The achievements of the right operating conditions within the test chamber during the test is assured by the presence of a copper water-cooled hemi-spherical calibration probe which is inserted in the plasma flow before the insertion of the model and measure the stagnation heat flux and pressure. Facility regulation parameters (air mass flow and current in the arc) are tuned in order to match on this probe a certain couple (stagnation pressure and stagnation heat flux) which corresponds to the desired operating condition in terms of the couple (H0, P0) evaluated through the extrapolation-from-flight methodology generally used. For the present test, the requirement was to achieve on the calibration probe a stagnation heat flux equal to 1040 kW/m^2 and a stagnation pressure equal to 1100 mbar.

The test has been executed on October 2008 [5]. The stagnation values of heat flux and pressure measured with the probe are reported in Table 2; these values were different from the required ones but, in any case, within the associated measurement uncertainty and feasibility limits due to the necessity to maintain stable conditions in the arc heater.

Table 2. *Measured test conditions.*

q_s [kW/m^2]	P_s [mbar$_a$]	t_c @ AoA=10° [s]
950	**11.8**	**5**

Measured heat flux was 950 kW/m^2, with a difference with respect to the required value of 90 kW/m^2 whereas stagnation pressure was 11.8 mbar instead of 11.0 mbar. In Figure 3 different images during the test execution are shown. After 28s from the insertion of the model in the plasma flow, the test article was damaged and the test has been interrupted. Therefore the numerical rebuilding, whose results will be reported hereinafter, has been done by taking into account only this phase of the experiment considering that the analysis of the damage goes beyond the purposes of the present work whereas the short duration does not invalidate the purposes of the proposed methodology.

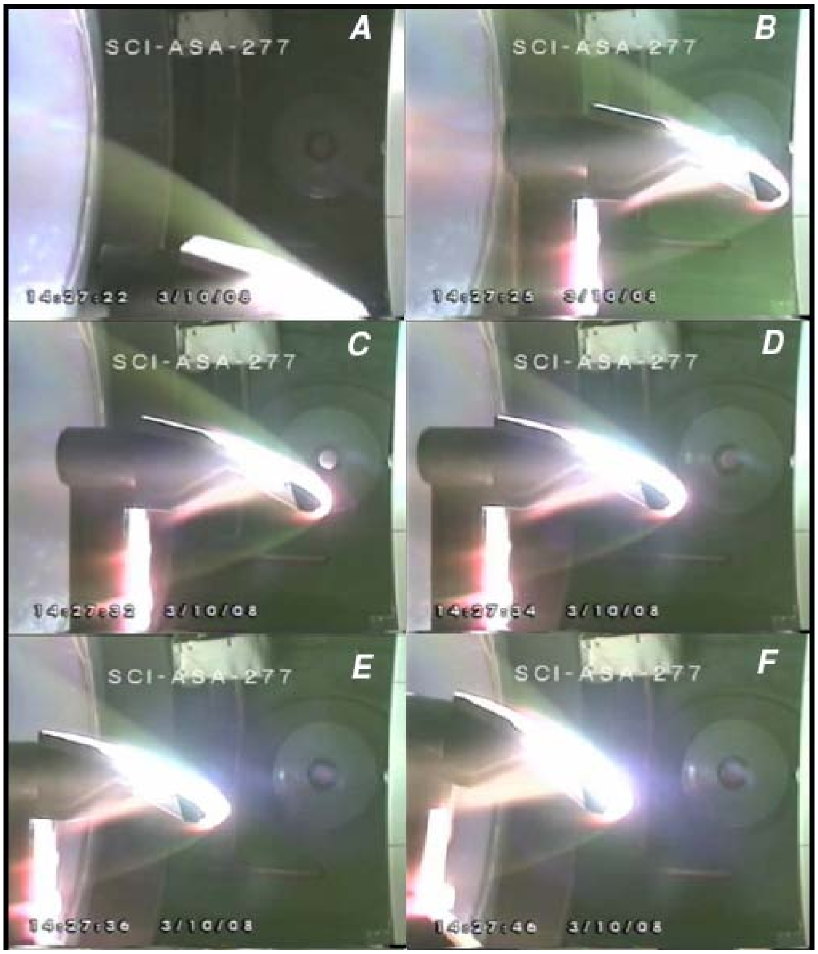

Fig. 3. *Different phases of the test: A) model enter the plasma flow; B) model arrives at centreline at a distance from nozzle exit section of 200 mm; C) after 5s the backward movement starts, in this figure the distance from nozzle exit section is about 450 mm; D) distance from nozzle exit section equal to 700 mm; E) model reaches the final position, distance from nozzle exit section 950 mm; F) after 5s in this position the model rotates to achieve the final angle of attack of 35 deg.*

