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A Generic Thermodynamic Assessment of Reusable High-Speed Vehicles

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ABSTRACT

Lifting based vehicles for either space transportation or sustained hypersonic cruise are exposed to high thermal loads during the atmospheric trajectory. The thermal protection system has therefore to efficiently manage the thermal load that penetrates the aeroshell in order to guarantee a satisfactory mission performance. In the present study, the thermal endurance of a LH2-fuelled Mach 8 hypersonic cruiser is assured by soaking the thermal load across the aeroshell into the on-board tank system. The so-produced boil-off acts as a coolant for other aircraft subsystems, like the cabin environmental control system. Further, in order to avoid over-board dumping of the vaporized fuel, a boil-off compression system is proposed to inject the fuel into the propulsion plant.

The numerical approach comprised a detailed model of the airframe, where the heat transfer across the interfacing areas between the different subsystems, namely tanks, cabin, propulsion plant and the aeroshell, was resolved based on one-dimensional engineering models. This methodology allowed the evaluation of the complete mission cycle, from the apron, through taxiing and airborne phases and back to apron.

1. INTRODUCTION

The thermal management of cruising high-speed aircraft plays a very important role. These vehicles are submitted to high heat loads originating from the viscous heating of the aeroshell and the internal flow paths. The latter become remarkably important in the case of the ram- or the scramjet powered aircraft due to the large extension of the internal flow paths needed for propulsion. Tools and methodologies to assess the overall thermo-mechanical balance since the early design stages are thus necessary. In this respect, a method based on engineering tools is presented.

The analysis is applied to the thermal design of a hydrogen-fuelled Mach 8 transport aircraft. The dual propulsion plant of this vehicle consist of an air turbo-rocket combined-cycle engine for boosting the aircraft up to Mach 3.5-4, and a dual-mode ramjet for the final acceleration and cruise phases. In this particular instance is mandatory to account for the cooling needs of the passenger cabin as well as the heat loads faced by the aeroshell and the propulsion vein.

The proposed design of the cabin thermal protection is based on a double wall with internal air circulation. By means of the thermodynamic cycle proposed, the tank boil-off provides cooling to the cabin and the environmental control system (ECS). The inclusion of an expander cycle for regenerative cooling of the propulsion plant provides mechanical power to drive the fuel pump, the compressor needed to inject the boil-off fuel into the propulsion vein and other on-board consumers.

2. PRELIMINARY EVALUATION

One of the purposes of the present study was to design a thermodynamic cycle able to balance the airframe thermal and mechanical loads. Such cycle should be able to handle the heat load which, in excess, penetrates into the airframe across the walls of the aeroshell. This energy has to be converted into on-board mechanical power or rejected by some means in order to safeguard the aircraft thermal limits, while making efficient use of the available on-board fuel. Therefore, and prior to laying out any feasible thermodynamic cycle, an estimation of the on-board thermal loads and power consumers was carried out.

This preliminary thermo-mechanical balance, evaluated at cruise conditions (Mach 8), allowed to determine the governing thermal loads, whereas an assessment during the aircraft mission is addressed in the following paragraph, once the cycle layout has been established.

2.1 Aeroshell thermal loads

The stagnation surfaces on the aeroshell leading edges contribute mainly through a reversible compression which leads to very high, though concentrated, heat fluxes. Assuming a vehicle cruising at Mach 8 and 32 km of altitude, the theory of Fay-Riddel results in a heat flux to the leading edges of the intake of less than 2 MW/m^2. Provided that the size of these surfaces is about 0.5 m^2, the overall heat power to the intake leading edges results in 1MW, which is one to two orders of magnitude lower than the overall heat power to the aeroshell.

The leading edges of wings and control surfaces are swept respectively at an angle of approximately 80° and 45° with regard to the free stream which, together with the reduced extension of these surfaces, leads to a negligible contribution in relation to the overall heat load across the aeroshell.

The estimation of the aeroshell viscous heating is based on the following correlation for the convective heat transfer coefficient (h_{conv}) across a turbulent boundary layer over a flat plate [1]:

$$h_{conv}=0.0292\ Re_1^{4/5}\ Pr^{1/3}\ k\ x^{-1/5} \tag{1}$$

Where the distance (x) to the leading edge is measured along the freestream and the thermal and transport properties are evaluated at the local Eckert reference temperature (T_{ec}) by assuming an ideal gas behaviour. The temperature dependency of the viscosity is described by Sutherland's Law, whereas polynomial regressions in function of the temperature are used for the specific heat at constant pressure and the thermal conductivity of air (k).

The Eckert temperature is computed assuming constant specific heat (C_p=1004 J kg^{-1} K^{-1}) as:

$$T_{ec} = T_\infty + \frac{T_w - T_\infty}{2} + 11\frac{T_r - T_\infty}{50} \tag{2}$$

$$T_r = T_\infty + Pr^{1/3}\frac{v_\infty^2}{2\,C_p} \tag{3}$$

The integration of Eq. 1 over the aeroshell results in an expression of the type:

$$\dot{Q}_{conv} = k_{conv}\,(T_r - T_w)\,A_x \tag{4}$$

$$A_x = \iint x^{-1/5}\,dA \tag{5}$$

Where the convective heat transfer parameter (k_{conv}) depends solely on the freestream conditions, and the surface integral (A_x) is a purely geometrical property that characterizes the dependency of the heat load from the aeroshell topology. Analytical expressions were worked out to evaluate (A_x) in the case of simple geometries (e.g. trapezoidal, triangular and their combinations) [2].

The aeroshell is thus discretized into a set of planar elements. The suction side of the aircraft semi-wing is modelled by two triangular elements exposed respectively to freestream conditions and a Prandtl-Meyer expansion. The corresponding elements are labelled (SS) and (PM) in Figure 1, where a single triangular element characterizes the aircraft pressure side (PS). The edge conditions considered for the aeroshell panels during Mach 8 cruise correspond to the freestream, Prandtl-Meyer expansion of 15° or post-shock wave with a flow deflection of 5° depending on the location over the aeroshell.

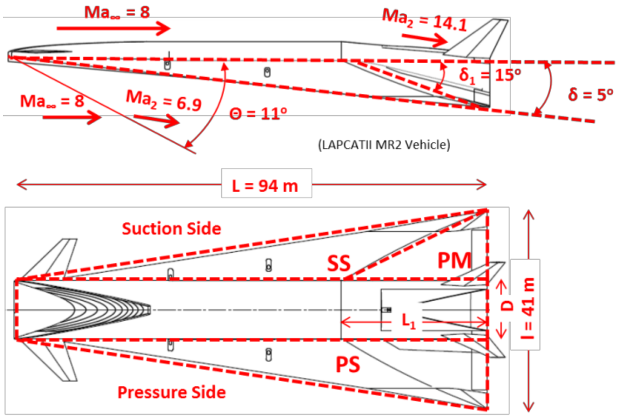

Figure 1. Reduced geometry and edge conditions over the aeroshell.

The fuselage is modelled as two rectangular elements exposed to the freestream or the post-shock conditions as corresponding to the pressure or suction sides. The surface of this rectangular element is approximated by the lateral surface of a cylindrical, straight and truncated cone for which area of the major and minor bases correspond respectively to the intake and the nozzle cross areas. The nozzle cross area at the exit plane is 111 m^2, whereas the intake inlet area is 38 m^2. The height of the truncated cone is equal to the vehicle length (94 m).

The heat load conducted into the airframe ($\dot{Q}_{cond}$) is evaluated as:

$$\dot{Q}_{cond} = \dot{Q}_{conv} + \dot{Q}_{rad} \tag{6}$$

$$\dot{Q}_{rad} = \begin{cases} -\epsilon\,\sigma\,(T_w^4 - 5^4)\,A + 1350\,A; & (SS, PM) \\ -\epsilon\,\sigma\,(T_w^4 - 288^4)\,A; & (PS) \end{cases} \tag{7}$$

Where the wall emissivity is ϵ=0.85 and the surface area of the corresponding aeroshell element is (A). The up-facing surfaces (SS and PM) are irradiated by the Sun at a rate of 1350 W/m^2 and irradiate to the outer space, supposed at a temperature of 5 K; the down-facing surfaces irradiate to the ground, supposed at 288 K.

Figure 2 shows the overall thermal load conducted into the airframe in function of the wall temperature and the breakdown of the contributions by each aeroshell panel. The panels reach radiative equilibrium at the wall temperature for which the convective load ($\dot{Q}_{conv}$) equals the radiative term ($\dot{Q}_{rad}$), i.e. at around 1000 K and 1100 K for the pressure sides of the fuselage and the wings respectively. The thermal load across the Prandtl-Meyer surface is not included in this chart since it amounts to only 1.3 MW for a wall temperature of 300 K and cancels at around 900 K when radiative equilibrium is reached.

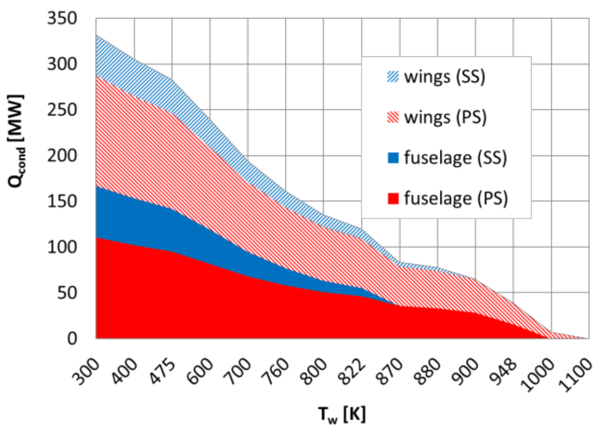

Figure 2. Breakdown of the conductive thermal loads into the aeroshell vs. wall temperature.

