Thermal design of heat pipe cooling systems: conceptual design and numerical development

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EXTENDED ABSTRACT

Commercial hypersonic transport represents one of the main goals of next future economic and technological challenges. Designing a civil high-speed aircraft for passenger transportation means evaluating technical, environmental and economic viability in combination with human factors, social acceptance, implementation and operational aspects.
In the past years, some innovative high-speed aircraft configurations have been proposed and in-depth evaluated with the main goal of demonstrating the economic viability of a high-speed aircraft fleet [1-4]. 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. Only a dedicated multi-disciplinary and highly integrated design concept could realize this, where aero-thermodynamic issues are evaluated together with the structural and propulsive issues, in the frame of a highly multidisciplinary project [5-9].
This paper describes the thermal design processes of heat pipes as vehicle cooling system, i.e. showing either the methodology and the supporting numerical simulations. A heat pipe can be simply described as a self-contained, two-phase heat transfer device which consists of a container, a wick, and a working fluid. At first, the incoming heat is collected at the heat pipe evaporator region; then, the heat is conducted through the container and into the wick/working-fluid matrix, where it is absorbed thanks to the evaporation of the working fluid. The heated vapor flows towards a slightly cooler region of the heat pipe, called condenser, where the working fluid condenses, rejecting the heat previously stored through the wick/working-fluid matrix and container. The heat pipe cycle is completed when the liquid comes back to the heated region (evaporator) making benefit of the capillary pumping action of the wick. During normal operation, heat pipes is characterized by a very high effective thermal conductance, maintaining a nearly uniform temperature over the entire heat-pipe length. As far as high-speed aircraft and space vehicles are concerned, ad-hoc tailored heat pipe arrays may be suitable for integration within wing and air-intake leading edges to transport the high net heat input occurring in proximity of the stagnation point to a cooler region, raising the temperature there above the radiation equilibrium temperature and thus rejecting the heat by radiation.

Both the applications rely upon the development of several finite element models to perform a parametric study aimed, on the one hand, at evaluating the pipe performance and, on the other hand, at optimizing main structure layout in terms of material and geometric thicknesses. In particular s numerical Ansys Parametric Design Language code [10; 11] has been set-up to verify the effective subtractive heat flux guaranteed by the selected heat pipe arrangement. The numerical code simulates the convection phenomenon as an equivalent conduction through pipe structure, where the thermal conductivity of the overall heat pipe is calculated by Eq. (1):

$$K_{eff} = \frac{Q * L_{eff}}{A_{hp} * (T_{evaporator} - T_{condenser})} \quad \text{Eq. (1)}$$

When the heat pipe is active, its thermal conductivity typically ranges from 10,000 to 100,000 W/m K, that is 250 to 500 times the thermal conductivity of solid copper and aluminium, respectively. Figure 1 shows the flowchart of APDL code.

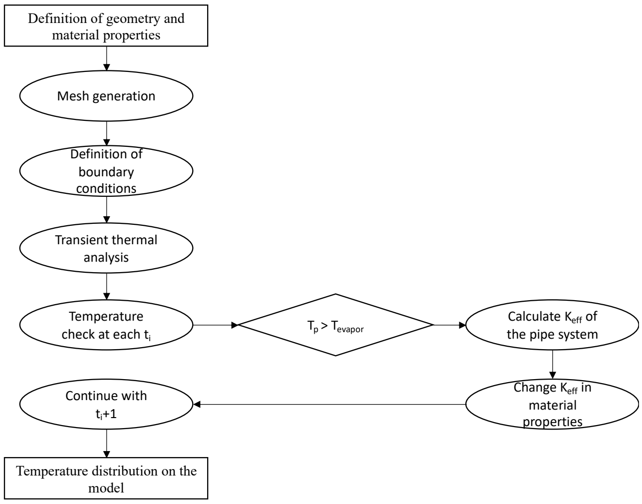

Figure 1. Flow Chart- Simulation Process

During the analysis the code retrieves the heat flux value (Q) at the interface Heat Pipe-Internal Crotch, the temperature in the evaporator and condenser zone ($T_{evaporator}, T_{condenser}$) at every simulation step. A check on the temperature in evaporator zone at each step is performed and if $T_{evaporator}$ is higher than the boiling temperature of pipe liquid, K_{eff} can be estimated using Eq. (1), using the $T_{condenser}$ and Q associated to the current step. Once the K_{eff} is evaluated, the conductivity of each material is updated accordingly.

Two test-cases are considered:

- Heat pipes designed for STRATOFLY (Stratospheric Flying Opportunities for High Speed Propulsion Concepts) MR3 hypersonic vehicle the crotch leading edge area which is subjected to convective over-heating due to their very small radii (about 2 mm).
- Heat pipes designed for a generic small LEO satellite

The first test-case is about STRATOFLY MR3 highly integrated hypersonic vehicle, where propulsion, aerothermodynamics, structures and on-board subsystems are strictly interrelated to one another, as highlighted in Figure 2 [4;5;6;9].