4. IR Measurements

During the test, surface temperature measurements have been carried out with IR thermography. The determination of the exact space position of a point on the image plane is not easy in the case of highly three-dimensional bodies. Therefore the necessity to work in a 3D frame requires the use of some auxiliary tools to predict what is possible to measure. In this way it is possible to foresee what the IR camera sees on the model, in order to choose the most suitable optic access, and to acquire images of the most interesting zones of the model. A 3D reconstruction of the facility test chamber has been carried out through CAD tools in order to identify the presence of obstacles in the test chamber that can influence the field of view of the IR system; in particular, for the present test, the large nozzle made difficult to measure the temperature on the frontal area of the model from all the optical accesses of the test chamber. In order to overcome this limitation, and then to observe the leading edge of the model, a mirror has been installed in the test chamber. The positioning of the mirror has been done considering that it has to be positioned in safe zone, far from the plasma flow, the angle between the normal to the mirror surface and the incident ray from the point of interest and the angle between the same normal and line between the centre of the mirror and the IR camera should be around 45deg in order to maximize the field of view and to reduce image distortions; the angle between the normal to the model surface and the line between the point of interest and the centre of the mirror should be lower than 45deg in order to avoid a too low signal/noise ratio due to the decreasing of the directional emissivity.

The mirror has been introduced in the 3D virtual model of the facility test chamber and the positioning has been optimized in order to determine the best solution considering the above mentioned requirements. The result of this procedure

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is shown in Fig. 4 where a rendering of the model seen through the mirror is visible. This result has been used to verify that the positioning is correct and that the optimization procedure worked well. For the present application a first surface mirror coated with enhanced aluminum with a superficial finishing of ¼ wave in the IR LW has been used. A support which allowed for suitable positioning and easy inclination of the mirror has been realized, as shown in Fig. 5.

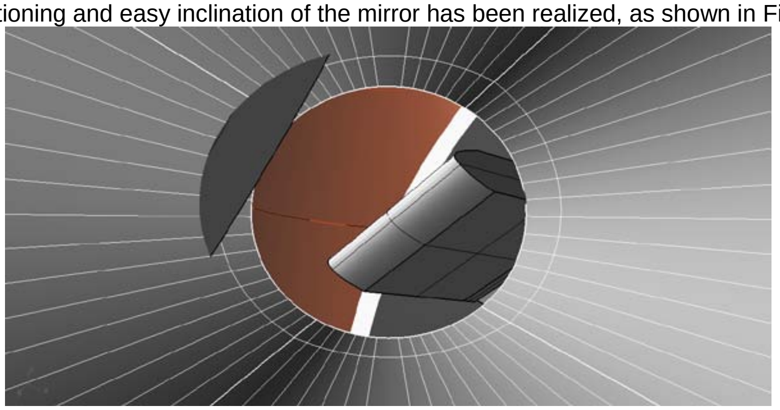

Fig. 4. *Image of the model as acquired through the mirror.*

Fig. 5*. Mirror positioning.*

The optical calibration of the IR system has been done using the pinhole camera model [6] which allows to evaluate some calibration parameters, depending on the positioning and orientation of the camera, focal distance and radial distortion of the lens. The calibration of the camera allows to determine the position in the image plane of a point in the 3D space. A special calibration target has been used as proposed by [7]: in this case an high contrast target, with control points at the same distance in two different orthogonal directions has been considered as shown in Fig. 6.

