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24 March 2025

# AERO-THERMAL DESIGN OF STRATOFLY MR3 HYPERSONIC VEHICLE

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## ABSTRACT

Civil hypersonic flights are one of the key technological challenges of next generation. The EC-funded STRATOFLY (Stratospheric Flying Opportunities for High-Speed Propulsion Concepts) project has the objective of assessing the potential of this type of high-speed transport vehicle to reach TRL6 by 2035, with respect to key technological, societal and economical aspects, namely thermal and structural integrity, low-emissions combined propulsion cycles, subsystems design and integration including smart energy management, environmental aspects impacting climate change, noise emissions and social acceptance, and economic viability accounting for safety and human factors. This paper presents the aerothermal design of the new STRATOFLY MR3 hypersonic vehicle.

***Index Terms***— Hypersonic, Aerothermodynamics, FEM, TPS, Thermal

## 1. INTRODUCTION

Civil high-speed transportation has always been hampered by the lack of range potential or a too high fuel consumption stemming from a too low cruise efficiency. Over the last years, however, radical new vehicle concepts were proposed and conceived having a strong potential to alter this trend.
Indeed, on the basis of various conceptual vehicle designs carried out in a succession of EC-supported research projects, such as LAPCAT I/II [1], ATLLAS I/II [2], HIKARI, HEXAFLY [3] and HEXAFLY International [4], it has been possible to mature a number of configurations leading to the airframe-integrated propulsion concept. These concepts make use of unexploited flight routes in the stratosphere, offering a solution to the presently congested flight paths while ensuring a minimum environmental impact in terms of emitted noise and green-house gasses, particularly during the stratospheric cruise phase.
In this context, the STRATOFLY (Stratospheric Flying Opportunities for High Speed Propulsion Concepts) project has been funded by the EC, under the framework of Horizon 2020 program with the main objective of shortening the flight time of one order of magnitude with respect to the state of the art of civil aviation, for civil passenger flights of at least 300 passengers along long haul and antipodal routes. Through the preliminary design of LAPCAT MR2.4 (Mach 8 waverider vehicle) and flying at stratospheric altitudes within the future CNS/ATM scenario, STRATOFLY project aims as well at a reduction of the impact on existing on-ground infrastructures in compliance with environmental compatibility and safety issues, assessing the overall economic feasibility of the solution.
This paper presents the full aerothermal assessment of the new STRATOFLY MR3 vehicle.
In particular, according to the characteristic of flight vehicle trajectory, this paper deals with the design trade-off activities [5 - 8] undertaken to provide thermal integrity of the vehicle. Three main design stages can be identified. Firstly, an overall thermal analysis leading to a preliminary definition and sizing of aircraft Hot Structures (HS) and Thermal Protection System (TPS) has been carried out. Secondly, an extensive numerical campaign aiming at thermal design optimization and hot structures and TPS sizing refinements has been performed. Finally, a full transient thermal analysis, using ANSYS commercial software, has been realized for the whole vehicle to assess the capability of the structure to withstand the aero-thermal environment of the reference mission from take-off until landing. Main conclusions are presented and discussed.

## 2. VEHICLE MR2.4 PRELIMINARY CONFIGURATION

One of the main objectives of the STRATOFLY project is to evolve and improve the starting reference configuration (i.e. LAPCAT MR2.4), in-depth investigating all the issues strictly related to the subsystems integration within the external vehicle configuration and assessing the feasibility of the concept not only from a pure technical perspective, but also from an operational standpoint.

The reference configuration is a waverider concept (Fig. 1), aiming at maximizing the lift–to-drag ratio (L/D) during cruise. This shape has been obtained following several iterations and it is able to guarantee an L/D of about 7 [1]-[3]. With an internal volume of approximately 10000 $m^3$ and a reference surface area of about 2500 $m^2$.

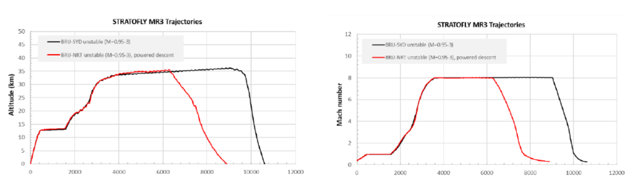
**Fig. 1. LAPCAT MR2.4 vehicle configuration.**

Starting from this configuration, different analyses have been carried out to assess the feasibility of the concept. In particular, the efforts have been devoted to both external vehicle configuration as well as its subsystems integration.

The current vehicle design is 94 m long and has a wing span of 41 m, and it hosts a passenger compartment accommodating 300 passengers and a highly integrated air-breathing propulsive subsystem able accelerating the vehicle up to Mach 8. Considering its high energy content, liquid hydrogen has been selected as propellant, to be stored in cryogenic integrated bubble tanks. This configuration is characterized by a maximum take-off weight of 400 tons and it shall be able to cover antipodal routes, reducing the travel time of one order of magnitude. STRATOFLY MR3 is a highly integrated vehicle, where propulsion, aerothermodynamics, structures and on-board subsystems are strictly interrelated to one another. [4;5;6].

## 3. REFERENCE TRAJECTORY

Two mission profiles have been studied by CIRA [6]: from Brussels to Sydney (about 19000 km) and from Brussels to Tokyo (about 12000 km). Trajectories have been computed and evaluated in terms of altitude, Mach number, aerodynamic efficiency and Angle of Attack time distribution (Fig. 2) with respect to project requirements. These last ones are respected for both the trajectories, but an unpropelled gliding descent to the destination airport is possible only for Brussels to Sydney mission. This is the reason why this latter is the reference trajectory for thermal simulations shown in present report.



