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An innovative Phase Change Material Device implementation in the [1]HEXAFLY Hypersonic glider

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Abstract

High-speed vehicles using a hot aero-structure concept require a different design strategy for mounting electronic units and handling their dissipated heat for which one cannot rely any longer on the heat-sink approach as in the case of cold structures. Phase Change Materials (PCM) offer the possibility to store thermal energy directly as latent heat of fusion. A PCM is a material having a high heat of fusion, whose change of state at the relevant temperature is able to store a large amount of energy. Highly dissipative electronic units such as transmitters can be directly mounted onto this PCM device. During the change of state, the temperature remains almost constant. Thanks to previous R&D projects, WalOpt and CRM have developed and qualified a PCM Heat Storage Device that is now available for flight. The modeled thermal behavior is described together with the chosen implementation to optimize the mass gain.

Keywords

High-Speed, Phase Change Material, thermal control, thermal spreader, mass saving.

Nomenclature

EFTV	Experimental Flight Test Vehicle
ESM	Experimental Service Module
PCM	Phase Change Material
PCM-HSD	Phase Change Material Heat Storage Device
TCS	Thermal Control System
TPS	Thermal Protection System

1. Introduction

For some years, ESA has launched studies and research activities to increase performance and reliability of thermal control systems for spacecraft and launchers. Presently, the technology of a Phase Change Material - Heat Storage Device (PCM-HSD) has matured and has reached a TRL 6 for short duration flight [1,2,3]. A PCM is a material having a high heat of fusion, whose state change at the relevant

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temperature can store and release a large amount of energy. During this change of state, the temperature remains almost constant [4].

In the endeavour to explore their application to the new generation of reusable high-speed space planes, whether used as first stages or high-speed transport vehicles, the capabilities of PCM-HSD devices are explored and revisited. Indeed, the related requirements are different with respect to the original applications as one is faced with longer exposure times to external aerodynamic heating along with a more extended operational time, i.e. combined ascent and descent time in combination with reusability aspects. In that respect, the HEXAFLY-INT (High-Speed Experimental Fly Vehicles - INTernational) Project is an unique European initiative and opportunity to explore their applicability to high-speed planes and offering the possibility to flight prove the efficiency of such a thermal control device.
The HEXAFLY-INT Project is an international consortium with partners from the European Union, Brazil and Australia aiming to develop and increase the TRL level for key technologies to High-Speed transportation. Hence the vehicle design, manufacturing, assembly and verification are carefully studied allowing the hypersonic glider to demonstrate a high aerodynamic efficiency in combination with high internal volume at a cruise Mach number of 7 to 8 in a controlled way based upon a hot structure and high-temperature materials [5,6,7,8]. The Experimental Flight Test Vehicle (EFTV) will be launched from a sounding rocket and perform then a gliding trajectory representing a return trajectory (Fig. 1).