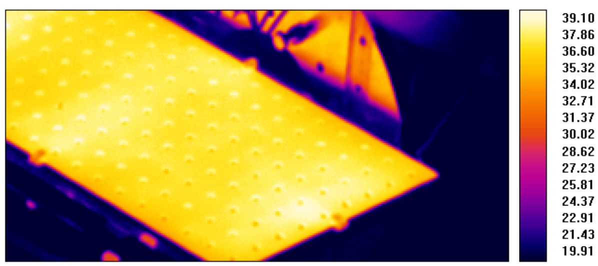

Fig. 6. *IR image of target plane for the optical calibration.*

The target element is made of aluminium and it is composed by a black perforated plate with high emissivity (ε=0.9) ahead a low emissivity steel plate (ε=0.15). In order to have a good contrast of the spots, the back surface of target is heated by Joule effect. The target plane has been positioned on the MSS of the facility and moved in different positions within the test chamber. Six different planes have been considered to determine the parameters of the camera model.

An AGEMA SC900 system was used for measurements. The camera has been equipped with a lens with 7deg semi-aperture angle to have a good resolution on the model and the images have been acquired with a frequency of 1Hz. In Fig. 7*A)* a row IR image acquired during test execution is shown. Emissivity has been assumed equal to 0.8 for the leading edge material.

In order to obtain the 3D surface temperature map from IR image on the same grid used for the numerical calculations [8], the *pin-hole* model has been applied and then the temperatures in each node of the grid has been obtained. Once the grid nodes have been projected, the gray scale levels have been derived through bi-dimensional interpolation and then related to the temperature levels by means of a radiometric calibration; this has been done by assuming a constant emissivity of the UHTC leading edge material equal to 0.8 and by neglecting the dependence of this value from the angle of view. In Fig 7 *B)* the surface grid of the wing leading edge is shown while the projection of the real points on the image plane and a 3D surface temperature map are shown respectively in Fig. 7 *C)* and *D)*.

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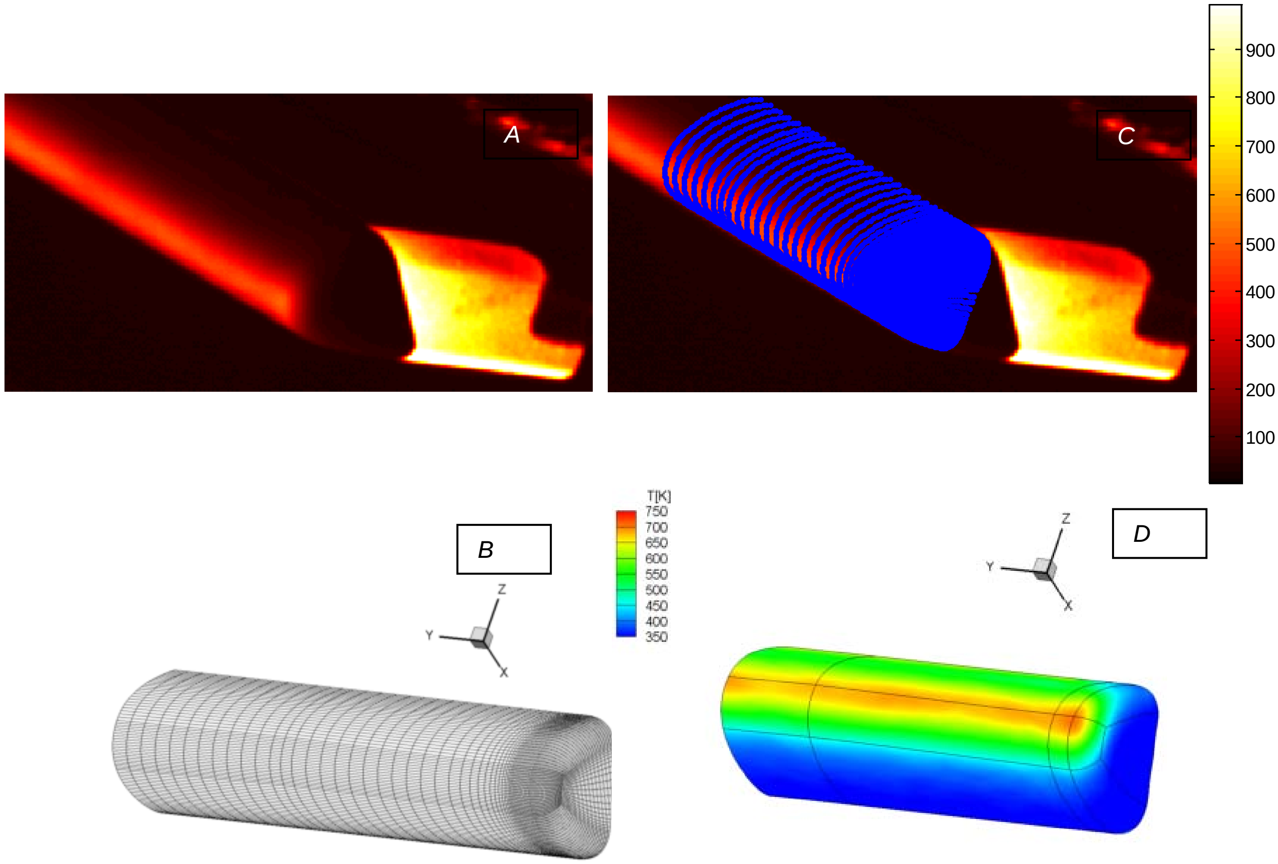