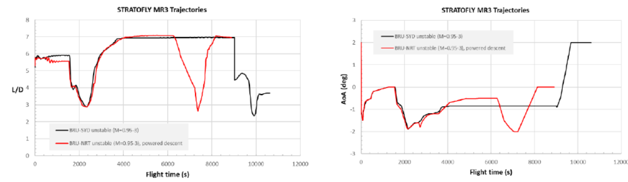




**Fig. 2. MR3 Flight Trajectories: Altitude (top left) Mach number (top right), Aerodynamic Efficiency (bottom left) and Angle of Attack (bottom right) time distribution [9]**

## 4. CFD

Previous aerothermal assessment [6] focused the attention on the choice of the best leading edge radius. The radius value of 11.3 mm seemed to be a good compromise between two opposite trends, i.e. the positive decreasing of thermal loads and the negative decreasing of mass flow rate and total pressure at the entrance of the combustor. Therefore, by means of the numerical code Ansys-Fluent® on a partial geometry (reduced domain) including in addition to the intake the combustor path, simulations have been carried out on the vehicle fuselage external layout in 6 different trajectory conditions. In particular, at M=4; M=6; and M=8 during the climb and descent phase have been analyzed.

CFD main results, in terms of flow temperature and heat transfer coefficient distribution are shown in Fig. 3 and Fig.4 at cruise conditions, i.e. at M=8 and 31.7 km of altitude, characterized by the following far field conditions: P=845.1 Pa, T=222.7 K.

Fig.5 highlights flow temperature and heat transfer coefficient distribution at Mach 8 for the crotch area. This area is the most critical area on the aerothermal point of view in terms of heat transfer coefficient (in the order of magnitude of 1.2 MW) and consequently of expected flow temperature.

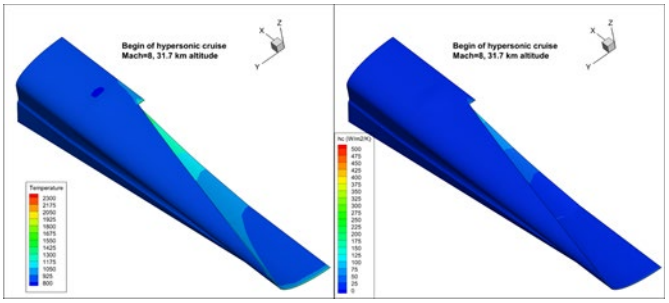



**Fig. 3. Flow Temperature and heat transfer coefficient distribution at Mach 8 (ISO view)**

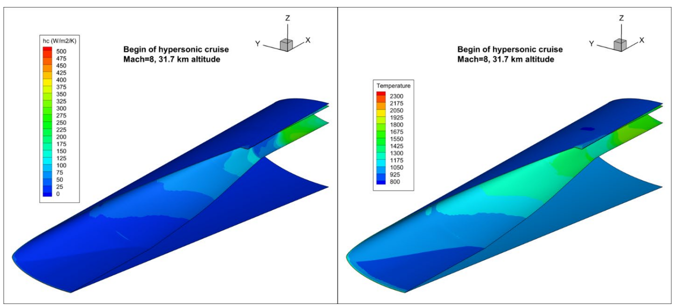



**Fig. 4. Flow Temperature and heat transfer coefficient distribution at Mach 8 (internal flow-path view)**

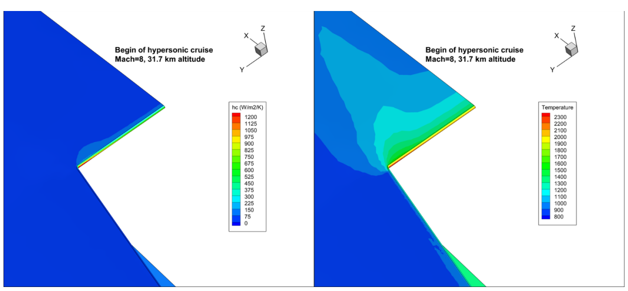



**Fig. 5. Flow Temperature and heat transfer coefficient distribution at Mach 8 (crotch area)**

## 5. THERMAL DESIGN

Different thermal design stages have been carried out and are here presented. Main results are summarized in the present section.

I. Firstly, an overall thermal analysis leading to a preliminary definition and sizing of aircraft Hot Structures and Thermal Protection System (TPS) has been carried out

II. Secondly, an extensive numerical campaign aiming at thermal design optimization and hot structures and TPS sizing refinements has been performed.

III. Thirdly, analysis has been performed for the whole STRATOFLY MR3 vehicle to assess the capability of the structure to withstand the aero-thermal environment of the reference mission

### 5.1. Phase 1

A full transient thermal analysis has been carried out on the preliminary geometry considered. Fig. 6 shows the thermal map at Mach 8 flight condition. As shown in figure, temperature is always under the material maximum service temperature except at some limited spots. Therefore, a set of points of interest on air intake leading edge has been chosen to better understand the structure thermal behavior (Fig. 7 and Fig. 9). Fig.8 and Fig.10 show the POI thermal behavior along the trajectory.