2.2 Cabin environmental control system

A system based on heat removal by convection of a stream of fresh air behind the cabin's wall was already envisaged during the ATLLAS [3] and ATLLAS II [4] projects. This particular environmental control system was inspired by the transpiration-cooled wall of the XB-70 cockpit [5]. A similar system is conceived here for the LAPCAT Mach 8 aircraft.

Figure 3 shows the proposed design where the cabin is ventilated by exhausting the vitiated air through the air gap between the cabin wall and the aeroshell, while fresh air is supplied to the cabin at the same rate ($\dot{m}_c$). During Mach 8 cruise the renewal rate of the cabin air does not suffice to remove the aeroshell heat which penetrates into the cabin, and increasing the amount of ventilation air to cope with the cabin heat load is not feasible since cooling of the captured air stream at Mach 8 is penalized with a significant thermal load of around 2.6 MJ per kg of air. Alternatively, the recirculated air within the wall ($\dot{m}_r$) is chilled down by means of a heat exchanger using the tank boiled-off hydrogen.

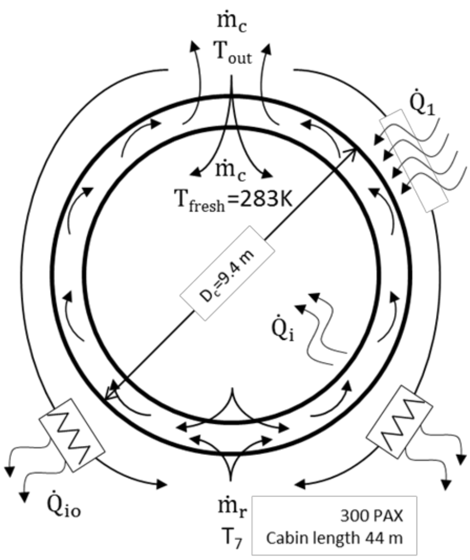

Figure 3. Layout of the cabin thermal protection system of the Mach 8 transport.

Figure 4 shows the disposition of the different layers: the aeroshell (1), the insulation layer (2), the air gap (4) and the cabin wall – inner insulation (5). The aeroshell is estimated to be at a temperature (T_1) of 1000 K during cruise (feasible with CMC materials) [2], whereas the cabin is assumed at a constant temperature (T_7) of 298 K. The insulation thicknesses (t_2, t_5), the air gap (s) as well as the thermal loads were estimated by means of a one-dimensional thermal model of the cabin double-wall.

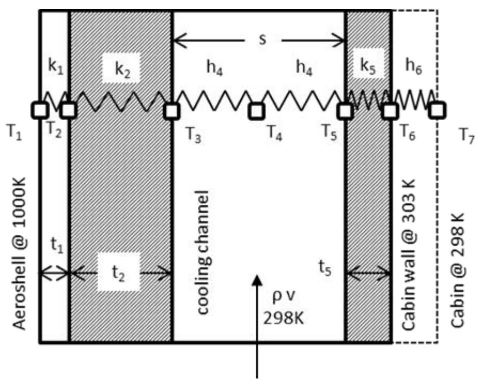

Figure 4. One-dimensional thermal model of the air-cooled wall of the Mach 8 transport cabin.

The temperature within the air gap (T_4) was calculated as:

$$\rho \; v \; s \; Cp \frac{dT_4}{dl} = Ue\,(T_1 - T_4) - Ui\,(T_4 - T_7) \qquad (8)$$

Where the thermal resistances (U_e and U_i) are evaluated from the thicknesses, the thermal conductivity (k) and the convective heat transfer coefficients (h) of each layer:

$$1/U_e = t_1/k_1 + t_2/k_2 + 1/h_4 \qquad (9)$$

$$1/U_i = 1/h4 + t_5/k_5 + 1/h_6 \qquad (10)$$

The air-gap outlet temperature (T_{out}) is obtained upon integration of Eq. (8) along the tangential direction of the channel (l):

$$T_{out} = \overline{T} - (\overline{T} - T_{in})\, e^{-L(U_e + U_i)/K} \qquad (11)$$

Where the length of the air gap (L) equals to half of the cabin perimeter (π D_c / 2), the channel inlet temperature is (T_{in}) and the average temperature ($\overline{T}$) is computed as:

$$\overline{T} = (U_e T_1 + U_i T_7)/(U_e + U_i) \qquad (12)$$

The heat picked up by the air gap is thus calculated as:

$$\dot{Q}_{channel} = (T_{out} - T_{in})\, 2\, K\, L_c \qquad (13)$$

Where (T_{out}) and (T_{in}) are the air temperatures at the channel outlet and inlet respectively. The thermal load ($\dot{Q}_{io}$) that has to be removed from the recirculated air flow ($\dot{m}_r$) is:

$$\dot{Q}_{io} = \dot{Q}_1 - \dot{Q}_i - \dot{m}_c\, C_p\, (T_{out} - T_{in}) \tag{14}$$

The thermal load to the cabin ($\dot{Q}_c$) comprises the heat penetration ($\dot{Q}_i$) by natural convection (h_6) on the walls and the heat release by the passengers, small on-board power and lighting, which is estimated at 140 W/PAX [4]:

$$\dot{Q}_c = \dot{Q}_i + 140 \text{ x PAX} \tag{15}$$

The ventilation rate needed to remove this heat load is:

$$\dot{m}_c = \frac{\dot{Q}_c}{Cp\,(T_7 - T_{fresh})} \tag{16}$$

The aeroshell heat load is:

$$\dot{Q}_1 = \dot{Q}_{channel} + \dot{Q}_i \tag{17}$$

The flow parameter (K) depends on the air velocity, density, specific heat and channel width:

$$K = v\, \rho\, C_p\, s \tag{18}$$

The flow parameter is computed by means of the closure equation:

$$\dot{Q}_i = (\overline{T} - T_7)\, U_i\, \pi\, D_c\, L_c - 2\, L_c\, K\, \frac{U_i}{U_i + U_e}\, (T_{out} - T_{in}) \tag{19}$$

Where the first term on the right hand side is the total thermal load to the air channel and the second term is the heat removed from the channel flow ($\dot{m}_r$+$\dot{m}_c$) by both cooling of the recirculated air ($\dot{Q}_{io}$) and mixing with the vitiated air exhausting the cabin.

The multi-bubble shaped cabin, with a capacity of 300 passengers, was approximated as a cylinder 44 m long (L_c) and 9.4 m of diameter (D_c). The aeroshell was 1 mm thick and performed with a thermal conductivity (k_1) of 20 W/m/K. A borosilicate glass fibre with thermal conductivity (k_2 and k_5) of 0.1 W/m/K was considered as insulation material.

A total wall of 20 cm was selected for a first estimation of the thermal loads into the cabin, which comprised an outer (t_2), inner (t_5) and air gap (s) thicknesses of 9, 3 and 8 cm respectively. This resulted in an aeroshell load ($\dot{Q}_1$) of 967 kW, with a load extracted from the recirculated air ($\dot{Q}_{io}$) of 898 kW and 12 kW across the cabin wall ($\dot{Q}_i$).

The flow rate of recirculated air ($\dot{m}_r$) was 56 kg/s, whereas the supply of fresh air ($\dot{m}_c$) at 283 K amounted to 3.6 kg/s, i.e. 30 ft^3/min/PAX for a 300 passengers aircraft. This figure is well above the normalized requirements for subsonic aircraft, which quote a minimum of 20 ft^3/min/PAX [4] [6]. The air velocity within the channel was below Mach 0.05.

The boundary layer bleed-off on the intake wall is used to supply the ventilation air. Therefore provision has to be made to cool down the stream prior expansion to 1 bar and 283 K. This heat removal amounts to 9.4 MW, hence the overall thermal load of the cabin environmental control system is 10.4 MW for cruise conditions at Mach 8.

2.3 Propulsion plant

The airframe is traversed by a propulsion vein consisting of combustion gases at elevated temperature (Figure 5), therefore the hot walls need to be re-generatively cooled by the fuel.

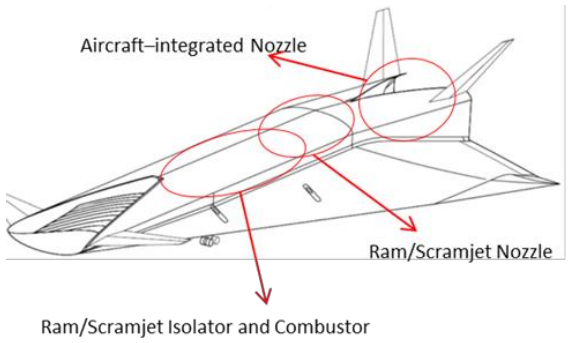

Figure 5. Location of the dual-mode ramjet isolator, combustor and nozzle and aircraft-integrated nozzle.

The heat load across the hot walls was estimated by computational fluid dynamics [7] [8] and classical heat transfer correlations. A first law analysis showed that the wall temperature reaches up to 1400 K. Based on the fuel demand during cruise condition, there is not enough cooling capacity to achieve lower wall temperatures.

Table 1 shows the heat pick-up of the regenerative circuit for a wall temperature of 1400 K. The fuel flow, and hence the thermal load, decrease linearly with the mass capture during climbing cruise at Mach 8. The hydrogen can reach up to 1250 K in the cooling circuit and hence a part of the heat pick-up can be transformed into mechanical power by means of an expander cycle, which could deliver up to 60-70 MW.

Cruise phase	*Altitude [km]*	$\dot{m}_f$ [kg/s]	$\dot{Q}$ [MW]	$\dot{W}$ [MW]
Start	28	21.6	378	70
End	32	14.7	270	60

Table 1. Variation of heat pick–up and expander power during cruise at a wall temperatures of 1400K.