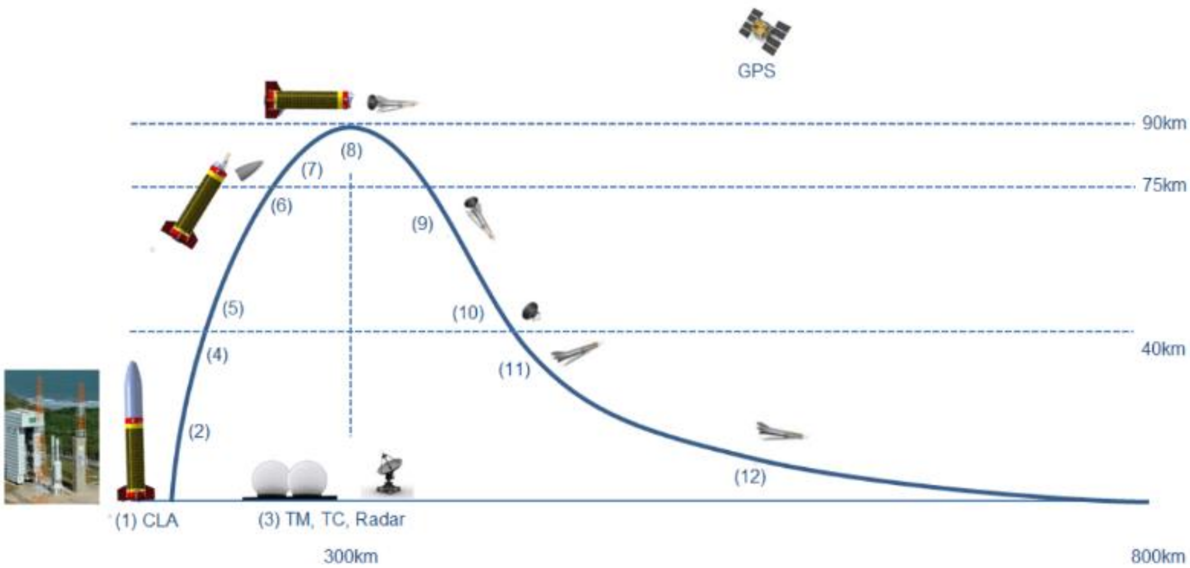

Fig. 1 HEXAFLY-INT profile mission

Throughout this trajectory, the EFTV is externally exposed to aerodynamic heating whereas the internal electronic equipment is dissipating heat. These units have an upper operational temperature limit which should not be crossed throughout the complete trajectory. However, as the EFTV is based upon a hot aerostructure (i.e. no heat shield mounted onto a cold structure as e.g. for the Space Shuttle), the thermal design methodology needs to minimize the heat soaking from the external walls either by conduction or radiation. During this trajectory the outer skin along the fuselage can reach temperatures well beyond 500°C. Direct radiation is at first instance prevented by internally mounted flexible thermal insulation layers (Aeroguard) from Promat. This technology implementation is realized by Promat and VKI which are described in [9,10].

Whereas electronic units are normally mounted directly on the primary structure allowing simultaneously for a good conductance while exploiting the heat sink principle, this design approach cannot be exploited and requires on the contrary a thermal insulation within the mounting procedures. The thermal control and heat dissipation of the electronic units require then dedicated solution.

It is useful to remind here the main justification of studying PCM as a possible thermal control mean. The PCM is one of several potential thermal-design approaches. In most space applications, criteria for design selection boil down to the one having the lowest mass and power requirements. Competing thermal-control approaches include using a solid heat sink made from a high-specific-heat material such as Aluminium (but also beryllium) or relaxing temperature stability requirements. In the trade-off with a solid heat sink, an efficiently packaged PCM will usually show a mass advantage over the solid heat sink. Two kinds of advantages can be reached when using a PCM heat storage:

- mass gain by sizing down or suppressing the thermal spreaders;
- decrease of the qualification temperature of the electronic equipment by limiting the temperature range.

Anyway, attention should be paid to the PCM container thickness, which can constraint the good conductance through the PCM. Volume of the PCM container should also be addressed carefully when analyzing its implementation.

We can focus the use of a PCM on one of these targets or mixing both.

A direct comparison of the mass for a PCM based design, with mass for a non-PCM design has been made in our preliminary study before the beginning of this project. It showed a large mass advantage for the PCM use. The use of a spreader would have involved an extra mass of about 16 kg, compared with the mass of the PCM-HSD of 2.3 kg. So, a saved mass of 13.7 kg.

The process for the choice of the PCM materials and the various used criteria have been presented previously [2][3][4]. The HEXAFLY-INT team has defined the thermal loads during the mission. The equipment that needs a specific thermal management is identified as:

- 4 telemetry transmitters (TM&TV-TX)
- 4 telemetry couplers (TM&TV-Coupler)
- 2 telecommand receiver (TC-RX)
- 1 telecommand coupler (TC-Coupler)
- 1 GPS Phoenix with its pre-amplifier
- 1 GPS Novatel

Numerous configurations have been studied by WalOpt to optimize the thermal behaviour, the place available and the mechanical resistance.

The 4 TM&TV-Couplers are fixed on an aluminium plate which is located above 2 TM&TV-TX. The GPS Phoenix and its pre-amplifier are fixed on another aluminium plate which is located above 2 TM&TV-TX. The GPS Novatel is located on the other side of the PCM HSD (Fig. 2).