***Fig. 7**. A) Row thermal image; B) Surface grid of the leading edge; C) Projection of real points on the image plane; D)Temperature map rebuilt on the object surface.*

5. Numerical rebuilding

As already specified, the achievement of the desired test conditions within the test chamber is assured by the insertion in the plasma flow of the hemispherical calibration probe. Numerical rebuilding, consequently, has to be carried out considering the actual values of heat flux and pressure measured by the probe and reported in Table 2. In this case, considering these values, the operating condition in terms of reservoir enthalpy and pressure which allows to obtain these results on the probe have been determined and then used to compute the flow inside the PWT conical nozzle and then around the model for the rebuilding of the test. This procedure assures a good characterization of the flow within the test chamber and then that the selected operating condition is suitable for the rebuilding of the results over the model. The selected condition for the rebuilding is characterized by a reservoir enthalpy of 13.76 MJ/kg and a reservoir pressure equal to 4.25bar.

The numerical rebuilding procedure has been applied considering a weak coupling between the external fluid dynamic field and the internal thermal field, considering different free-stream conditions ahead the model according to its movement within the test chamber. By analyzing the characteristic times of the phenomenon, it has been deduced the possibility to consider different steady state computation of the fluid dynamic field whose dynamic behaviour is much faster than heat propagation inside the material, on the other side, through unsteady thermal simulations. In synthesis, the internal thermal field has been evaluated through a series of successive unsteady computations considering the heat flux due to the external flow as a fixed input for each step; at the end of each thermal computation, this input due to the external flow has been updated by repeating the CFD computations considering either different free-stream conditions due to the movement of the model within the test chamber either the updated wall temperature distribution derived from the thermal analysis.

Numerical rebuilding has been done starting from the entrance of the model in the plasma flow by carrying out 16 computations (CFD + thermal) as shown in table 3 where for each time also the positioning of the model considered for the

CFD analysis is indicated. In Fig. 8 external and internal temperature flow-field is shown. Heat flux propagation inside the structure is quite evident.

***Table 3**. Conditions for the numerical rebuilding.*

Id Run	Time [s]	Distance from nozzle exit [mm]	A.o.A. [deg]
1	0	200	25
2	2	200	25
3	4	200	25
4	6	200	25
5	8	200	25
6	10	450	25
7	12	700	25
8	14	950	25
9	16	950	25
10	19	950	25
11	20	950	27
12	21	950	29
13	22	950	31
14	23	950	33
15	24	950	35
16	28	950	35

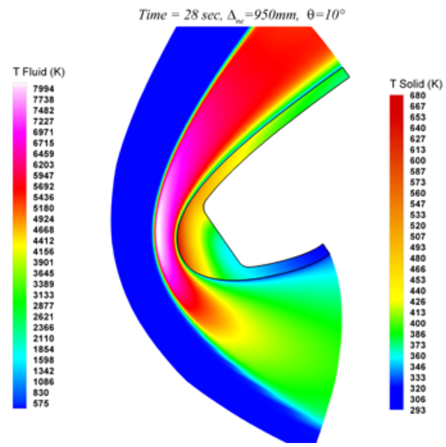

***Fig. 8**. External and internal temperature fields.*

6. Experimental vs numerical results comparison

After considering three points in the middle section of the test article, the temporal temperature profiles measured with IR thermography and obtained with the numerical rebuilding of the test have been compared. The points chosen for the comparison are respectively the stagnation point, a point on the upper side of the wing section and a point on the lower side of the wing section. A sketch with the three considered points is shown in Fig. 9 A).