3. DETAILED MODEL

The developed thermal model allowed to compute the heat transfer characteristics of the various aeroshell panels. The thermal conduction is resolved next by thermally coupling the aeroshell with the insulation, tank system and cabin (Figure 6). The interfacing areas between the different aircraft subsystems were considered, allowing to evaluate the heat conducted across the aeroshell into the cryogenic tanks and the passengers cabin as well as the interface temperatures. At first, the interfaces with the propulsion plant were considered isothermal, since regenerative cooling of the walls is foreseen. Nonetheless the need of thermally coupling the propulsion plant and airframe at a later stage is acknowledged.

A thermodynamic cycle was laid out, where the heat load which penetrates the aeroshell generates boil-off within the cryogenic tanks (Figure 7). A fraction of this gaseous fuel provides cooling to the cabin and is subsequently compressed upon mixing with the remaining fuel boiled off. The compressed hydrogen is then used to cool down the propulsion plant and the ventilation air within the air pack and supplied to the propulsion vein. On the other hand, the liquid hydrogen is pumped through an expander cycle to cool down the walls of the propulsion unit and produce mechanical power prior injection into the combustion chamber.

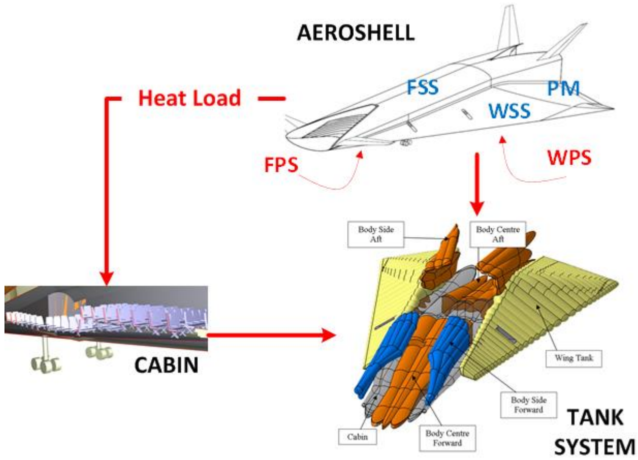

Figure 6. Thermal interaction between the aircraft subsystems.

The analysis was carried out with EcosimPro [9] and the European Space Propulsion System Simulation (ESPSS) libraries [10] [11]. The resulting model allowed the estimation of the airframe performances during the vehicle mission, from take-off through cruise and up to landing.

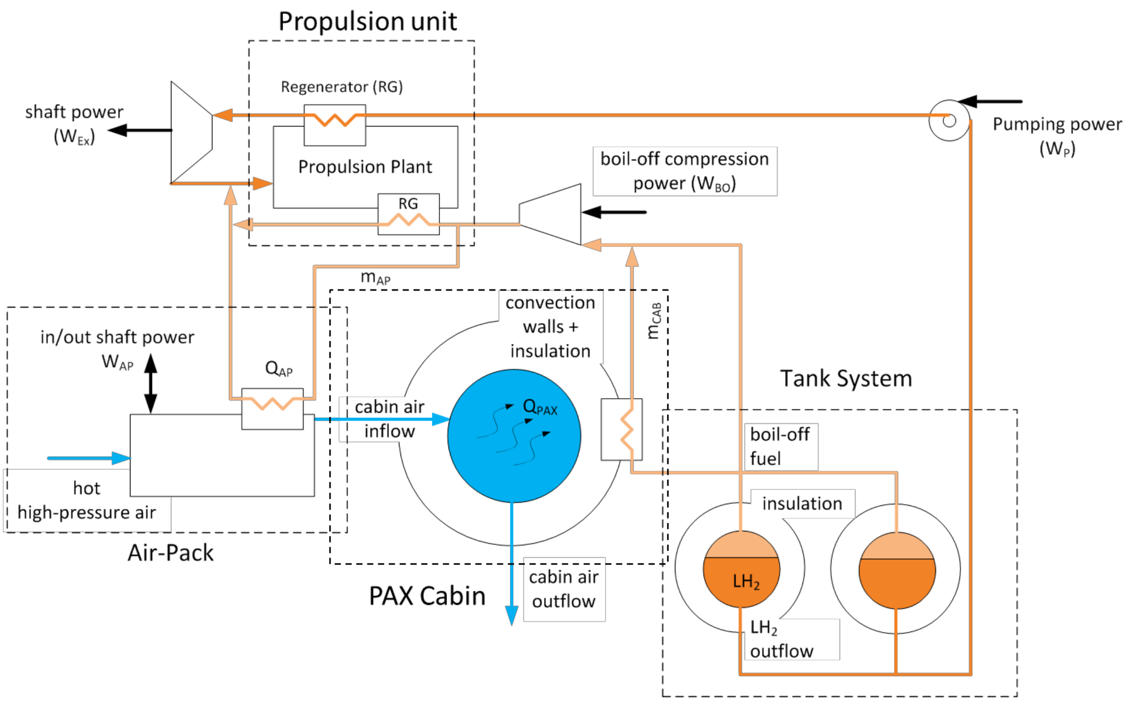

Figure 7. Thermodynamic cycle layout of the Mach8 transport.

3.1 Aeroshell

A more precise evaluation of the heating across the thermal protection system was achieved by discretizing the aeroshell into separate patches, which corresponded to the interfaces between the aeroshell and the intake with the underlying tank unit or cabin. Figure 8 shows the symbolic model, where the aeroshell panels are located on the fuselage suction (FSS) or pressure side (FPS), the wing pressure (WPS) or suction side (WSS) or the Prandtl-Meyer surface (PMS) as appropriate.

The approach explained in the previous paragraph was used to determine the thermal characteristic of each aeroshell patch. Each surface was thus characterized by the wetted area (A) and the integral

(A_x), in Table 2, and exposed to the freestream conditions or to the conditions downstream of a Prandtl-Meyer expansion of 15°, a 5° wedge deflection (fuselage and wings pressure side) or a 20° deflection along the intake ramp. The conditions behind a normal shock wave were adopted at the lower Mach numbers for which the oblique shock solution did not exist. The radiation to and from the surfaces was considered in the same manner as addressed earlier.

The aeroshell was 1 mm thick with thermal properties corresponding to CMC, i.e. thermal conductivity of 15 W/m/K, heat capacity of 1350 J/kg/K and density of 2000 kg/m^3. The insulation was considered part of the fuel system, hence the related material thicknesses and properties are provided in the next paragraph.

Element	Interface*	A [m^2]	A_x [m$^{9/5}$]
Semi-wing SS	WT	495	201
Semi-wing PM		243	211
Semi-wing PS		592	331
Fuselage SS	BSFT	143	91
	BSAT	125	58
Fuselage PS	BCFT	174	102
	CABIN	384	193
	BCAT	77	36

(*) See next paragraph for an explanation of the different elements.

Table 2. Geometrical properties of each element for half configuration.

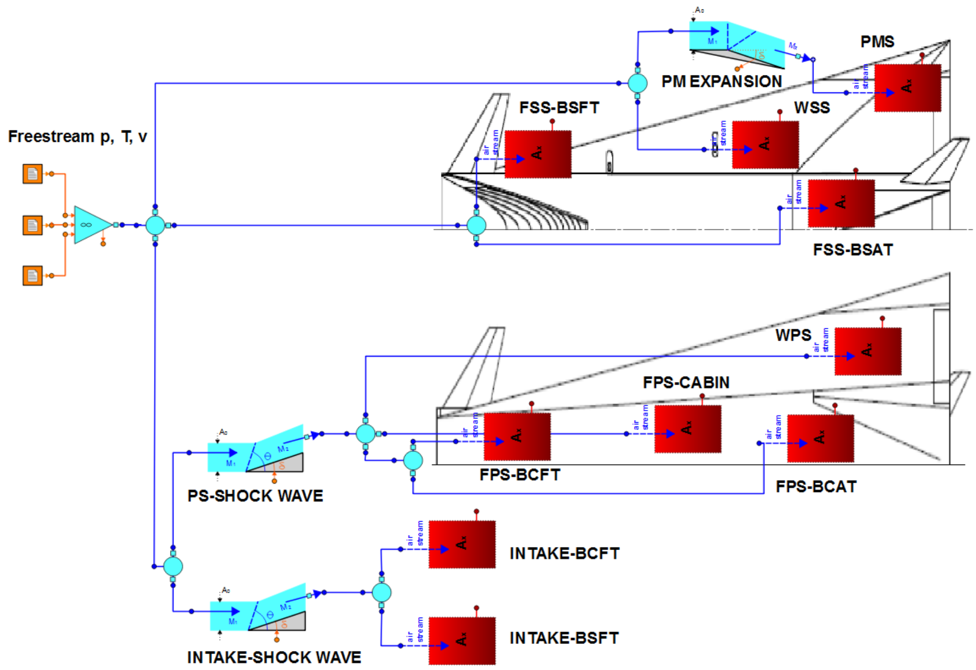

Figure 8. Symbolic model of the aeroshell.

3.2 Tank system

The tank system is comprised of different tank units located into the wings and the fuselage, namely the body-centre aft (BCAT), body-centre forward (BCFT), body-side aft (BSAT), body side forward (BSFT) and wing (WT) tanks, in Figure 6. The state of the cryogenic fuel is described by an homogeneous model of liquid of vapour in thermodynamic equilibrium. The tank units are thus characterised by their volume, the lateral surface and the characteristic length. Since the aircraft comprises a symmetry plane, only one-half of the tank system is modelled.