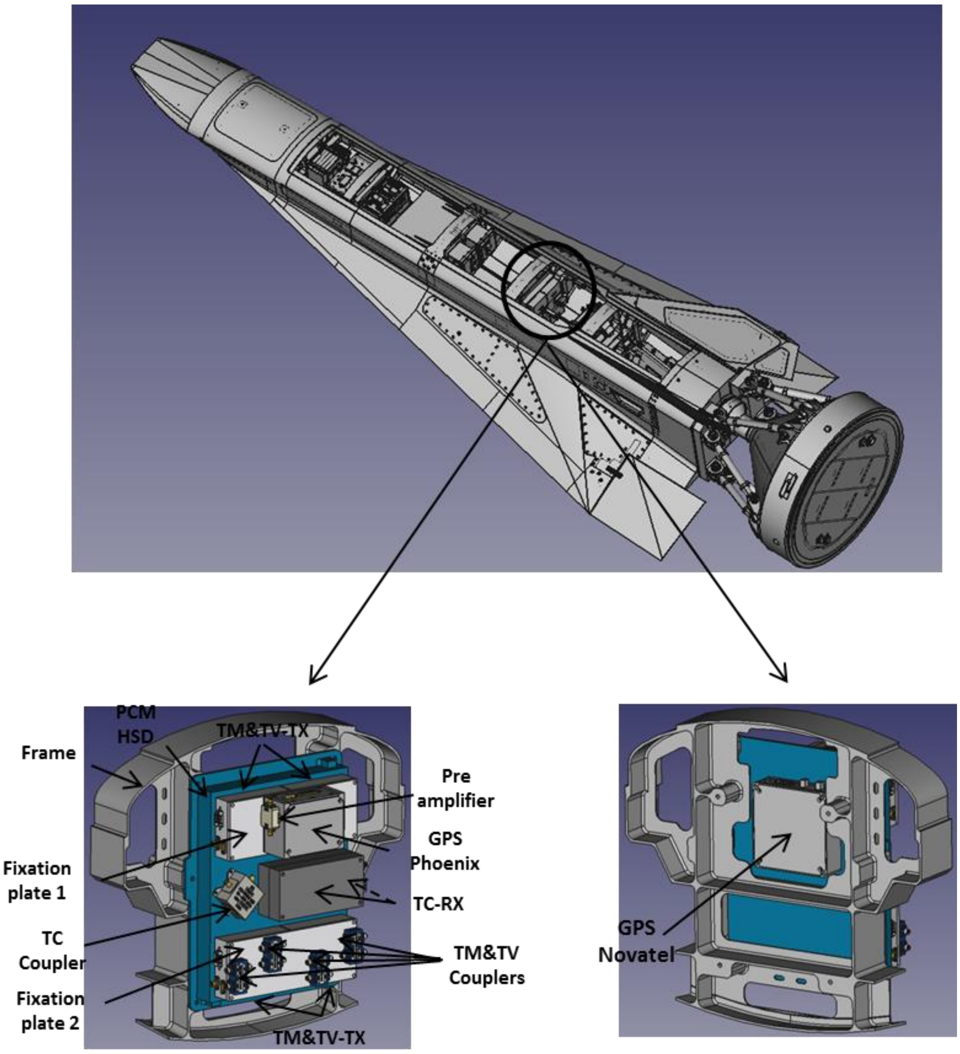

Fig. 2 Insertion of the equipment and their PCM-HSD into the EFTV

The complete mission is composed of different phases:

- Pre-flight operations (from the switch ON of the equipment to the ignition of the booster);
- Flight composed of 3 sub-phases:
    - Boosted phase (from the ignition of the booster to the separation of the booster);
    - Ballistic phase (from the separation of the booster to the separation of the ESM);
    - Glided phase (from the separation of the ESM to the splash-down of the EFTV).

Equipment is switched ON during all pre-flight operations and the flight. It is submitted to its own thermal dissipation, the thermal radiation with the internal environment, the thermal conduction from the fixations to the structure, the thermal free convection with the internal air.
The PCM-HSD and its equipment are submitted to quasi static g-loads and vibrational g-loads during the boosted phase of the flight. They are submitted only to quasi static g-loads during the other phases of the flight.
The PCM-HSD and its equipment are also submitted to two shock g-loads: one during the booster ignition and one during the EFTV/ESM separation.

The thermal boundary conditions of the PCM-HSD are:

- No radiation exchange;
- No convection inside;

- Conduction from the frame: the frame is at 20°C up to the launch, then increasing as shown on Fig. 3;
- Insulating washers in Vespel between the assembly and the frame;
- Pre-flight duration: 1200 sec, flight 840 sec;
- Heat load:

  4 TM&TV – TX: 97.6 W
  2 TC-RX: 7.28 W
  2 TM&TV couplers: 3.2 W
  GPS Phoenix: 3 W

The heat to be stored throughout the complete 2040 s mission is E = 226 603 J.

