ESPSS Model of a Simplified Combined-Cycle Engine for Supersonic Cruise

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ABSTRACT

The thermodynamic efficiency of a high speed propulsion engine can be augmented if the cooling capability of the on-board cryogenic fuel is exploited for the heat rejection part of the propulsion cycle. This paper presents a simplified model of a combined Brayton cycle with a supersonic air breathing turbo rocket engine that has been simulated using the European Space Propulsion System Simulation libraries (ESPSS Libraries for EcosimPro). Standard ESPSS models of the various heat exchanger modules, combustors, fitting and turbo-machinery elements were used to represent the physical behavior in design and off-design operation.

The goal of this paper is to obtain the main turbo-machinery and heat exchangers characteristics needed concerning geometrical dimensions which allow to obtain a predefined engine thrust. The start-up operations needed to fulfil stabilized cruise conditions and the ascent line performances were also simulated.

INTRODUCTION

Potential supersonic aircrafts are currently under investigation. Such a system requires an efficient propulsion plant able to carry the vehicle to the cruise Mach number and maintain it during the flight duration. The design of components such as heat exchangers or turbo-machinery is crucial in order to achieve the expected performances. Consequently, a powerful simulation tool appears as a needed solution to carry out a first evaluation of the most suitable designs.

In this sense, the ESPSS libraries are chosen as the natural simulation solution, being the ESA's recommended tool for the simulation of space propulsion systems. The main features of the libraries are:

- Standard fluid database for a wide range of simulations.
- Two-fluid, two-phase networks with detailed simulation of transient aspects due to inertia (water-hammer), heat exchange or control processes.
- Liquid, hybrid and solid rocket engines with one or more combustion chambers including turbo-machinery and two-phase cooling systems.
- Simplified study of movement and attitude of satellites, orbital transfers and orbit control coupled to the propulsion system.
- A standalone library with the necessary components for the calculation of steady performances of rocket engine cycles under design and off-design conditions.

These libraries are based on EcosimPro, a powerful software for programming components and resolving mathematical problems, with the following main features:

- A user-friendly appearance thanks to an easy-to-use Graphical User Interface (GUI), each library containing palettes of components represented by symbols, which can be used to quickly build complex systems graphically.
- Object-oriented programming, which enables the abstraction of components' behavior (equations and data), inheritance and aggregation.
- State-of-the-art solvers and the possibility to exchange and share models or model data.

SIMULATION MODEL

Two models have been built using the ESPSS libraries and EcosimPro: one for steady conditions (design point, see *Figure **1***) with simplified heat exchangers (HXs) and the other for transient conditions (startup and cruise, see *Figure **2***) with a higher fidelity representation of the heat exchangers geometry. Both models share the general topology, which consists of three circuits:

Air circuit: The "Intake" represents the flight conditions in Mach number and altitude, to be selected in a particular experiment (the name given in EcosimPro to the configuration for a simulation) as boundary conditions. The recovery conditions downstream the intake shock wave are calculated depending on the intake geometry and flight regime. Then, the air is cooled in a heat exchanger "HX1_1", which heats the closed loop of Helium, then pressurized in the compressor "C1", heated in the pre-burner to increase the temperature of the Helium circuit in "HX1" and finally burned in the combustor "CC".

In order to maximize the heat exchange, the Air/Helium heat exchangers are considered of the type shell & tubes in a cross-flow disposition. The tubes of "HX1_1" are located within the engine nacelle behind the intake and wrapped in coils around the engine axis with the air flowing radially inwards and across the pipes.

He circuit: The helium circuit is a closed Brayton cycle. The Helium is heated up through the heat exchangers “HX1_1” and “HX1” recovering thermal energy from the Air and the preburner. Then it is expanded across the turbines “T1” and “T2”, cooled down in the heat exchanger “HX2”, compressed in “C2” and finally fed back to the heat exchanger “HX1_1”, thus closing the cycle.

“HX2” is of the type plate and fins, thus providing enough wetted area to cool down the Helium before compression. The Helium Turbine “T1” is mechanically connected to the Air compressor, but not directly coupled to the Air conditions like in an air turbo-rocket cycle. The Helium is further expanded across Turbine “T2”, which drives the Helium compressor “C2”.