A detailed contribution to the tank heating was calculated by considering the different interface surfaces with the aeroshell panels and propulsion vein, in Table 3. The overall tank surface accounts as well for the interfaces between the tank units, which are considered adiabatic. The interface with the propulsion vein was modelled as isothermal at 300K.

The heat transfer coefficient to the inner wall is based on generic heat transfer correlations based on the tank hydraulic diameter, as implemented in the ESPSS libraries. Different insulation thicknesses of 10, 2 and 4 cm were considered respectively for the body centre, body side and wing tanks. The insulation material was a borosilicate glass fibre of 56 kg/m^3 with a thermal conductivity of 0.1 W/m/K and specific heat of 1255 J/kg/K. The shells of the tanks have a common thickness of 1mm, with generic thermal properties corresponding to an aluminium alloy. The initial state of the fuel within the tanks corresponds to subcooled hydrogen at 1 bar and 15 K.

	CABIN	WSS (Excl. PMS)	PMS	WPS	FPS	FSS	Intake	Propulsion	Tank surface
CABIN	0	0	0	0	**276**	0	**124**	**152**	853
BCAT	**28**	0	0	0	**58**	0	0	58	160
BCFT	**77**	0	0	0	**129**	0	**102**	**28**	369
BSAT	0	0	0	0	0	**125**	0	209	418
BSFT	0	0	0	0	0	**143**	**143**	0	286
WT	**183**	**328**	**161**	**489**	0	0	0	0	1245

Table 3. Aeroshell and propulsion plant interfacing areas with the fuel tanks of half configuration [m^2].

Figure 9 shows the symbolic model of the tank system, which comprises the tank units of the equivalent half configuration. The tank depletion is solely driven by hydrostatic pressure and the ullage pressure rise due to boil-off within each tank. The liquid level within the tanks is computed in function of the void fraction, so that the liquid is emptied through the lower flanges whereas the vaporised fuel is vented through the upper flanges. Anti-return valves mounted on each flange prevent the appearance of reversed flow. The liquid and one of the vapour flanges of the tanks are connected to common manifolds (ML and MG) which discharge to the fuel and the boil-off lines.

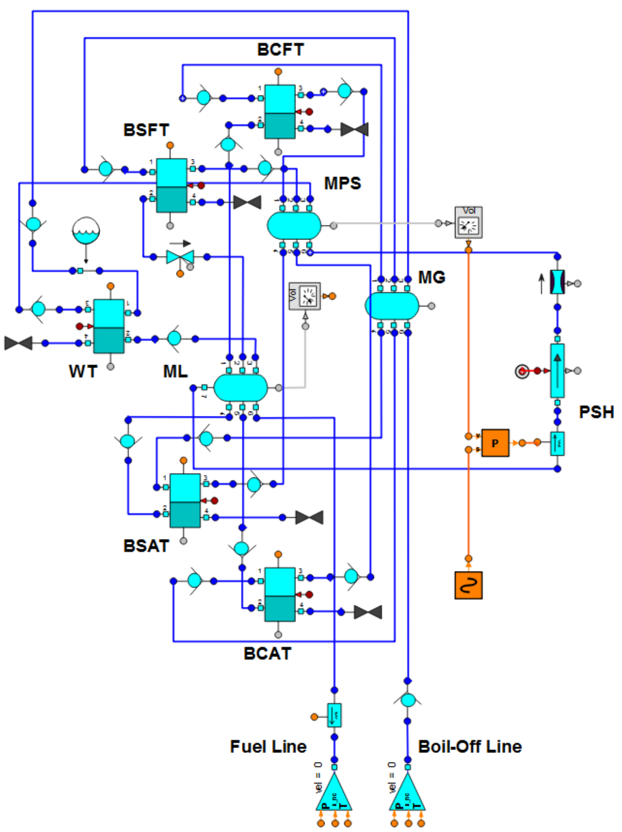

Figure 9. Symbolic model of the tank system.

The vapour flanges of the pressurization system are connected to a common manifold (MPS). The pressure in this manifold is regulated to around 1.5 bar by a feeding fuel previously vaporised through a heat exchanger at ambient temperature (PSH). Then, the anti-return valves of each tank, set for opening at a differential pressure of 0.5 bar, guarantee a 1 bar gauge pressure during the initial ascent, while the boil-off is not sufficient for tank pressurization.

4. RESULTS

A Brussels-Sydney mission with 240 km of subsonic range was considered for the calculation of the airframe heat loads. The flight time of this mission was 2 h and 47 min. In order to compare the thermal loads experienced cruising at Mach 8 with respect to Mach 5, the Mach 8 aircraft was flown over the LAPCAT A2 Mach 5 transport mission including the fuel consumption, i.e. with the A2 propulsion plant [12]. The A2 mission flight time was 4 h and 38 min. Figure 10 shows a comparison of both trajectories. The cruise phase takes place with increasing flight altitude for both the Mach 8 (continuous line) and Mach 5 (solid line) aircraft. The instantaneous fuel consumption is shown in red.

Table 4 shows the trip fuel (TF), range (R) and flight time (FT) spent over each ascent, cruise and descent phases for the Mach 8 and Mach 5 missions.

The principal consumers or generators of mechanical power are the fuel pump, the boil-off compressor (BOC), the air-pack (AP) of the cabin ECS and the expander turbine. The technical power (electrical, hydraulic, etc.) was estimated at 130W per passenger, whereas the on-board passenger services (small power, entertainment and lighting) was estimated at 70W per passenger [4]. A total load of 60 kW for a 300 passengers aircraft is therefore foreseen in the balance of mechanical power:

$$W_{BAL} = W_{Expander} - W_{Pump} - W_{BOC} - W_{AP} - 60\text{ kW}$$

Figure 11 shows that a positive balance of mechanical power is possible by regulating the inlet pressure of the expander in the range from 60 to 70 bar. On top of this, if the inlet pressure is raised, the expander can deliver from to 10 to 20 MW of extra mechanical power during the cruise phase.

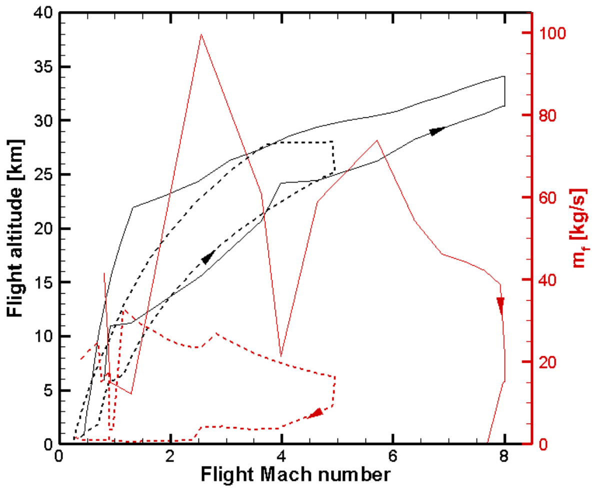

Figure 10. Comparison of Mach 8 and Mach 5 missions: trajectory and fuel consumption.

	Ma	Asc.	Cruise	Desc.	TOTAL
Fuel	8	74.2	106.4	0.2	181
[Mg]	5	49.2	116.3	6.5	172
Range	8	1975	13263	1493	16732
[km]	5	2060	15024	1616	18700
Time	8	0.5	1.6	0.6	2.8
[h]	5	0.89	2.78	0.95	4.6

Table 4. Mach 8 and Mach 5 mission comparison.

The principal power consumers at flight speeds below Mach 4, were the boil-off compressor, with a peak power around 1.5 MW, and the air-pack, with a peak power under 1 MW. Regarding the power shortage during deceleration and descent, while the boil-off compression is un-necessary, the air-pack (Figure 12) and airframe services (60kW) stand as sole consumers with a peak power around 2 MW. The possibility of running the ATR turbomachinery and combustor at part load could be considered to cope with these low though highly transient power demand.

The air-pack had to compress the incoming air stream to cabin pressure at the start of the acceleration and at the end of the descent phases, where the power demand peaks up to 2 MW (Figure 12). On the other hand, an air cycle can be envisaged to provide up to 3 MW of power during cruise by expanding the ventilation air to cabin conditions. The pressure recovery of the ventilation air was assumed 95% below Mach 0.85 and 15% above Mach 1.5 (linear decay in between). The thermal load incurred by cooling down the ventilation air, reaching up to 10 MW for the Mach 8 mission, was absorbed by the tank boil-off.

Table 5 comprises a first estimation of the operational ranges of the aircraft subsystems. The figures highlight the need of designing flight hardware able to handle high mass flows of gaseous hydrogen at elevated temperatures and pressures. In particular, the design of the boil-off compressor and the expander turbine may pose important technological challenges. This could be alleviated or mitigated by alternative cycles.

The total boiled-off mass was quite substantial with regard to the trip fuel, i.e. 78 t (43%) and 102 t (59%) for respectively the Mach 8 and the Mach 5 mission profiles, whereas the fuel mass flow rate required for the Mach 8 cruise phase was only 34% to 40% higher than for cruising at Mach 5.