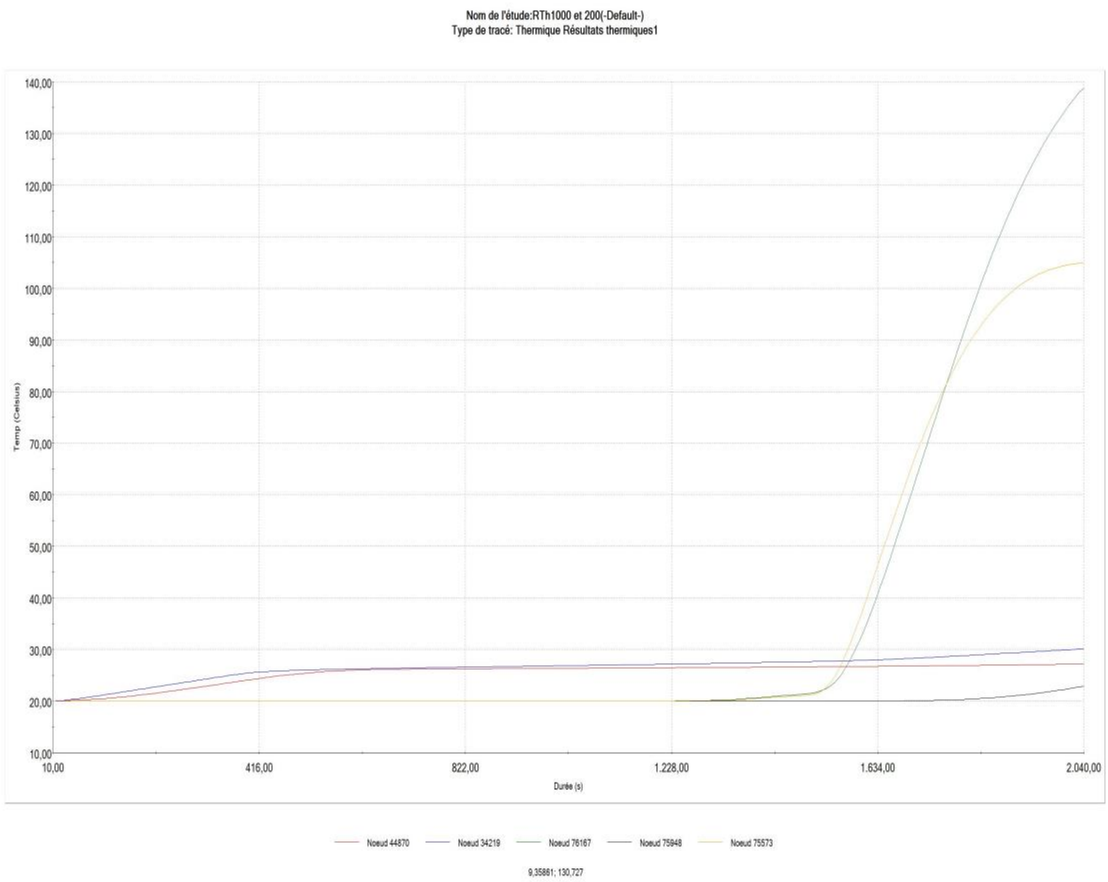

Fig. 3 Frame I/F temperatures during the mission

2. PCM-HSD Design

The main characteristics of the PCM are given hereafter:

- Melting range: 27 – 29 °C
- Specific heat solid/liquid: 1 910/2 220 J/kg.K
- Latent heat: 210 500 J/Kg

The latent heat and other main characteristics have been verified on the batch ordered, as we have noticed some dispersion in the previous batches.

A Finite Element Model has been created to assess the behaviour of the whole assembly. This model has taken various assumptions as far as the thermal boundary resistance between the components is concerned. Some results are shown in Fig. 4 and Fig. 5.