H2 circuit: The hydrogen “Fuel” flow, whose inlet conditions are 30K – 100 bar (downstream the Pump), is heated in a plates heat exchanger “HX2” cooling down the Helium circuit (regenerative part of the Helium Brayton cycle). Then the flow is divided into two branches: one goes to the pre-burner, and the other enters into the combustor.

The code takes into account real properties of Hydrogen, both in sub-critic and super-critic conditions. The cycle is regulated by two gaseous hydrogen valves (GH2) in the transient model:

- The first one feeding the pre-burner “PB” and controlled to maintain a constant turbine “T1” inlet temperature.
- The second one is controlled to maintain a predefined “HX2” helium discharge temperature.

A faithful and straight-forward EcosimPro/ESPSS representation of the above explained combined-cycle air-breathing rocket engine model is shown here below, where each physical device has an ESPSS component associated. The system topology has been easily modeled by linking the different components of this particular engine.

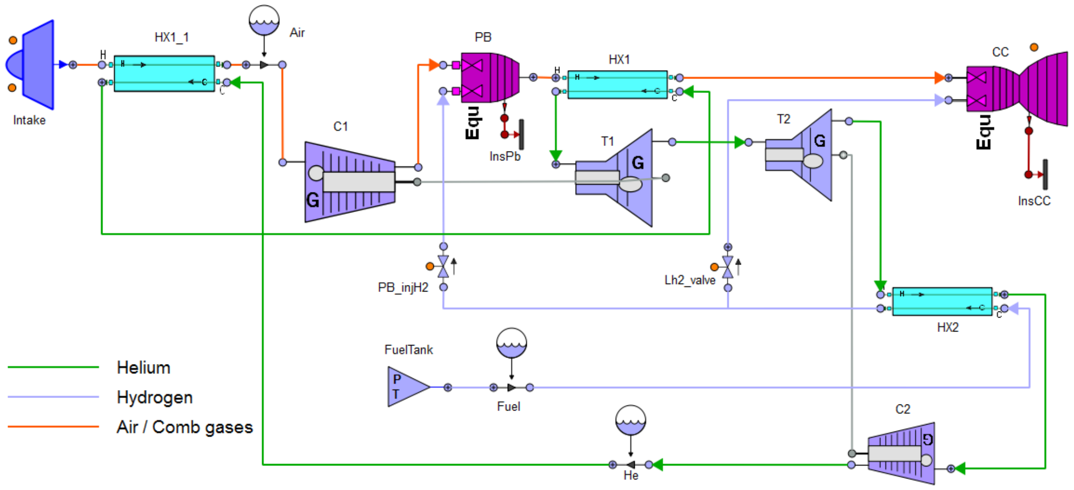


Figure 1 ***Design Model***

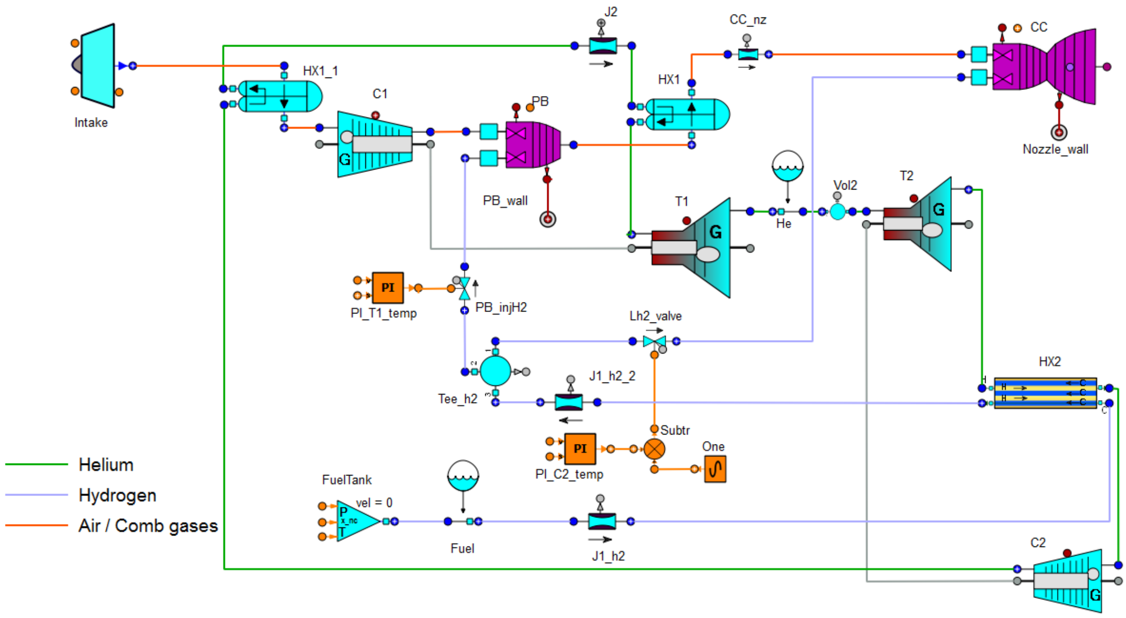


Figure 2 ***Transient Model***

CALCULATION METHOD

This section contains a brief summary of ESPSS User Manual (see [1]).

Design Models:

ESPSS design models aim at calculating directly the steady solution corresponding to a transient model. The system of equations is basically obtained by removing the time derivatives from the formulation of the transient model, hence resulting in a highly non-linear and coupled system of equations.

Design models contain the design conditions (engine performances and imposed operating conditions) as a part of the components' input data. The remaining unknowns, e.g. nominal operating conditions and design parameters, can be computed thanks to the EcosimPro capability of re-ordering the whole system of equations of the model. The so-computed variables define the turbo-machinery and valves. A complete engine sizing (including the nozzle throat diameter) can also be done by imposing specific mission requirements.