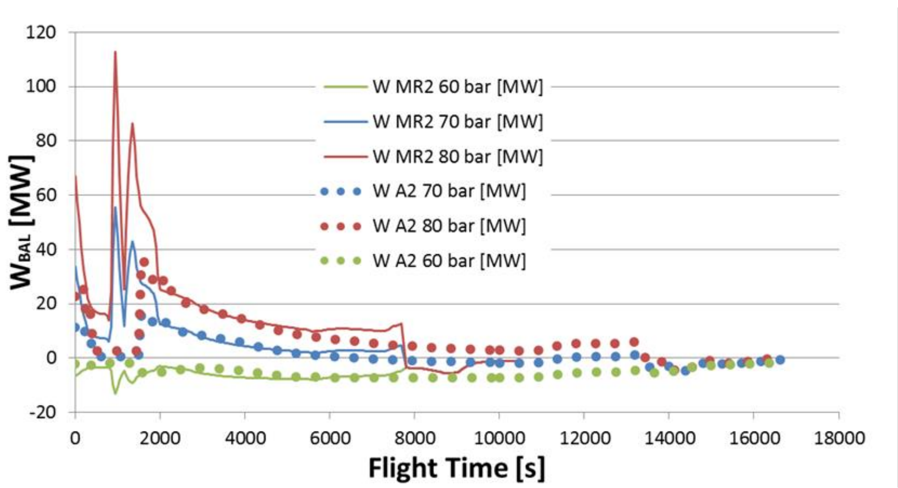

Figure 11. Power balance on the expander shaft for inlet pressure of 60, 70 and 80 bar during the Mach 8 (MR2) and the Mac 5 (A2) missions.

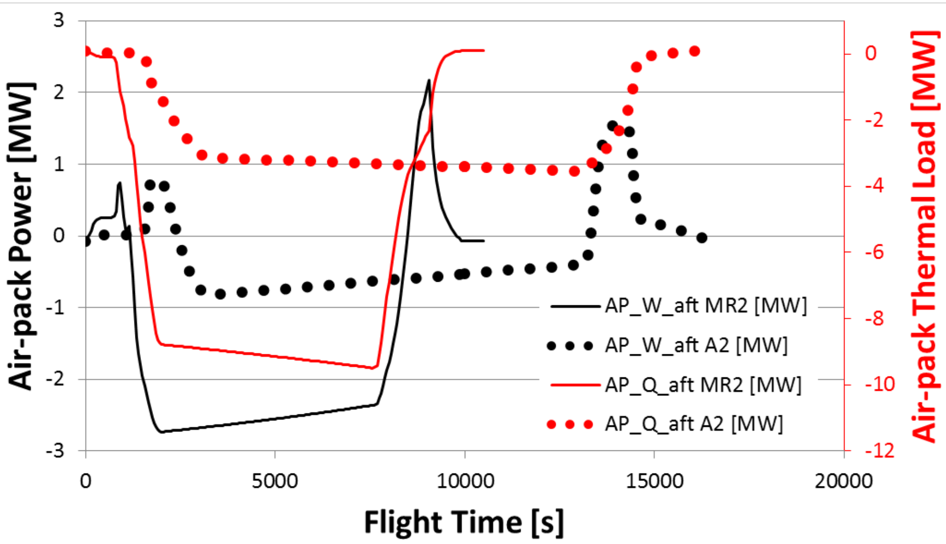

Figure 12. Air-pack mechanical and thermal loads during the Mach 8 and Mach 5 missions.

Component	Temperature [K]		Pressure [bar]		Mass flow	Power
	In	Out	In	Out	[kg/s]	[MW]
Fuel Pump	20	[26÷28]	1	[60÷80]	[0÷100] [0÷35]	[1÷15] [0.5÷5]
Boil-off compressor	[20÷280] [20÷280]	[150÷950] [240÷950]	1	60	[0÷8] [0÷6]	[0÷15] [0÷7]
Air Pack	[240÷3240] [260÷1310]	300	[0.03÷14.3] [0.06÷1.8]	0.75	3.6	[2.2÷-2.7] [1.6÷-0.8]
PAX & Technical power	-	-	-	-	-	60 kW
Expander	1300	[1200÷1300] [1250÷1300]	[60÷80]	60	[10÷100] [6÷32]	[0÷120] [0÷40]

Table 5. Operation range of the airframe systems. The bottom ranges refer to the Mach 5 mission, when different from the Mach 8 mission values.

5. CONCLUSIONS

A methodology to evaluate the aeroshell viscous heating was established and applied to estimate the on-board heat loads and power consumers during the Mach 8 cruise phase of a transport aircraft. This preliminary analysis allowed to design a thermodynamic cycle suitable to balance the airframe thermal and mechanical loads. The proposed airframe thermal management system was then evaluated in detail along both Mach 8 and Mach 5 reference missions, from take-off to landing. In this manner, the influence of the mission on the performance of the airframe thermal management system performance was assessed.

The main outcomes from the study were:

- The proposed thermal management system is viable from the thermodynamic stand point; the system thermal and mechanical loads can be effectively balanced.
- Any boil-off is not to be considered lost as it can be redirected to the propulsion plant. This allows relaxing the tank insulation thicknesses and weight.
- The aeroshell is passively cooled by heat conduction into the cryogenic tanks. This allows disposing of a complex and heavy active system comprising coolant channels running along the aeroshell and the pumps required to circulate the cooling fluid.
- The proposed cycle topology was feasible for both a Mach 8 and a Mach 5 missions.

The following items are provided as an outlook for further investigation:

- The sizing of the system components (turbomachinery, heat exchanging elements and piping), including weight estimation, is deemed crucial to assess the overall system viability.
- The propulsion plant performance must be integrated further into the airframe system, e.g. regarding the cooling needs of the propulsion vein and the utilization of common turbomachinery units shared with the airframe, i.e. the expander turbine of the air turbo-rocket units.
- The optimization of the airframe thermal management system will lead to a trade-off solution between the tank and cabin insulation requirements, the boil-off produced during the aircraft mission and the overall system weight.
- The previous optimization of the airframe system can eventually result in the need of modifying the cycle layout to reach a feasible design. In line with this, the utilization of a different working fluid with higher density than hydrogen can be necessary for the extraction of power from the expander without incurring an excessive weight of the turbine as well as the associated piping.
- Regarding the propulsion plant, a maximum wall temperature of 1000K cannot be guaranteed by cooling the walls with the nominal fuel demand during cruise, i.e. without incurring extra fuel consumption. The feasibility of such regenerative cooling system requires allowing the wall temperature to rise up to 1400 K which is within reach of presently available CMCs. The heat drawn by the cooling system can then be converted into shaft power by means of an expander cycle, provided that the pressure of the regenerative cycle can be raised above 60 bar.

ACKNOLEDGEMENTS

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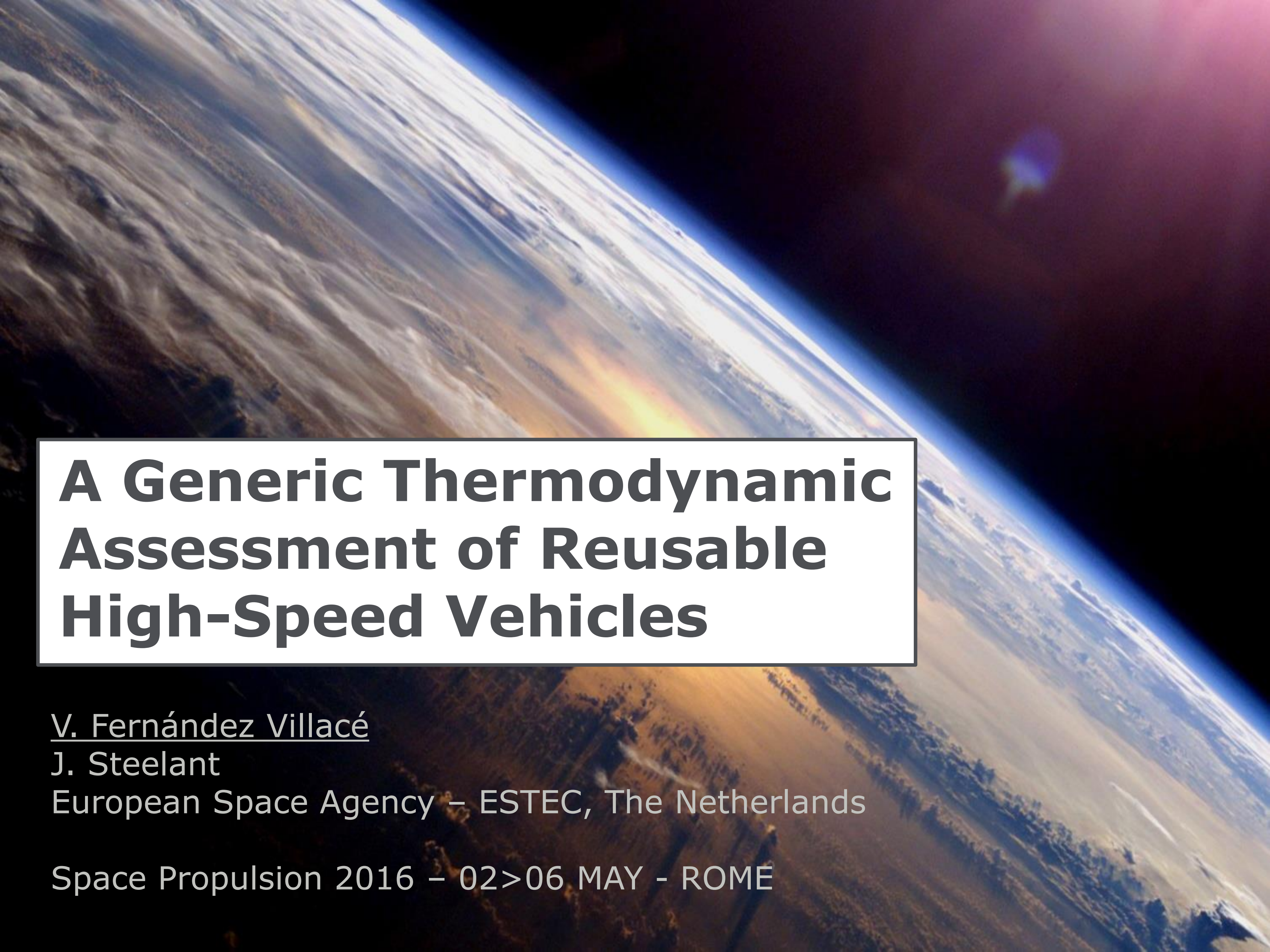