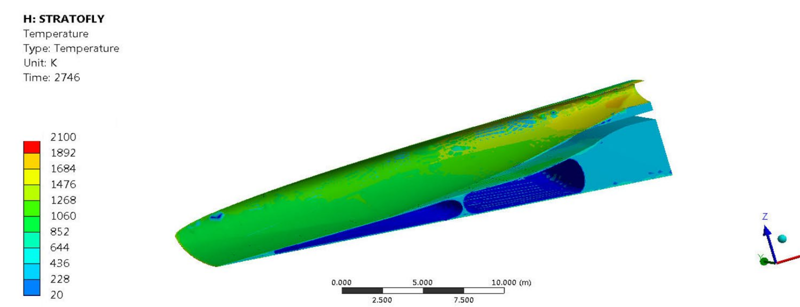



**Fig. 6. Thermal map at Mach 8**

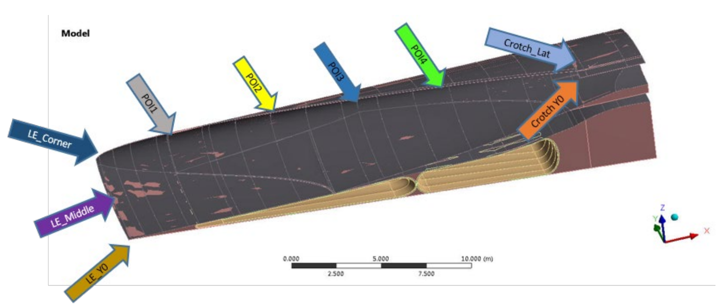



**Fig. 7. POI selections on the FEM**

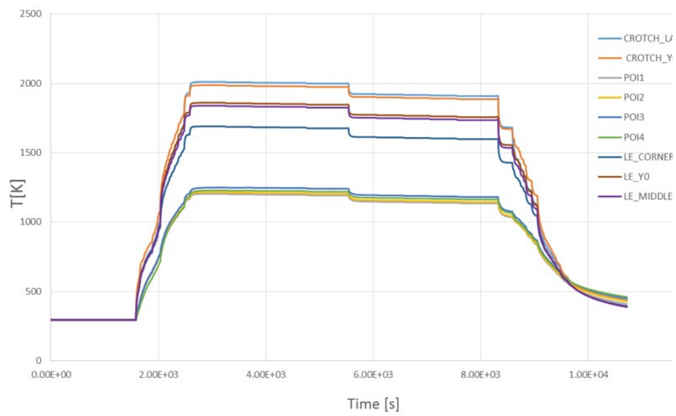



**Fig. 8. Air intake POI thermal behavior**

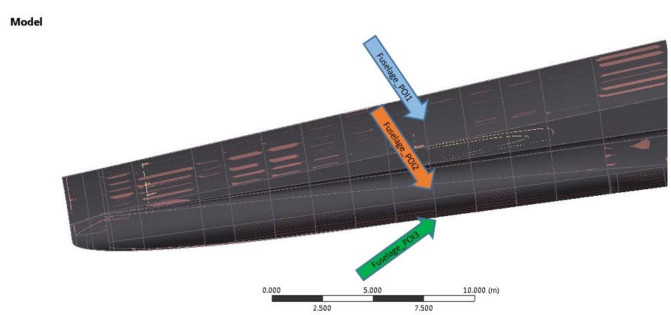



**Fig. 9. POI selections on the fuselage**

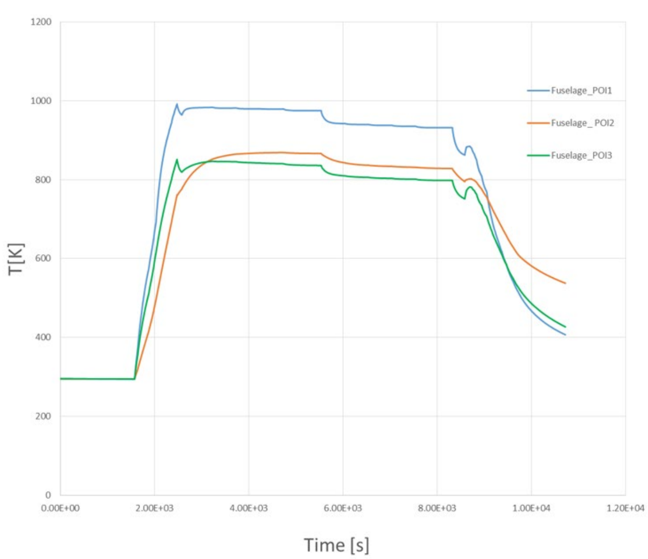



**Fig. 10. Fuselage POI thermal behavior**

As expected, it is confirmed that the Crotch will have to be cooled since the temperatures reached exceed 1600°C, i.e. the maximum operative temperature of CMC materials. On the other hand, CMC can be widely used for the main structure of STRATOFLY vehicle and its employment could be considered also for intakes, wing and vertical tail leading edges if the local heat flux does not exceed 0.7 MW/m$^2$.

### 5.2. Phase 2

Following the main results described in section 5.1, the need of a thermal design optimization came out. This led to a very detailed air intake leading edge thermal design.

The authors started investigating the possibility to couple high-temperature material with active cooling strategies. For this specific application, considering the volumetric constraint imposed by the MR3 air-intake, the heat-pipe concept has been further investigated. The typical sizing procedure described in literature [9][10][11] has been used to derive proper heat pipes architecture candidates. Specifically, the adopted process consists in four main steps, described in Fig. 11.

After a set of evaluations, the proposed heat pipe arrangement, which results to be capable of withstanding and managing the heat flux generated by the identified thermal environment is reported in Fig. 12 where Potassium (K) has been considered as driving fluid and Nickel (Ni) is selected as material for both primary structure (container) and wick of the heat pipe because of fluid compatibility.