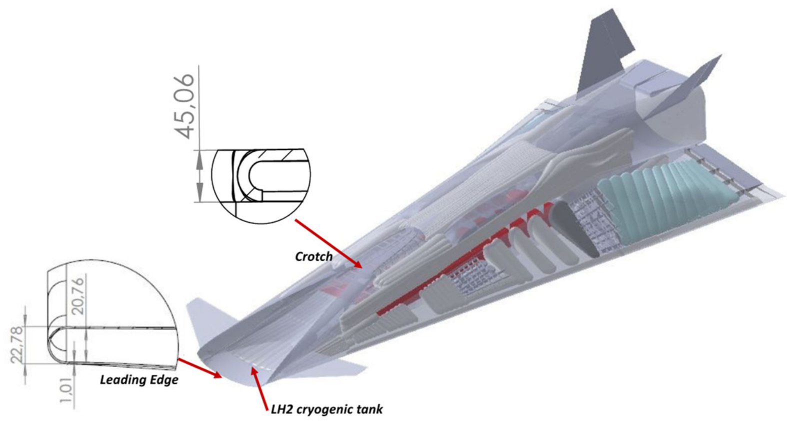

Figure 2. STRATOFLY MR3 arrangement constraints within the air intake leading edges

Air-intake leading edges are subjected to convective over-heating due to their very small radii (about 2 mm). Therefore, ad-hoc efficient cooling systems must be designed. Heat pipes systems have been chosen as driving system. First of all, design and sizing activities consist in the definition of feasible integrated architectures, and selection of the most appropriate working fluids and compatible wick and case materials. The analysis of the heat transfer limits (the capillary, entrainment, viscosity, chocking and boiling limits) is here suggested as guideline for the identification of a suitable design space and rational down-selection of the most promising solution. Different alternative solutions have been thoroughly analysed, including two different heat pipes layouts (single tubular and dual-channel architecture), five liquid metals as fluids (Mercury, Caesium, Potassium, Sodium and Lithium) and relative wick and case materials (Steel, Titanium, Nickel, Inconel® and Tungsten) and three leading-edges materials (CMC, Tungsten with low emissivity painting and Tungsten with high emissivity painting). Considering the volumetric constraints imposed by the peculiar design of the embedded air-intake of the MR3, a dedicated heat-pipe architecture, inspired by the NASP project, has been developed. This architecture has been suggested for both the lower lip as well as for the crotch air-intakes. In both cases, the proximity of the foremost cryogenic tanks suggests a longitudinal orientation of the pipes, parallel to the longitudinal axis of the vehicle. The 22 mm radius of the air-intake leading edges allows to adopt a dual-channel architecture instead of a more traditional tubular architecture. The proposed solution increases the exposed area of the evaporator, thus potentially increasing the heat transfer capability. As schematically reported in Figure 3, the suggested heat pipe solution is completely integrated into the air-intake structure, assuming that the heat pipe case is perfectly bonded with the panels of the aircraft skin. Eventually, a perfect bonding is also ensured between the case and the wick. Finally, it is worth noting that the rearrest part of the condenser region shall be properly interfaced with the tank external structure, to guarantee the required heat rejection.

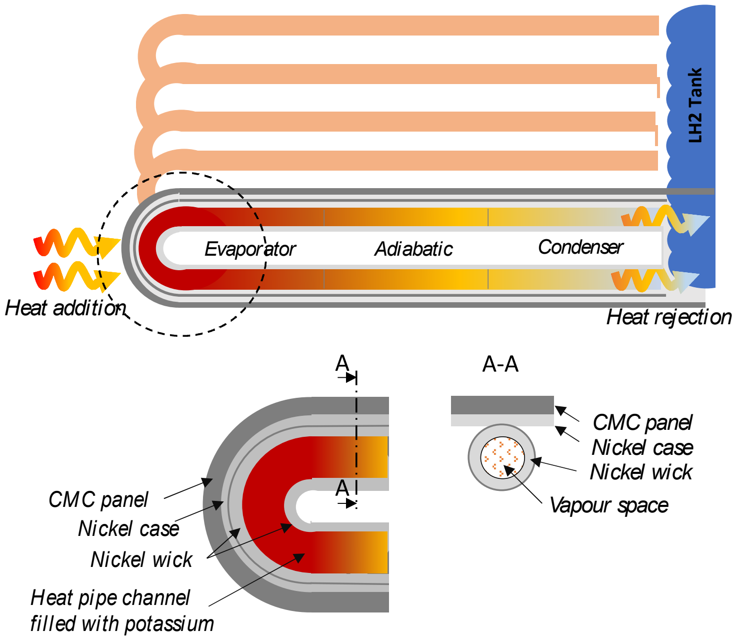

Figure 3. Overall heat pipe arrangement for the selected case study

A standard Low Earth Orbit satellite has been considered for the simulations of the second test case. Several heat sources, as represented in figure 4, are computed:

1. Direct solar flux depending on sun distance, with a mean value around 1367 [W/m^2] at 1AU (1414 [W/m^2] at winter solstice and 1322 [W/m^2] at summer solstice [12]).

2. Albedo planetary reflected radiation. For Earth, the mean reflectivity is assumed to be near 30%. But it can vary locally up to 40 or 80%above shiny clouds and from 5 to 10% for ocean and forests [12].