A Generic Thermodynamic Assessment of Reusable High-Speed Vehicles

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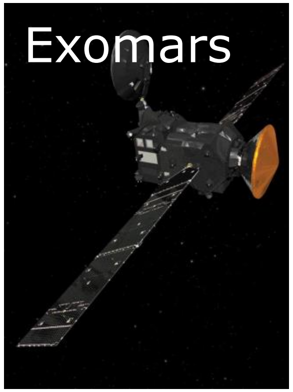
Space Propulsion 2016 – 02>06 MAY - ROME

Foreground



Flight Duration (L/D)

Heat $\propto$ ΔTemperature X Surface X **Time**

GUIDELINE

- **CRUISE ANALYSIS**
    - **Aeroshell**
    - **Cabin**
    - **Propulsion**
- MISSION ANALYSIS
    - Aeroshell
    - Fuel Tanks
    - Results

CRUISE - Aeroshell

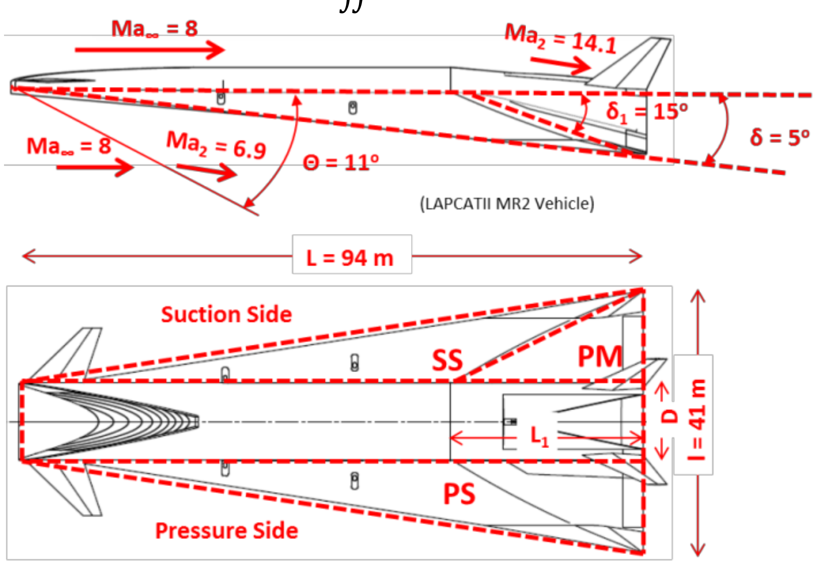
- Negligible heating through stagnation surfaces (1MW)
- Aeroshell viscous contribution :

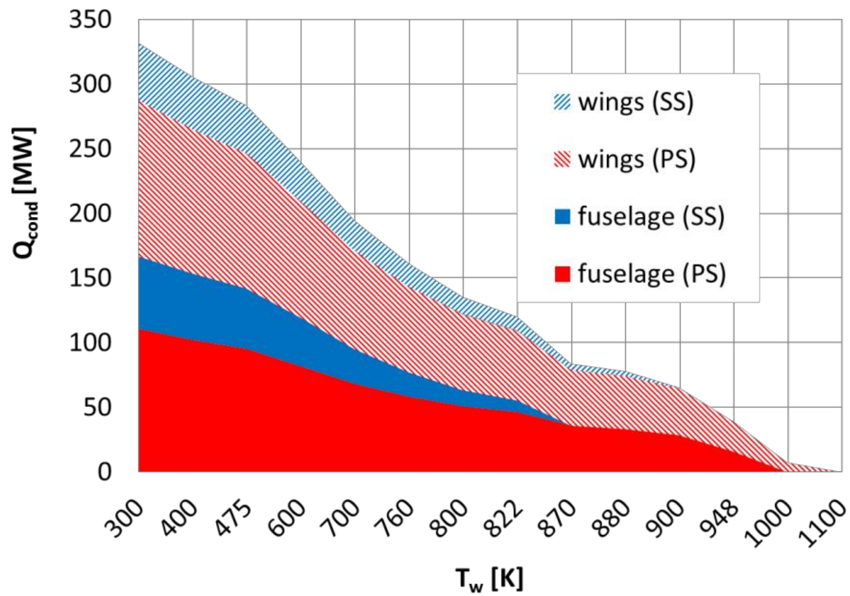
$$h_{conv}=0.0292\ Re_1^{4/5}\ Pr^{1/3}\ k\ x^{-1/5}$$

$$\dot{Q}_{conv} = k_{conv}\,(T_r - T_w)\,A_x$$

$$T_r = T_\infty + Pr^{1/3}\,\frac{v_\infty^{\,2}}{2\,C_p}$$

$$A_x = \iint x^{-1/5}\ dA$$

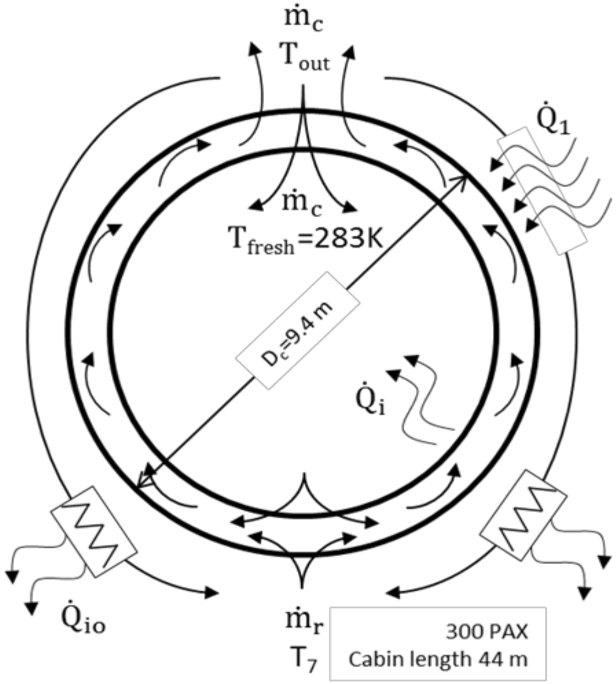


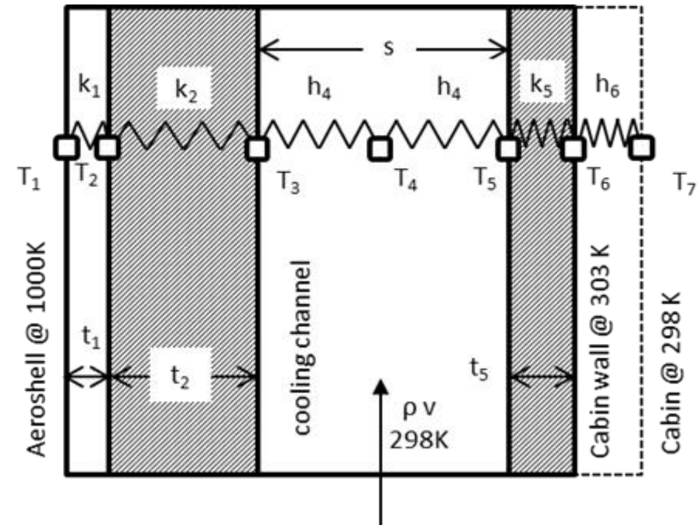


$$\dot{Q}_{cond} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

- Radiative equilibrium at around 1000 K and 1100 K for the pressure sides (ϵ=0.85)

CRUISE - Cabin

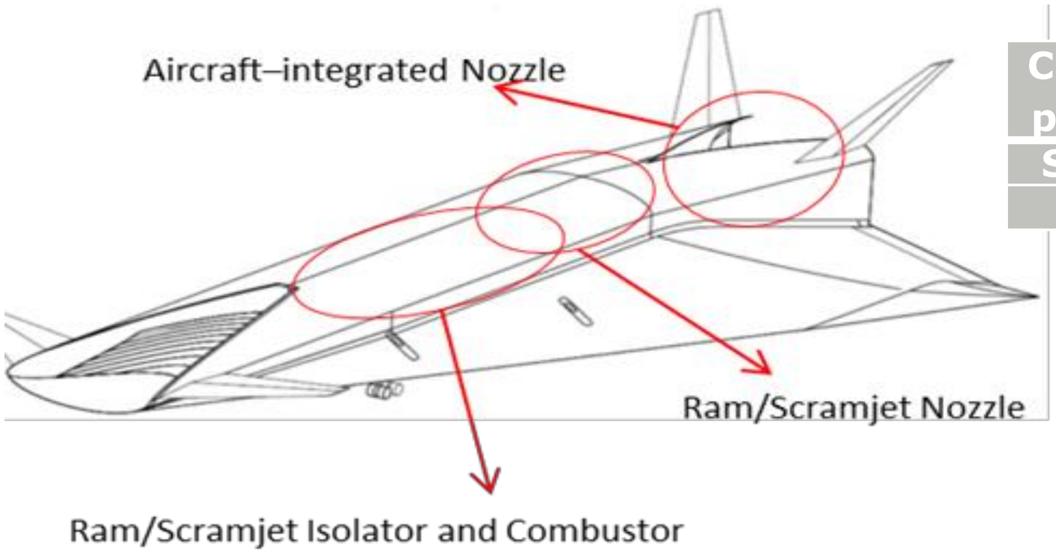




▲ 1D model of cabin wall

- Cabin cooled by ventilation air + recirculation cooler
- One-dimensional model > Estimation of wall thicknesses & heat loads
- Insulation with borosilicate glass fibre (k_2=k_5=0.1 W/m/K)
  - 20 cm wall: t_2=9cm, t_5=3cm, s=8 cm
  - Loads: $\dot{Q}_1$=967 kW, $\dot{Q}_{io}$=898 kW, $\dot{Q}_i$=12 kW
  - Mass flows: $\dot{m}_r$=56 kg/s, $\dot{m}_c$=3.6 kg/s
  - Removal of 9.4 MW from ventilation air