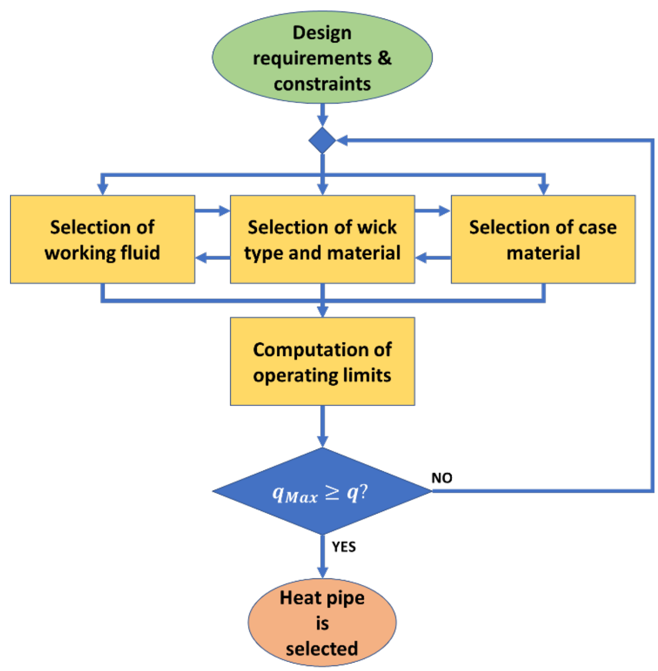



**Fig. 11. Heat Pipe sizing process**

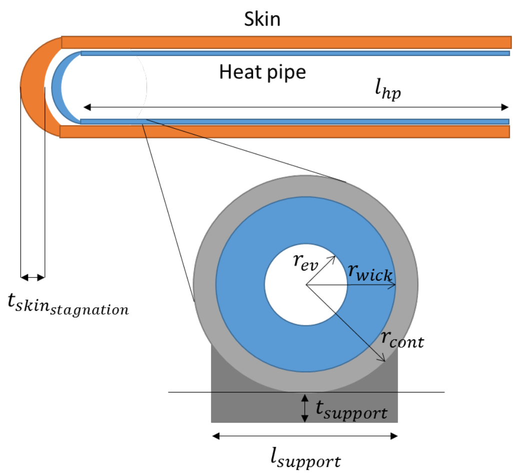



**Fig. 12. Most promising heat pipe arrangement**

The following geometrical parameters identify heat pipe arrangement:
$t_{skin_{stagnation}}$ is the skin thickness measured from stagnation point [m];
$l_{hp}$ is the length of rectilinear segment of heat pipe [m];
$r_{cont}$ is the external radius of heat pipe container [m];
$r_{wick}$ is the external radius of heat pipe wick [m];
$r_{ev}$ is the external radius of vapor channel [m];
$t_{support}$ is the thickness of the support flange connecting one heat pipe module with the skin [m];
$l_{support}$ is the width of the support flange connecting one heat pipe module with the skin [m].
In order to accommodate the heat pipes a general upper scaling of the vehicle has been necessary. In order to thermally design the crotch, a parametric approach has been followed. Indeed, starting from a basic geometry layout, as depicted in Fig. 13 different main geometric parameters have been identified.

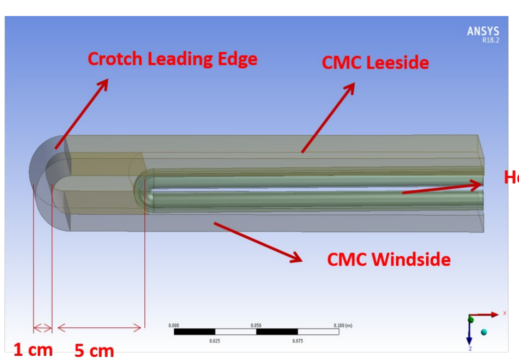



**Fig. 13. Crotch geometry basic layout**

In particular, 10 different transient thermal analyses along the flight trajectory performed to evaluate the time dependent temperature of the crotch leads to identification of 3 different possible solutions:

- A) Tungsten LE - High Emissivity Paint
- B) Tungsten LE – UHTC coating
- C) CMC LE

Following boundary conditions are considered.
The convective boundary conditions summarized in Table 1 have been considered and have been applied on the structural corresponding wet area. Structure upper scaling leads to CFD – structure wet area mis-alignment as shown in Fig. 14.

| L.E. Radius [mm] | MFR Eff. [-] | HF Crotch [MW/m$^2$] | Temp Crotch [K] |
|---|---|---|---|
| 11.30 | 0.969 | 1.092 | 2215 |
| 22.50 | 0.944 | 1.136 | 2234 |

**Table 1. Convective boundary conditions at Crotch from CFD [1]**

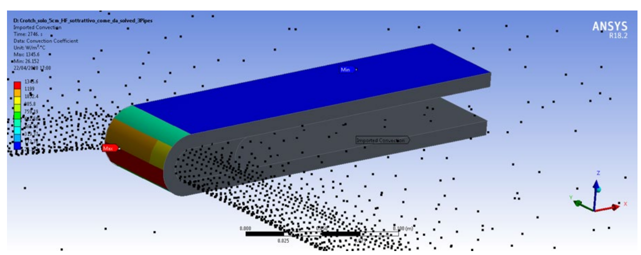



**Fig. 14. CFD – structure wet area mis-alignment**

A portion of the crotch has been modeled (corresponding to three pipes width on spanwise direction) and the following additional general boundary conditions have been considered:

- Radiation to ambient for external surfaces (ε=0.8);
- Adiabatic wall at cut surfaces location
- Subtractive heat flux applied at leading-edge internal additional part / heat pipe interface; (Fig. 15)

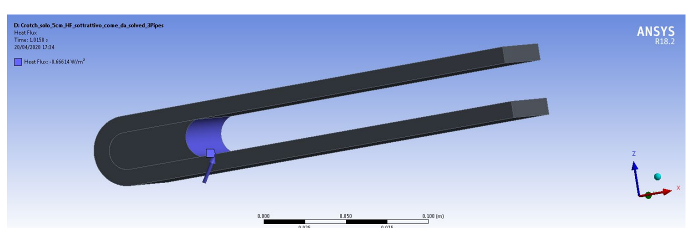



**Fig. 15. Subtractive heat flux location**

The 3 layouts are all safe but solution C must be preferred in terms of global weight, performance of heat pipe required and to avoid different material interface thermal stresses. For sake of simplicity only results for CMC leading edges are here shown.
Firstly, four different simulations have been performed varying the subtractive heat fluxes from the pipe. This allows checking the effect on maximum temperature on the crotch. Fig. 16 (a) shows the different fluxes whose peaks range from 700 kW/m2 for run 1 to about 950 kW/m2 for run 4. Fig. 16(b) shows the corresponding results in terms of maximum temperature on the crotch. It is clear that CMC acts as a very effective thermal barrier. Indeed, an increment in subtractive heat fluxes of the 25%, results in a 4.85% temperature reduction. Finally, run 4 conditions are retained because this scenario represents the one that keeps the CMC temperature under the theorical service operative temperature fixed at 1600°C. Figure 17 shows the thermal map on CMC leading edge at maximum time instant. The temperature reaches, in this case, a peak value of 1598°C at 2634s.