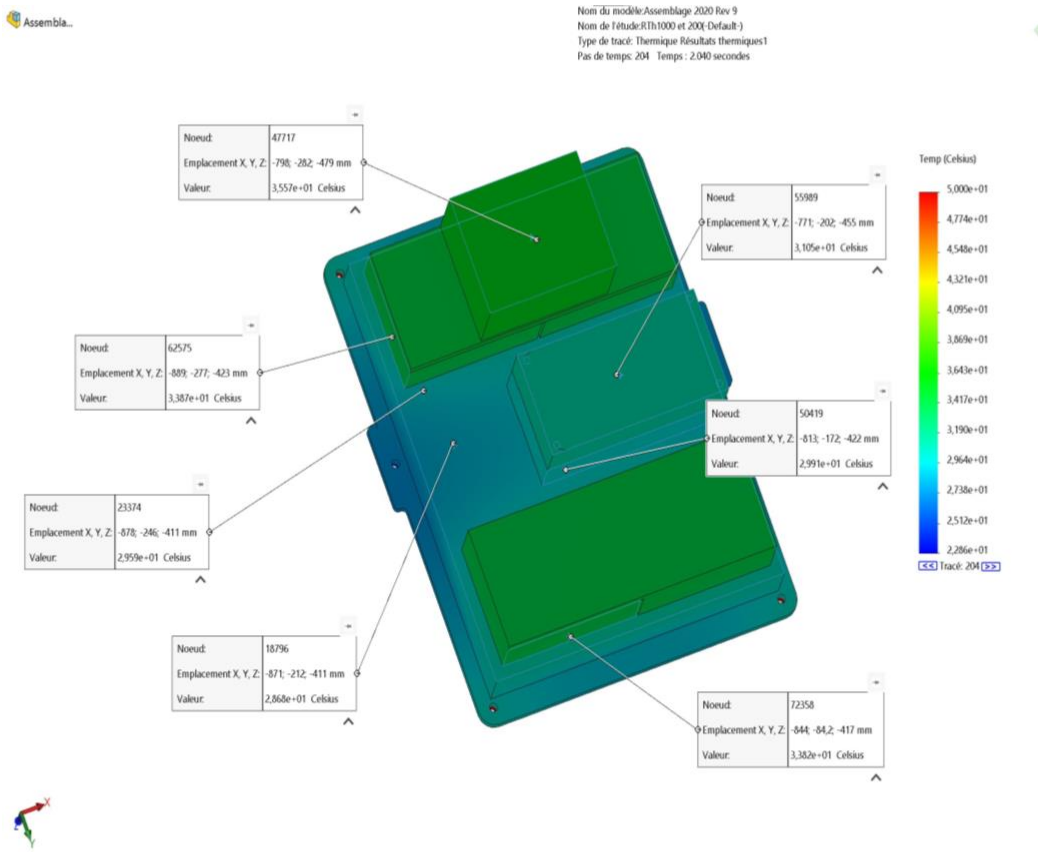

Fig. 4 Temperatures at the end of the mission (I)

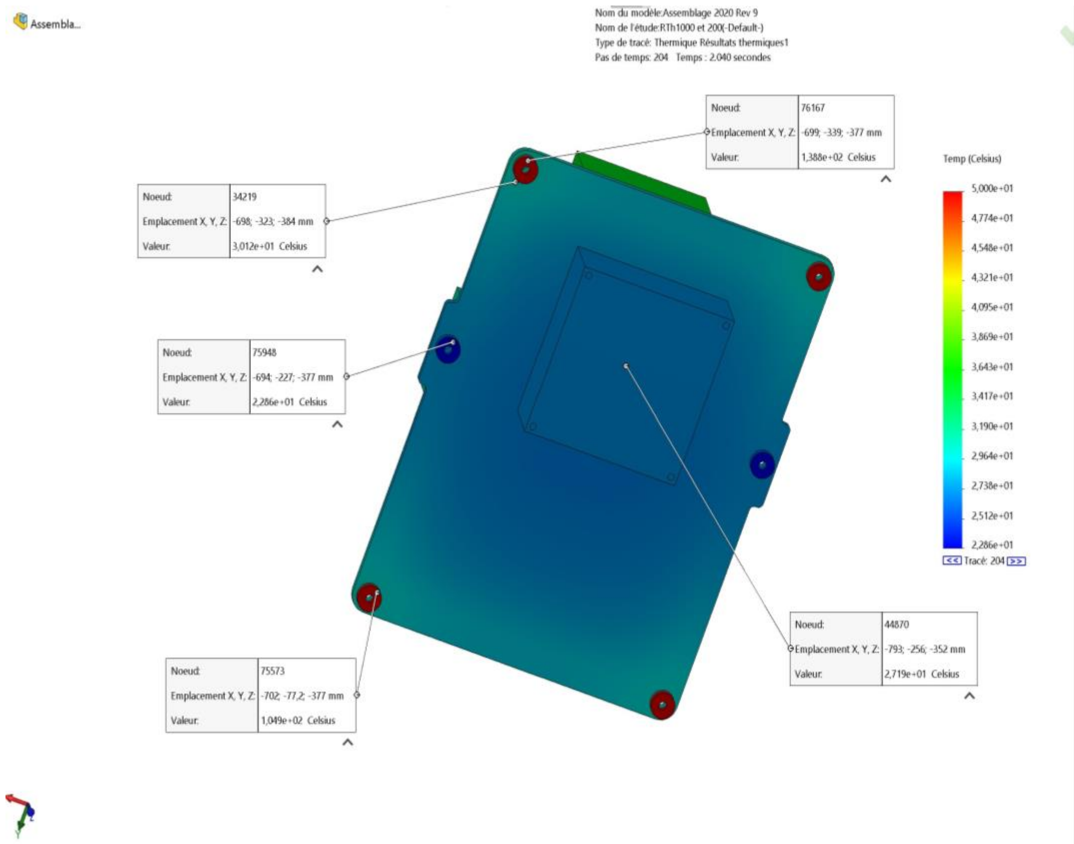

Fig. 5 Temperatures at the end of the mission (II)