CRUISE - Propulsion



Cruise phase	Altitude [km]	$\dot{m}_f$ [kg/s]	$\dot{Q}$ [MW]	$\dot{W}$ [MW]
Start	28	21.6	378	70
End	32	14.7	270	60

- Large internal flow path > High Thermal loads from the ram-/scramjet
- Wall heat load estimated by CFD (1D&3D) and heat transfer correlations
- Regenerative cooling of walls
- ➢ Energy analysis shows wall temperature T_w=1400 K
- ➢ Insufficient cooling capacity for lower T_w based on cruise fuel demand
- ➢ Mach 8 cruise at rising altitude
- ➢ Linear decrease of fuel flow ($\dot{m}_f$) and thermal load ($\dot{Q}$) with mass capture
- ➢ Expander cycle delivers up to 60-70 MW mech. power from heat pick-up

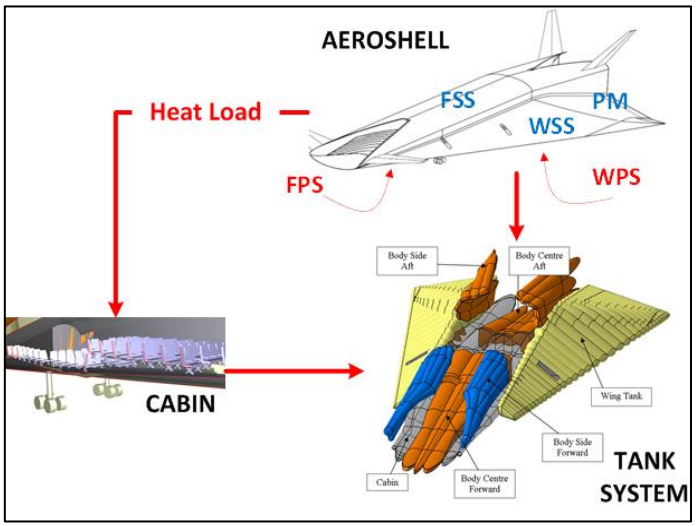
GUIDELINE

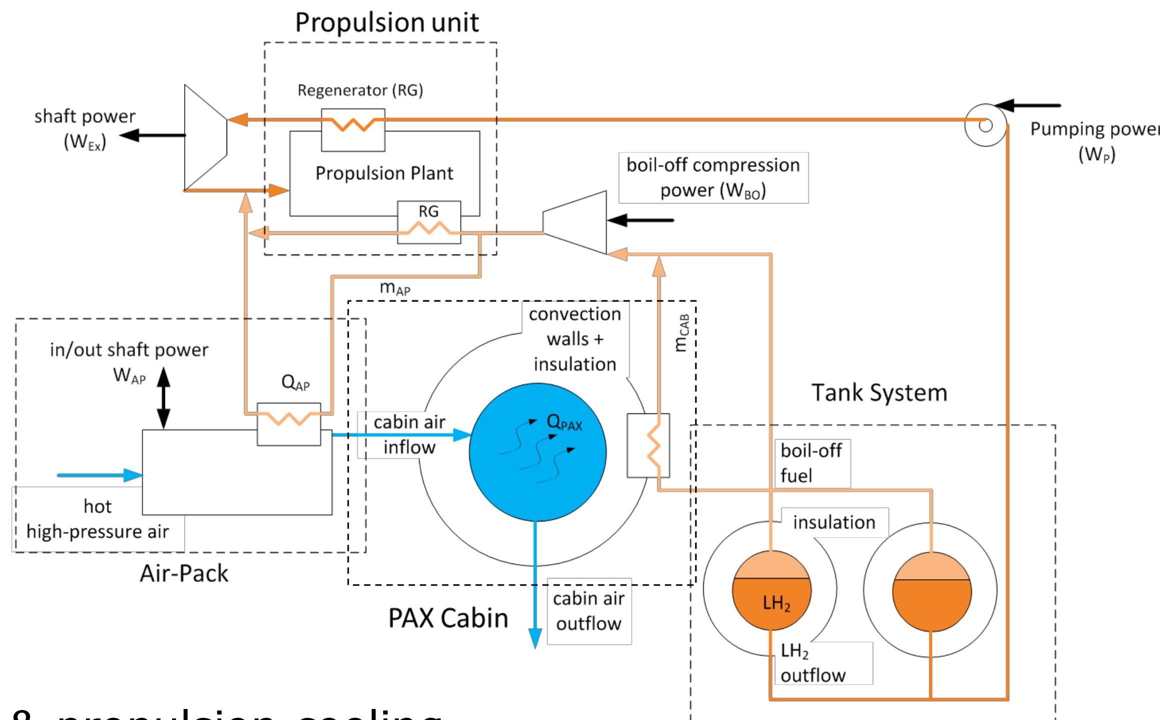
- CRUISE ANALYSIS
    - Aeroshell
    - Cabin
    - Propulsion
- **MISSION ANALYSIS**
    - **Aeroshell**
    - **Fuel Tanks**
    - **Results**

MISSION ANALYSIS

Detailed model:

- Conduction resolved coupling aeroshell & insulation & tank system & cabin
- Regenerative cooling of propulsion walls -> isothermal interface (300K)



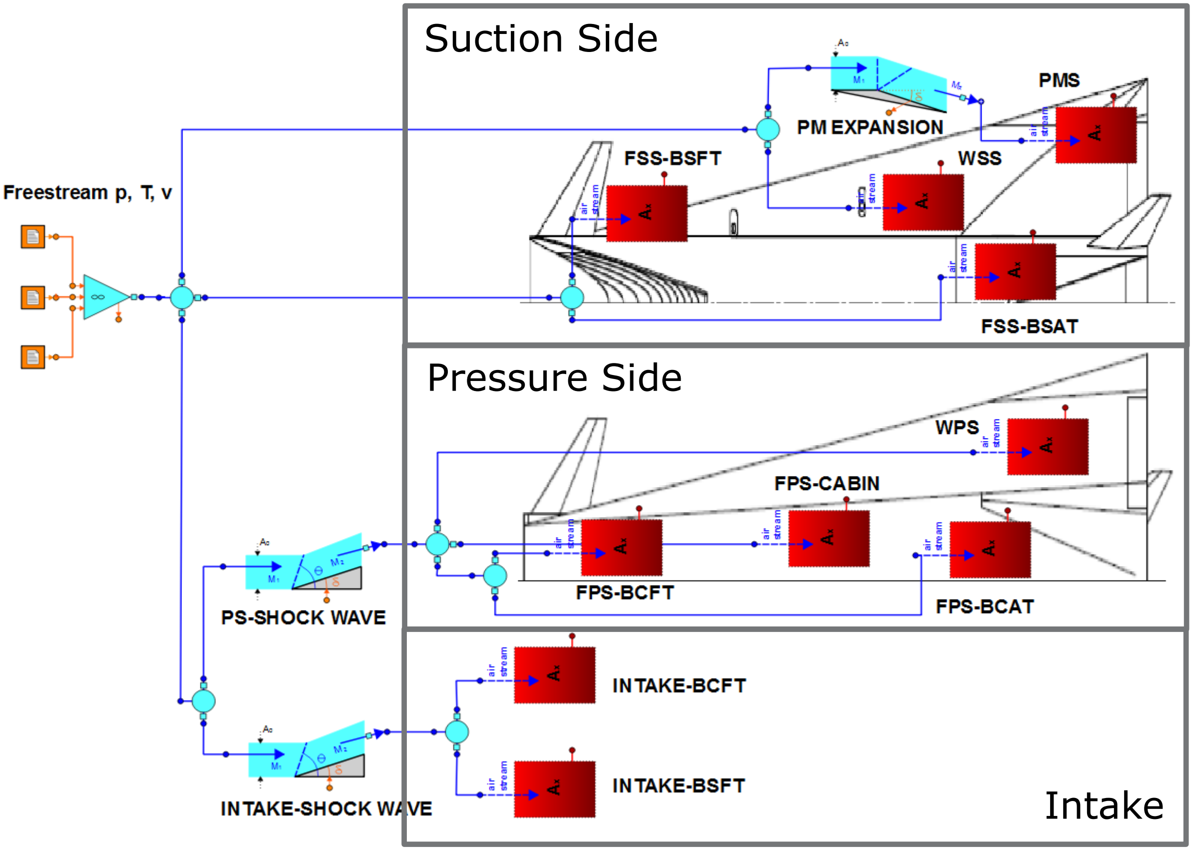


Thermodynamic cycle:

- Tank boil-off used for cabin & propulsion cooling
- No overboard spillage of boil-off
- Expander turbine produces mech. power

MISSION - Aeroshell

- Aeroshell patches corresponding to interfaces of aeroshell & intake/tank/cabin
- Geometrical characterization of each patch (A, A_x)
- Appropriate edge conditions to teach panel (15º expansion, 5º & 20º deflection)