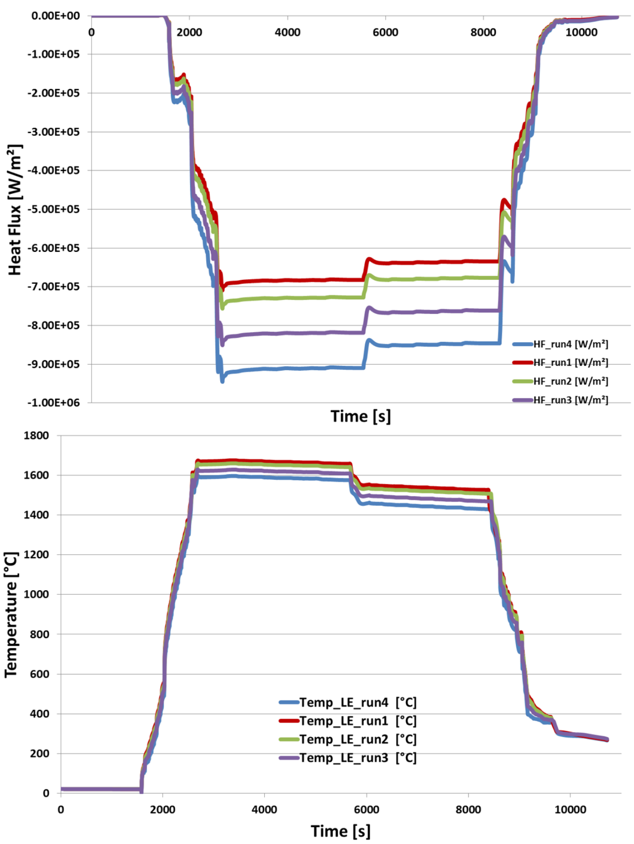



**Fig. 17. (a) Subtractive heat fluxes from heat pipe; (b)Maximum temperature evolution at CMC crotch w.r.t different subtractive heat fluxes**

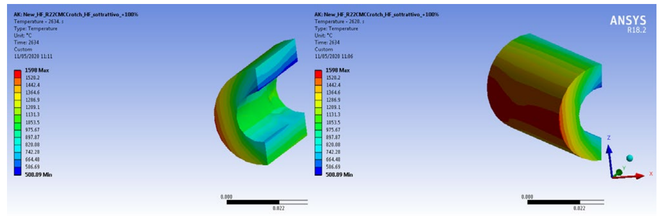



**Fig. 18. Thermal map on CMC leading edge at maximum time instant**

## 5.3. Phase 3

A final full transient thermal analysis has been performed for the whole vehicle.
A complete solid geometry has been considered for the final analysis. Finally, about 1000 different bodies have been imported in Ansys Workbench R21 as input to the thermal model (Fig.18). Geometry includes the airframe, the canards, tanks, heat pipes, passenger cabin and all the different structural internal components, such as beams, rods, stiffeners etc.
Following the results of transient thermal analysis, vehicle's material layout has been frozen as follows:

- External Structure-CMC, including the propulsive flow path (intake, combustor, nozzle); (Fig. 19)
- Tanks- Internal Frame and Structure – Aluminium; (Fig. 20)
- Passenger Cabin - CFRP* as baseline; (Fig. 19)
- Heat pipe: Nickel / Potassium.

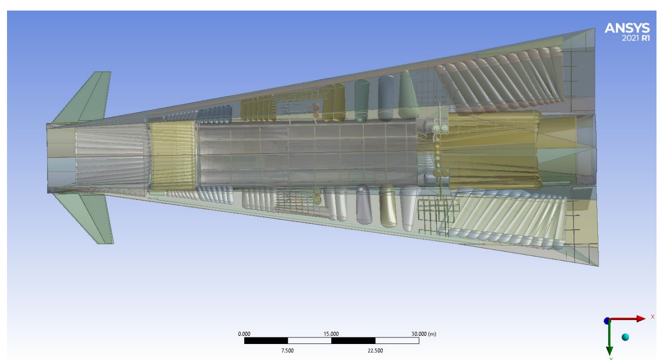



**Fig. 18. MR3 geometry layout: different views.**

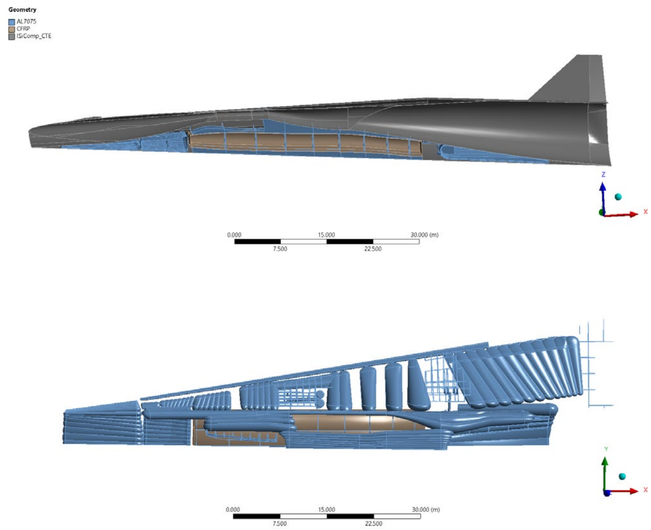


**Fig. 19. MR3 Material layout for main structural components, tanks and passenger cabin**

A full solid mesh has been developed having about 2.9-million nodes mixing HEXA20, TETRA10, WEDGE 15 and PYR13 solid finite elements in Ansys language (see Fig. 20).