3. Earth infrared radiation. Earth can be modeled as an equivalent black-body emitting at 255 K [12].

4. Internal dissipated power in electronic components (Joule effect)

Once the operational, design and interface requirements are available, the heat pipe design activities, consisting in the definition of feasible integrated architectures and selection of the most appropriate working fluids, compatible wick and case materials have been carried out. The analysis of the heat transfer limits (the capillary, entrainment, viscosity, chocking and boiling limits) has been followed as guideline for the identification of a suitable design. This step has been a preparatory activity for the Finite Element Modelling (FEM) analysis subsequently performed. Moreover, the methodology has been verified by applying the APDL internal developed numerical code able to verify the effectiveness of the designed pipes. This numerical activity is currently in progress. Nevertheless preliminary results are coherent w.r.t boundary conditions and the material considered.

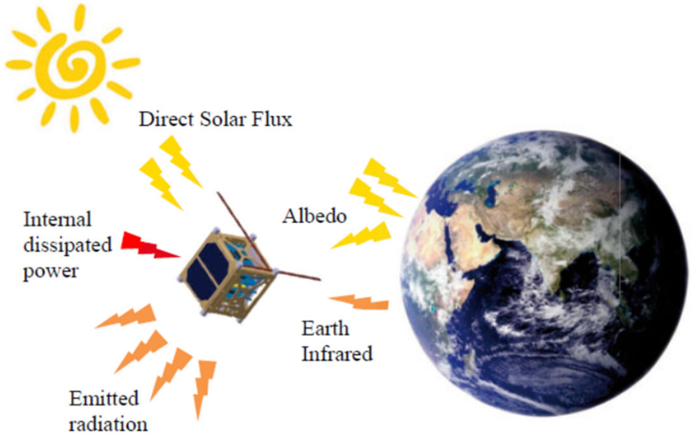

Figure 4 LEO satellite heat flux

REFERENCES

[1] Steelant J., Varvill R., Defoort S., Hannemann K., Marini M. Achievements Obtained for Sustained Hypersonic Flight within the LAPCAT-II Project. *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Glasgow, Scotland, AIAA-2015-3677, 6-9 July 2015.

[2] Steelant J. ATLLAS: Aero-thermal loaded material investigations for high-speed vehicles. *15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*. Dayton, Ohio, USA, AIAA 2008-2582 , doi 10.2514/6.2008-2582, 28 April – 1 May 2008.

[3] Steelant J. et al. Conceptual Design of the High-Speed Propelled Experimental Flight Test Vehicle HEXAFLY, *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference.* Glasgow, Scotland, AIAA 2015-3539, 6-9 July 2015.

[4] Di Benedetto S. et al. Multidisciplinary Design and Flight Test of the HEXAFLY-INT Experimental Flight Vehicle Hexafly-Int. *HiSST: International Conference on High-Speed Vehicle Science Technology*. Moscow, Russia, 2018

[5] Scigliano R., Marini M., Fusaro R., Viola N. Preliminary Aero-Thermal Assessment of the High-Speed Propelled Vehicle STRATOFLY, *32nd ISTS (International Symposium on Space Technology and Science) & 9th NSAT (Nano-Satellite Symposium).* Fukui, Japan, 2019-e-06, June 2019.

[6]. Scigliano R., Marini M., P. Roncioni, Fusaro R., Viola N., STRATOFLY High-Speed Propelled Vehicle Preliminary Aero-Thermal Design. *International Conference on Flight Vehicles, Aerothermodynamics and Re-Entry Missions and Engineering FAR 2019.* Monopoli, Italy, 30th September - 3rd October 2019.

[7] Scigliano R., De Simone V., Marini M., P. Roncioni, Fusaro R., Viola N. Preliminary Finite Element Thermal Analysis of STRATOFLY Hypersonic Vehicle*. 23rd AIAA International Space Planes and Hypersonic Systems and Technologies Conference - AIAA HYPERSONICS 2020.* Montreal, Quebec, Canada, 10.2514/6.2020-2422, March 10-12, 2020.

[8] Scigliano R., De Simone V., Marini M., Fusaro R., Ferretto D., Viola N., Thermal Protection System Preliminary Design of STRATOFLY High-Speed Propelled Vehicle, *32nd Congress of the International Council of the Aeronautical Sciences*. Shanghai, China, ICAS2020-0493, 6-10 September 2021.

[9] Roberta Fusaro, Davide Ferretto, Nicole Viola, Roberto Scigliano, Valeria De Simone, Marco Marini: *Liquid Metals Heat-Pipe solution for hypersonic air-intake leading edge: Conceptual design, numerical analysis and verification*, Acta

Astronautica, Volume 197, 2022, Pages 336-352, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2022.05.034.

[10] ANSYS Inc., Thermal analysis guide, Release 21.1, 2020.

[11] ANSYS Inc., Structural analysis guide, Release 21.1, 2020

[12] Federica Torre, "Analisi termica del satellite ALSat#1, Master thesis at Scuola universitaria della Svizzera italiana, 2019