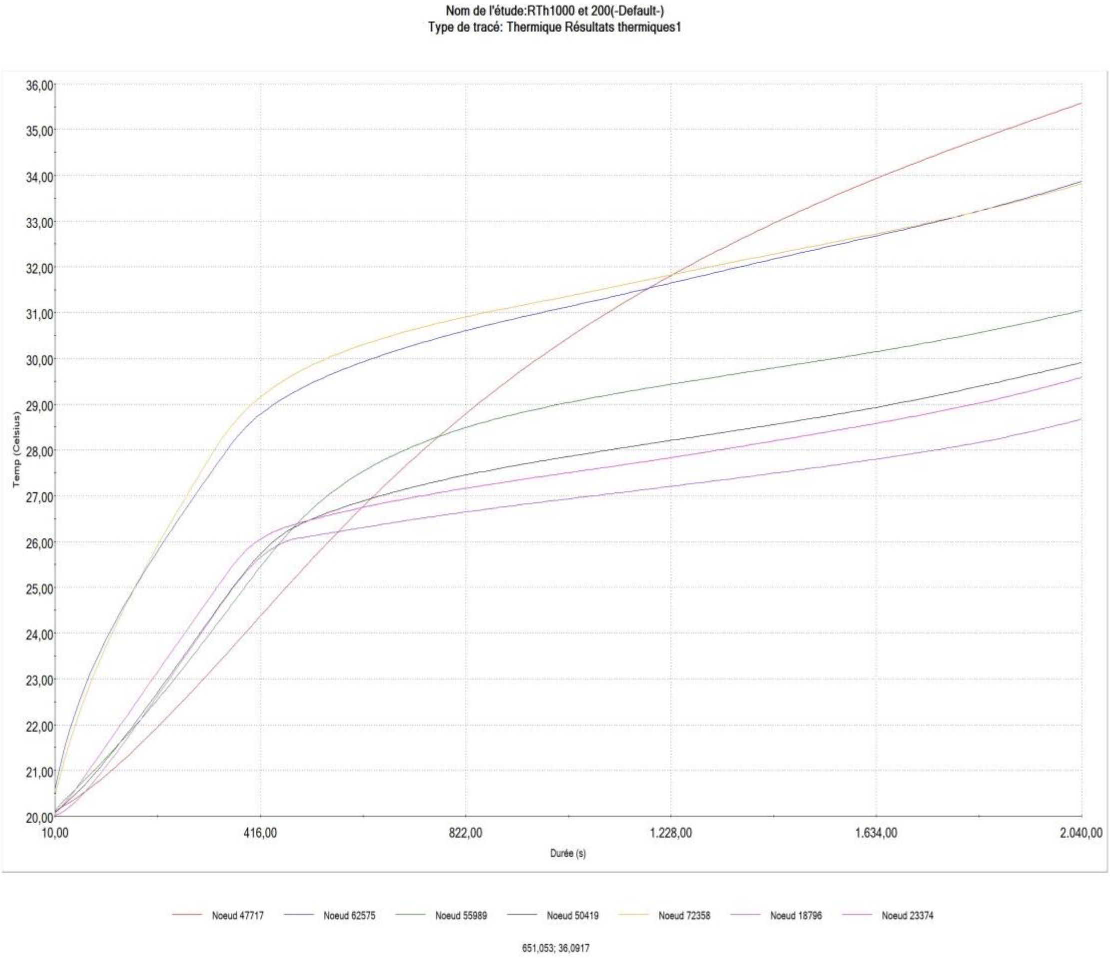

Fig. 6 Evolution of Unit temperatures during the mission

The nodes temperatures on this figure correspond to the following positions:

Node 47717: GPS Phoenix
Node 62575: TM&TV-TX
Node 55989: TC-RX (upper)
Node 50419: TC-RX (lower)
Node 72358: TM&TV-TX
Node 18796: PCM-HSD top cover
Node 23374: PCM-HSD top cover near TM&TV

It can be seen that the maximum temperature is reached with the GPS Phoenix, with a maximum of 35.6 °C.