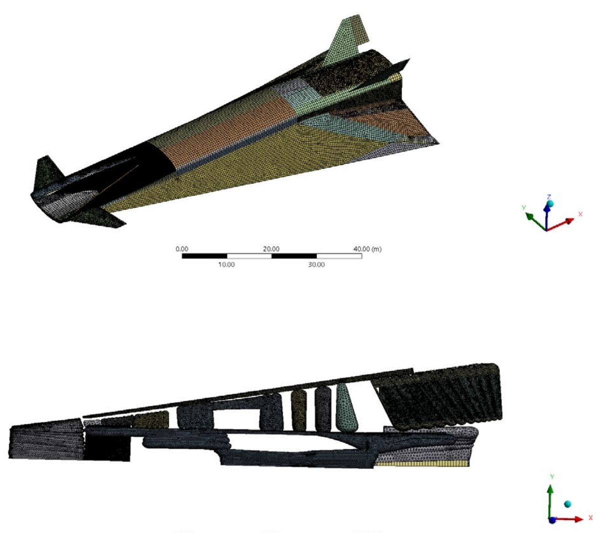


**Fig. 20. 3D Mesh for MR3 airframe**

Different boundary conditions have been applied.
In particular:

1. External convective heat flux, computed by CFD at Mach 4, 6 and 8 in climb and descent conditions, has been applied to the external airframe surfaces (Fig. 21).

2. On the same surfaces, a radiation to ambient condition with emissivity value of ε=0.8 has been considered as well.

3. A variable subtractive heat flux as shown in Fig. 16a) (run 1) is applied on internal crotch surface to simulate the cooling effect of heat pipe positioned inside (Fig. 23).

4. A convective heat flux distribution is imported on combustion chamber surfaces to simulate the dual-mode-ramjet (DMR) engine operation during the flight (Fig. 23.). The distribution takes into account the presence of a cooling jacket on the combustor section, i.e. the convection applied is a net convection between the hot contribution coming from CFD calculation, i.e. the effect of air-hydrogen combustion process, and the subtractive contribution of the cooling jacket. In order to correctly estimate the cooling jacket subtractive heat fluxes, input data from PoliTo EcoSimpro TEMS have been acquired in terms of pressure, temperature and mass flow along the whole trajectory. Fixing two relevant conditions at Mach 8 and Mach 6 ascent, and taking into account the impacted surface area of 39.45 $m^2$, it is possible to compute the cooling jacket subtractive heat flux of about 1.5 $MW/m^2$ for Mach 8 and of about 1.75 $MW/m^2$ at Mach 6.

5. A radiation to very conservative hot ambient temperature condition with emissivity value of ε=0.8 is set up for internal surfaces of combustion chamber, nozzle and divergent section.

6. To properly integrate the cooling effect coming from LH2 tanks within thermal analysis all along the reference mission, a simple analysis of LH2 tanks reference temperatures has been done by PoliTo and results show how estimated temperature varies from 20 K to 80 K for internal surfaces and from 200 K to 260 K for external ones. These values have been considered as boundary conditions for thermal analysis.

7. Radiation surface to surface between the combustion chamber and the leeside panel has been imposed with emissivity value of 0.8.

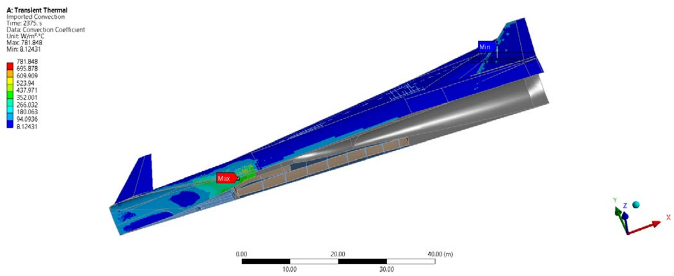


**Fig. 21. Imported convection on external surfaces**

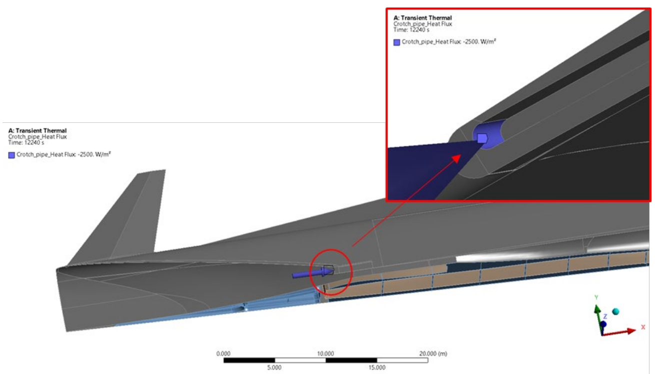


**Fig. 22. Subtractive heat flux resulting from the Heat Pipes**

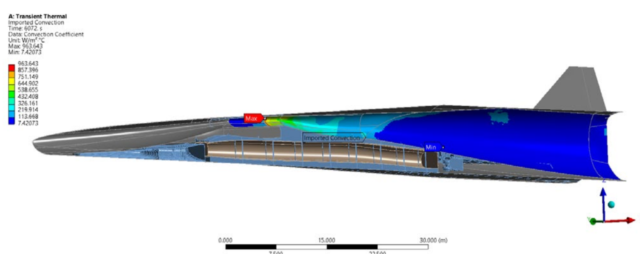


**Fig. 23. Imported convection on internal combustion chamber surfaces.**

Results are summarized in the following.

- Fig. 24 shows the temperature map at maximum temperature time instant (Mach 6) of the whole vehicle on different point of view. Two main phenomena can be highlighted: on the one hand the heat sink effect of tanks, especially on the wing panels but not only, is immediately evident, on the other hand the combustion chamber seems to overcome the CMC thermal allowable.