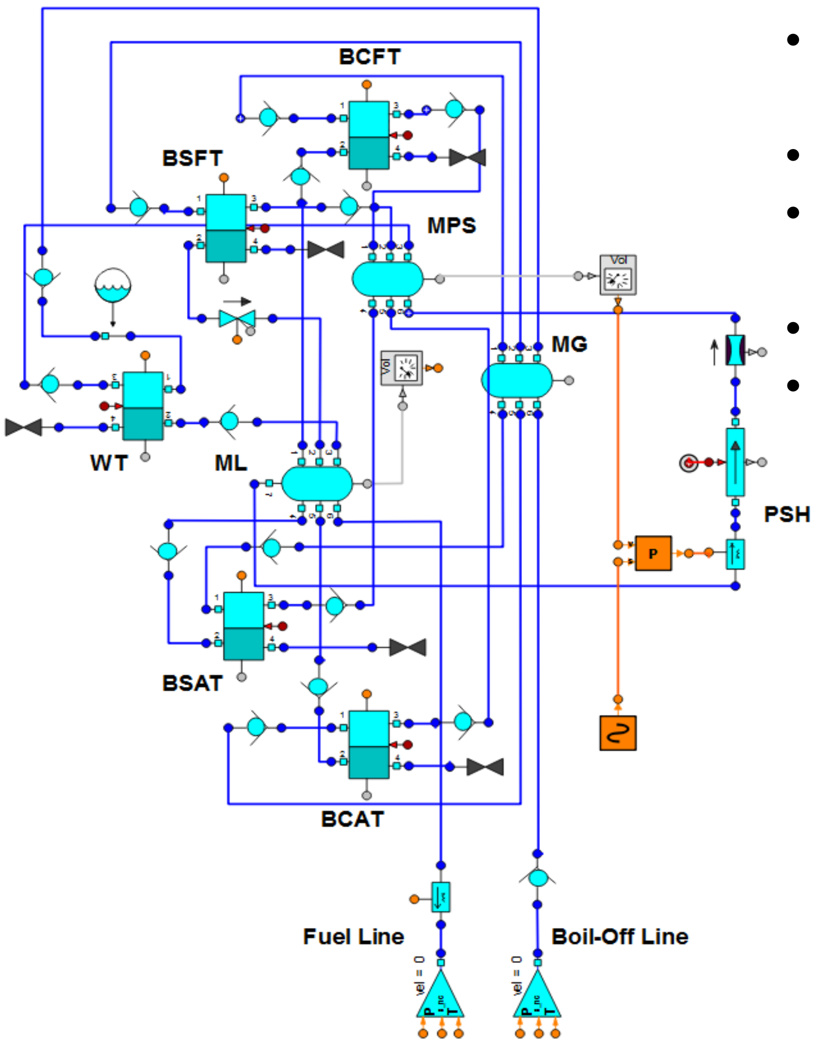


Element	Interface*	A [m²]	A_x [$m^{9/5}$]
Semi-wing SS	WT	495	201
Semi-wing PM		243	211
Semi-wing PS		592	331
Fuselage SS	BSFT	143	91
	BSAT	125	58
Fuselage PS	BCFT	174	102
	CABIN	384	193
	BCAT	77	36

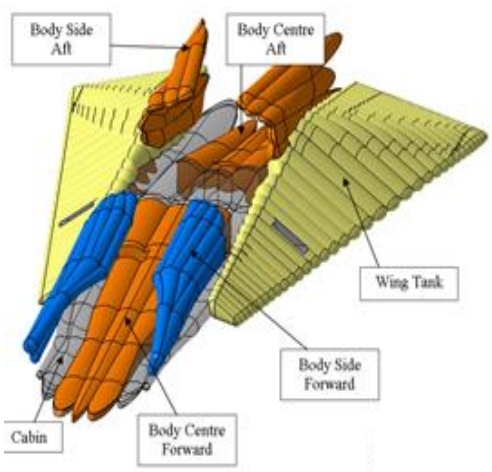
$$\dot{Q}_{conv} = k_{conv}\,(T_r - T_w)\,A_x$$

$$A_x = \iint x^{-1/5}\, dA$$

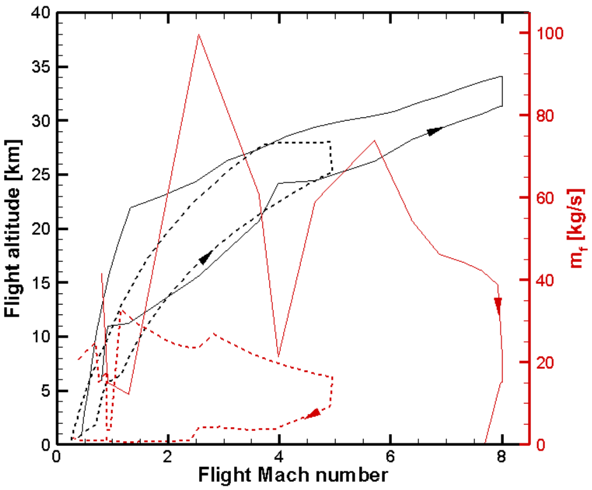
MISSION – Fuel Tanks



- 5 Independent units into wings and fuselage
- Homogeneous gas model
- Depletion by hydrostatic and ullage pressure
- Calculation of tank liquid level
- Pressurisation by vaporising fuel through heat exchanger at ambient temperature



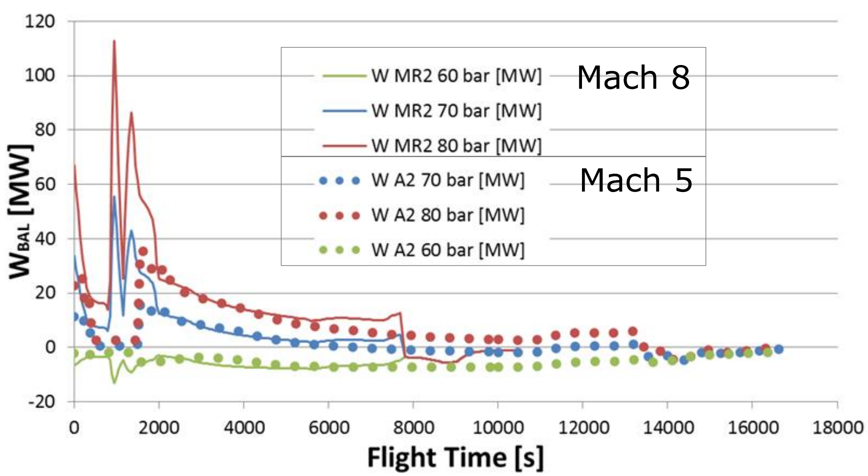
MISSION - Results



- Both Brussels-Sydney Mach 8 and Mach 5 cruise flown
- Different propulsion plants for each mission

	Ma	Asc.	Cruise	Desc.	TOTAL
Fuel [Mg]	8	74.2	106.4	0.2	181
	5	49.2	116.3	6.5	172
Range [km]	8	1975	13263	1493	16732
	5	2060	15024	1616	18700
Time [h]	8	0.5	1.6	0.6	2.8
	5	0.89	2.78	0.95	4.6

- Power consumers : fuel pump, the boil-off compressor (BOC), the air-pack (AP) of the cabin ECS, technical and on-board power (60 kW)
- Power generator: expander turbine



$$W_{BAL} = W_{Expander} - W_{Pump} - W_{BOC} - W_{AP} - 60\ kW$$

- Positive balance of mechanical power by regulating expander inlet pressure from 60 to 70 bar

MISSION - Results

- Substantial boiled-off fuel over trip fuel: Ma 8 > 78 t (43%); Ma 5 > 102 t (59%)
- Preliminary estimation of the turbomachinery operational ranges
- Need for flight hardware working at high flows of hot high-pressure gaseous-H_2
- ➢ This may pose important technological challenges
- ➢ This could be alleviated or mitigated by alternative cycles

Component	Temperature [K]		Pressure [bar]		Mass flow	Power
	In	Out	In	Out	[kg/s]	[MW]
Fuel Pump	20	[26÷28]	1	[60÷80]	[0÷100] [0÷35]	[1÷15] [0.5÷5]
Boil-off compressor	**[20÷280]** **[20÷280]**	**[150÷950]** **[240÷950]**	1	**60**	**[0÷8]** **[0÷6]**	[0÷15] [0÷7]
Air Pack	[240÷3240] [260÷1310]	300	[0.03÷14.3] [0.06÷1.8]	0.75	3.6	[2.2÷-2.7] [1.6÷-0.8]
PAX & Technical power	-	-	-	-	-	60 kW
Expander	**1300**	**[1200÷1300]** **[1250÷1300]**	**[60÷80]**	**60**	**[10÷100]** **[6÷32]**	[0÷120] [0÷40]

Blue = Ma 8; Red = Ma 5; Black = same range for both Ma 5 & Ma 8

CONCLUSIONS & OUTLOOK

- The **thermal and mechanical loads are balanced** by the thermal management system proposed
- **Boil-off is not lost** > tank insulation thicknesses and weight can be relaxed
- **Passive cooling of aeroshell** by heat conduction into the cryogenic tanks vs. complex and heavy active cooling system
- The proposed cycle topology is feasible for both a Mach 8 and a Mach 5 missions.

Outlook of further investigations:

- System components **sizing** (turbomachinery, heat exchanging elements and piping) and **weight estimation**, is crucial for system viability.
- **Integration of propulsion plant** into the airframe system: regenerative cooled walls and reuse of common turbomachinery units (expander turbine)
- Propulsion plant **wall temperatures > 1000K** (up to 1400K) at nominal cruise-fuel demand
- **Optimization** to determine trade-off solution between tank/cabin insulation, overall boiled-off fuel and system weight
- Different cycle layout may result, e.g. by utilization of a **different working fluid** with higher density than hydrogen

Thank you!

A Generic Thermodynamic Assessment of Reusable High-Speed Vehicles

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