The Mechanical loads have also been studied. According to the specification, the Ultimate Equivalent Static load is the following:

FX = 30,80 g corresponds to the axial load applied on the bolts fixing the e-units on the PCM-HSD
FY = 9.98 g
FZ = 9.36 g towards the top/down sides of the glider

The Von Mises stresses under shear loads are shown on the following figure of the FE model.

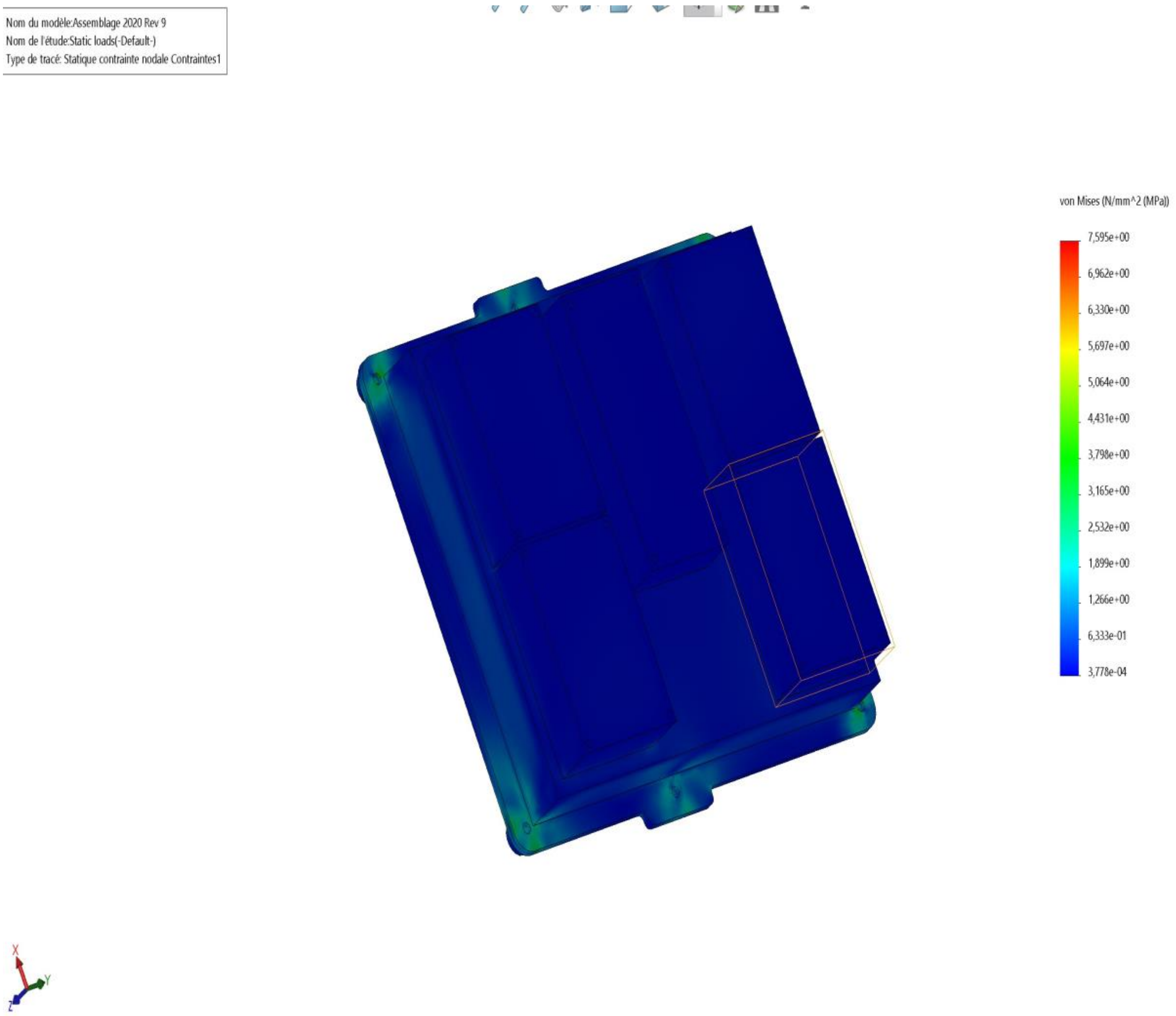

Fig. 7 Von Mises stresses under shear loads

The eigen frequencies of the PCM-HSD have been computed with a FE model and the first one at 575 Hz is shown in the following figure. Other computations have been made, taking into account the electronic units and PCM mass.