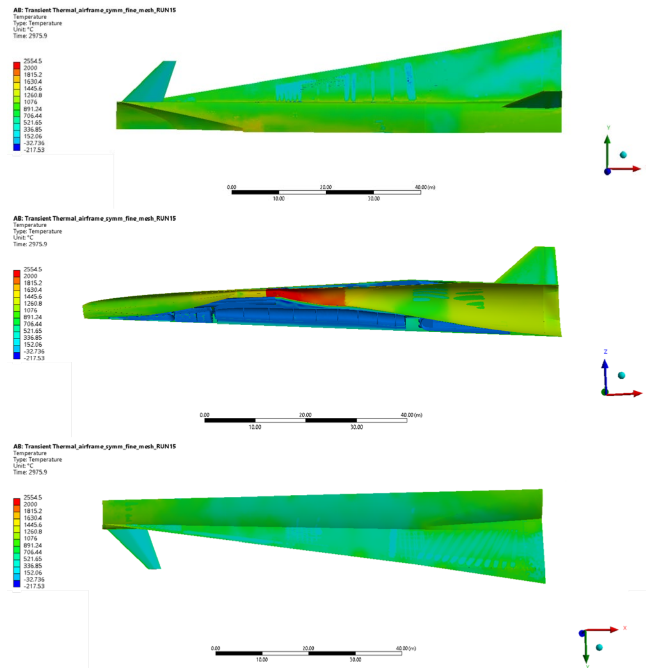


**Fig. 24. Temperature map at maximum time instant (Mach 6) – a) top view; b) internal view; c) bottom view.**

- Fig. 25 shows the temperature map at maximum temperature time instant (Mach 8) on external CMC airframe, i.e. on the main structure, for different point of view. It can be remarked that the structure is thermally safe (temperature always under 1600°C) with the exception of small limited spot on the wing leading edge.

- Fig. 26 shows the temperature map at maximum temperature time instant on the wing (Mach 8) for different points of view. The wing presents a hot spot at the beginning of the leading edge.

- Fig. 27 shows the temperature map at maximum temperature time instant on the canard (Mach 8) for different points of view. The component is safe on the thermal point of view.

- Fig. 28 shows the temperature map at maximum temperature time instant on the passenger cabin [12]. It can be highlighted that there are only two hot spots linked to thermal contact with the surrounding support structure. As shown in Fig. 29 the aluminium structure is overheated by the nozzle on the upper part and by the windside airframe panels on the lower part. This leads to two main conclusions:

- The stiffener box cannot be manufactured in Al7075 but a CMC material is more appropriate.
- These thermal contacts between the passenger cabin and the stiffener box must be avoided in the real configuration by appropriate insulation.

➢ Fig. 30 shows the temperature map at maximum temperature time instant on the propulsive flow path at Mach 6 and Mach 8 flight conditions. The following aspects must be highlighted:
- The effect of the radiation surface to surface between the external faces of combustor and the airframe leeside panels is effective to lower the temperature under CMC allowable. Nevertheless, due to the low CMC conductivity (the CMC acts as thermal barrier) the internal surfaces do not beneficiate of this condition.
- The heat sink effect of front additional tank is evident along the path. Nevertheless, the beneficial effect is localized to the perfect contact areas.
- At Mach 8 the combustor exceeds the indicated allowable of about 300 °C, but at Mach 6 the overcome is of about 900°C. This is linked to an excessive heat load. Indeed, as shown in Fig. 30 that area is impacted by extremely high heat fluxes values for a very long time (about 500 s at Mach 6, and about 6030 s at Mach 8) leading to an enormous Heat Load (about 1500 MW at Mach 6 and 1000 MW at Mach 8). Therefore, further detailed CFD computations as well as detailed thermo-structural FEM analysis must be set to ensure the combustor survival along the proposed trajectory, by considering a larger subtractive heat flux (i.e. a more effective cooling jacket for the combustor) if TEMS is able to satisfy this new requirement, and/or a more performant CMC material for combustor section.

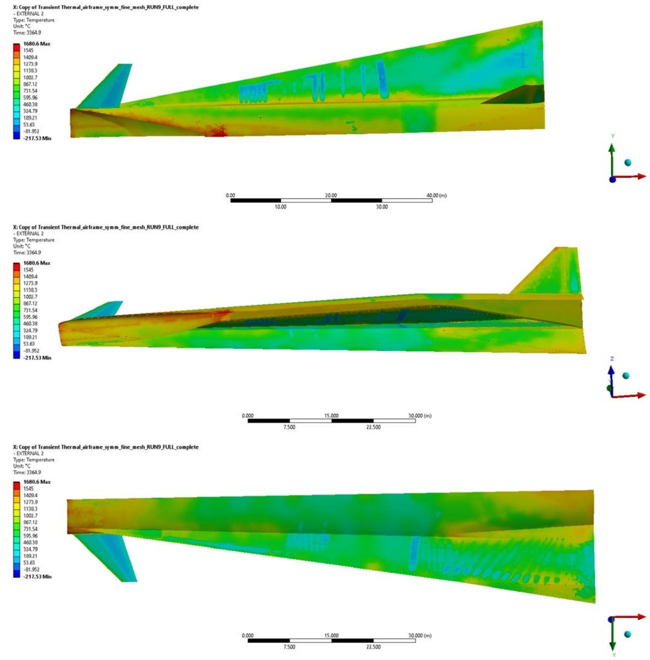


**Fig. 25. Temperature map at maximum time instant on external airframe (Mach 8) – a) top view; b) internal view; c) bottom view.**