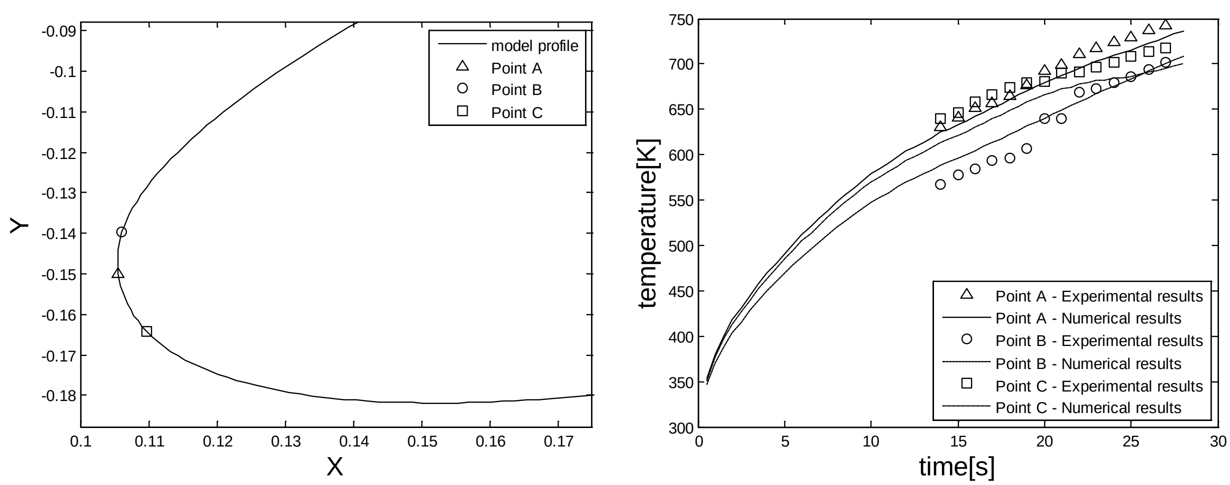

***Fig. 9.** A) Sketch of the points considered for the comparison B) Temperature temporal profiles*

In the Fig 9 B), for each point, the IR experimental temperature time histories are plotted together with the results of numerical analysis. The three curves show a good agreement especially for what regarding the slope. The differences between numerical and experimental results are higher in the case of the point B and C. In these cases the viewing angle is very high so the errors related to the optical calibration are amplified especially for the frames related to the rotation of the model.

For the most severely stressed point of the leading edge (A), you may notice a difference between the numerical curve and the experimental curve of about 20K at the last time step. For the upper point (B) the difference between numerical and experimental curve remains low initially but decreases after the rotation. Completely different situation occurs at the point downwind (C), where the experimental curve is clearly affected by errors related to the high viewing angle before the rotation while after the rotation it has a good agreement with the numerical curve.

Of course, in order to reach the good agreement between the experimental and numerical data, all the uncertainties have been reduced. The real test conditions have been determined in detail; the uncertainties related to the knowledge of the material were reduced: not only in terms of emissivity or catalysis but also in terms of thermal conductivity, capacity and density to accurately rebuild also the thermal field inside the model.

7. Conclusion

The experimental and numerical activities carried out for the analysis of the PWT test on the wing leading edge model have been presented. The IR images have been processed through an ad-hoc developed mapping procedure to be directly compared with the results of the numerical analysis carried out through a non standard approach based on the unsteady simulation of the test and a coupling between the external aerodynamic field and the internal thermal field. A good agreement has been found between the experimental and numerical results. It has to be remarked that some uncertainties are associated to this type of numerical rebuilding especially for what concerns the characteristics of the material.

In any case, the possibility to apply the developed numerical/experimental procedure to rebuild a so articulated test, due to the adopted procedure and the dimensions of the model itself, has been demonstrated.

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