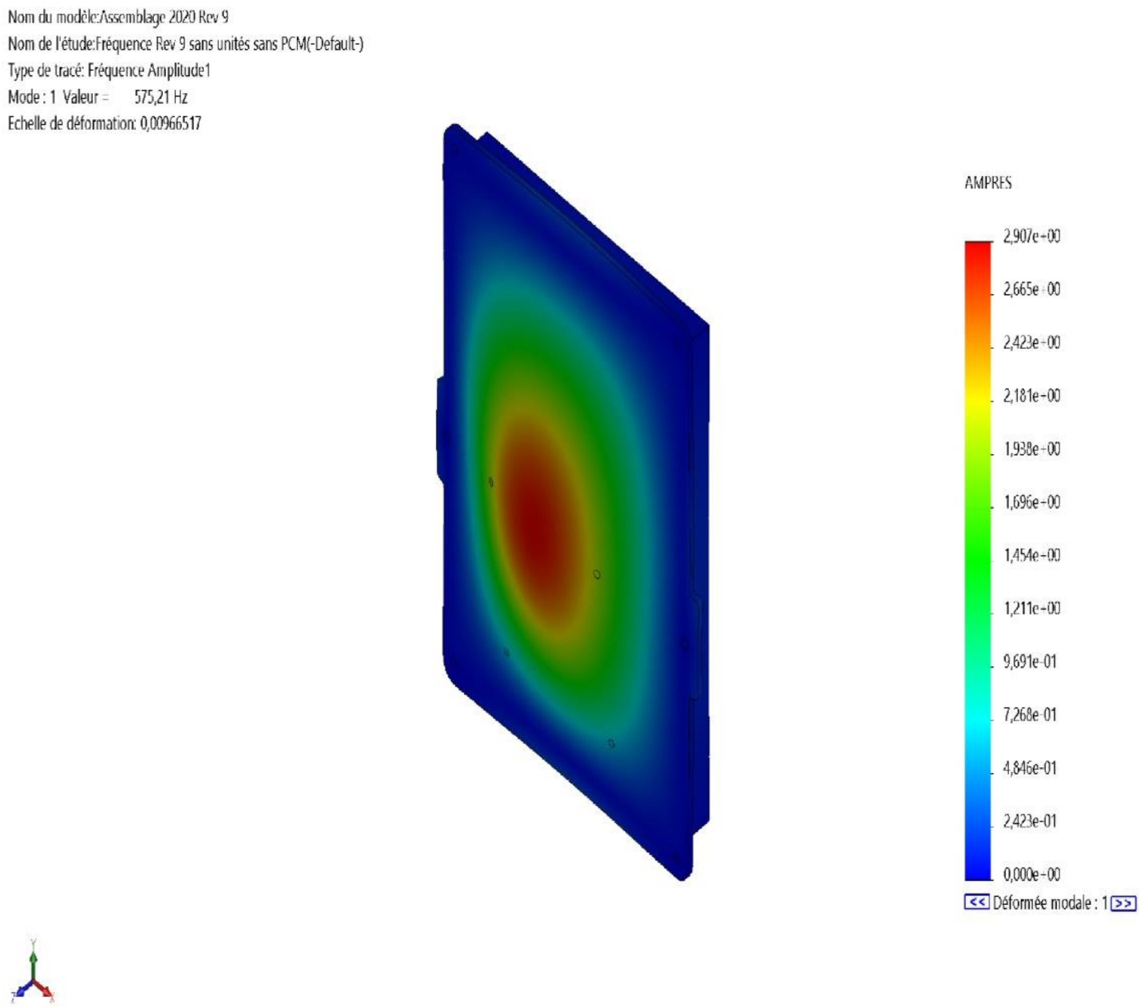

Fig. 8 First eigen frequency of the PCM-HSD

3. PCM-HSD Flight Model

The Flight Model of the PCM-HSD is presently finished and will be shortly tested at DLR. The following figure shows this model before filling with the PCM.

Fig. 9 Flight Model of the PCM-HSD

4. Conclusion

A PCM-HSD was developed for an extended high-speed flight on board of an experimental flight vehicle and is presently under tests. Its performance is expected to satisfy the thermal load with a mass of 2.3 kg instead of 16 kg for a more classical solution. The possibility to customize the design has shown a great versatility versus the available space and cooling of a large amount of equipment. The heavy mechanical loads are sustained by the thermal control system itself, evolving therefore towards a complete thermo-mechanical device.

5. Acknowledgment

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