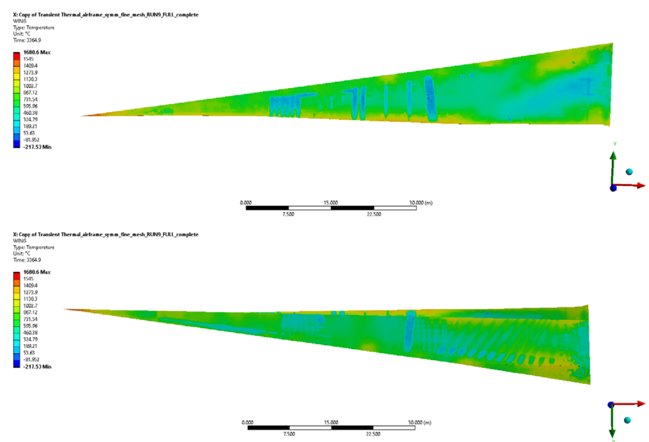


**Fig. 26. Temperature map at maximum time instant on the wing (Mach 8) – a) top view; b) bottom view.**

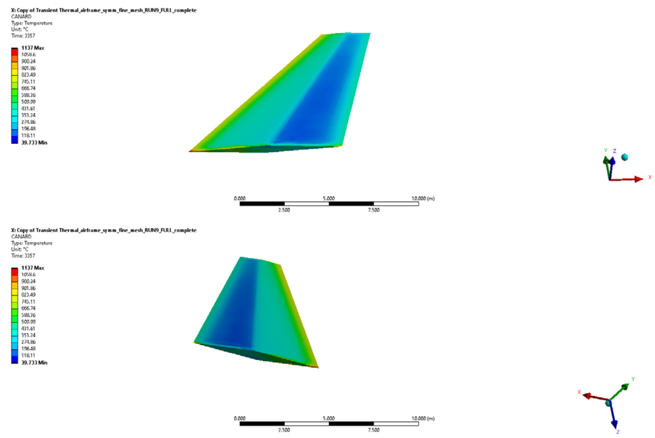


**Fig. 27. Temperature map at maximum time instant on the canard (Mach 8) – a) leeside view; b) windside view.**

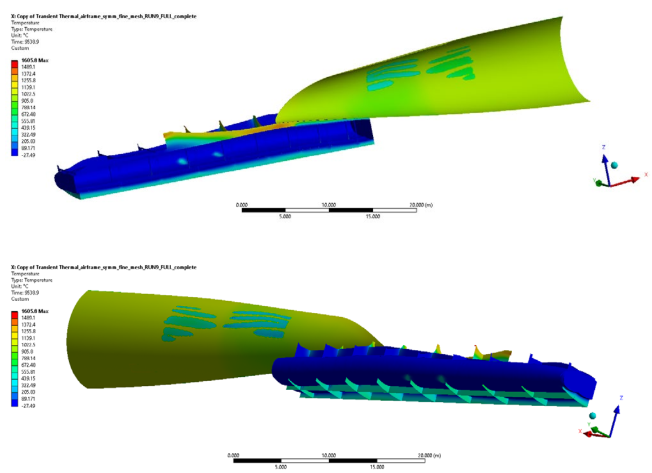


**Fig. 28. Temperature map at passenger cabin and surrounding stiffener box structure (a – internal view; b – external view): heat transfer mechanism.**

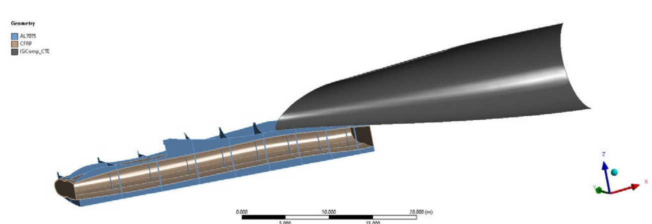


**Fig. 29. Passenger cabin, stiffener box, nozzle material distribution.**

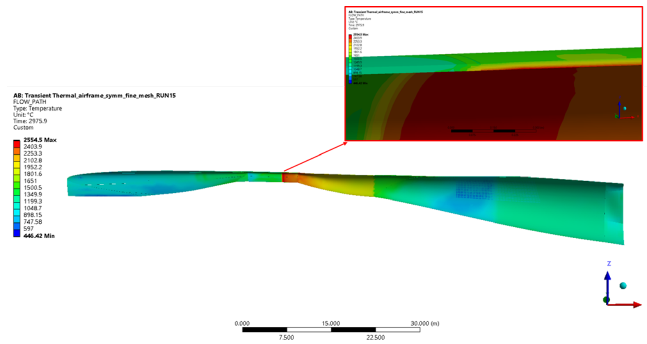


**Fig. 30. Temperature map at maximum time instant on the propulsive flow path (Mach 6).**

## 6. CONCLUSION

Different thermal design stages have been presented in the current report. Main conclusions are summarized in the present section.

I. Firstly, an overall thermal analysis leading to a preliminary definition and sizing of aircraft Hot Structures and Thermal Protection System (TPS) has been carried out. Main result of this stage is that:
   a. the Crotch will have to be cooled since the temperatures reached exceed 1600°C, i.e. the maximum operative temperature of CMC materials. On the other hand, CMC can be widely used for the main structure of STRATOFLY vehicle and its employment could be considered also for intakes, wing and vertical tail leading edges if the local heat flux does not exceed 0.7 $MW/m^2$.

II. Secondly, an extensive numerical campaign aiming at thermal design optimization and hot structures and TPS sizing refinements has been performed. Main results are:
   a. CMC can be used for the airframe structure.
   b. The Crotch optimal design consists of 1 cm of CMC at LE, and the use of a heat pipe system for cooling which maintains the temperature within the limits is required.
   c. CMC Lower lip air intake with no heat pipe is sufficient to withstand the aerothermal environment.

III. Finally, a full transient thermal analysis has been performed for the whole STRATOFLY MR3 vehicle to assess the capability of the structure to withstand the aero-thermal environment of the reference mission. Main results can be summarized as follows:

a. The CMC airframe structure is thermally safe (temperature always under 1600°C).
b. The heat sink effect of tanks is high and important. Nevertheless, the thermal benefit of these contacts is localized to the perfect contact areas and due to the low CMC conductivity (the CMC acts as thermal barrier) this leads to strong temperature variation in relatively narrow areas, i.e. leads to potential structural failure for thermal stresses. Therefore, we strongly suggest to avoid perfect bonded thermal contacts between tanks and structure by insulating materials.
c. The heat pipes designed in the second stage are confirmed to be effective in cooling the crotch.
d. Passenger cabin is thermally safe with the exception of two hot spots linked to thermal contact with the surrounding stiffener box structure. This leads to two main conclusions: the stiffener box cannot be manufactured in Al7075 but a CMC material is more appropriate and that perfect bonded thermal contacts between the passenger cabin and the stiffener box must be avoided in the real configuration by appropriate insulation.
e. The combustor exceeds the CMC temperature allowable at Mach 6 and Mach 8. This is linked to an excessive heat load. Therefore, further detailed CFD computations as well as detailed thermo-structural FEM analysis must be set to ensure the combustor survival along the proposed trajectory, by considering a larger subtractive heat flux (i.e. a more effective cooling jacket for the combustor) if TEMS is able to satisfy this new requirement, and/or a more performant CMC material for combustor section.

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