Typically, the design conditions comprise pump and turbine efficiencies, pressure ratios, characteristic speeds, combustor pressure and mixture ratio and efficiency of some heat exchangers. Calculated variables are the nominal operating conditions such as the cycle mass flows, valve cross-areas, pressure drops, temperatures as well as the turbo machinery power and torque.

The design model does not calculate the geometry of the heat exchangers. These simplified components (HX1_1 and HX2) are based on the conservation of mass and energy by imposing efficiency and pressure drop. The pressure drop across the hot and cold streams of the heat exchangers is defined as a percentage of the inlet pressures.

Transient Models:

ESPSS transient models are explicit. This means that any state variable (mass flow, mass and energy at each fluid volume) is calculated by the conservation equations. The thermal and transport properties are retrieved by interpolating in real fluid property tables. The conservation and dependent variables (pressure, temperature, etc.) are calculated at each time step. The conservation equations in general form for *fluid volumes* are included below:

$$\frac{\partial \omega}{\partial t} + \frac{\partial\, f(\omega)}{\partial x} = \Omega(\omega)$$

$$\omega = A\begin{pmatrix} \rho \\ \rho x^{nc} \\ \rho x_d^{\ nc} \\ \rho x^{chem}[i] \\ \rho v \\ \rho u \end{pmatrix};\ f(\omega) = A\begin{pmatrix} \rho v \\ \rho v x^{nc} \\ \rho v x_d^{\ nc} - D\dfrac{\partial \rho x_d^{\ nc}}{\partial x} \\ \rho v x^{chem}[i] \\ \rho v^2 + P + qn \\ \rho v h - \lambda \dfrac{\partial T}{\partial x} \end{pmatrix}$$

$$\Omega(\omega) = \begin{pmatrix} -\rho A\, k_{wall}(\partial P/\partial t) \\ -\rho x^{nc} A k_{wall}(\partial P/\partial t) + V(R_d - R_a) \\ -\rho x_d^{\ nc} A k_{wall}(\partial P/\partial t) + V(R_a - R_d) \\ -\rho x^{chem}[i] A k_{wall}(\partial P/\partial t) \\ -0.5(\Delta\xi/\Delta x)\rho v|v| A + \rho g A + P(dA/dx) \\ -\rho u A\, k_{wall}(\partial P/\partial t) + \Delta Q/\Delta x + \rho g v A \end{pmatrix}$$

where ρ, x^{nc}, x_d^{nc}, $x^{chem}[i]$, P, u are the mixture density, non-condensable mass fraction, non-condensable mass fraction diluted in the liquid phase, mass fraction of chemical species, pressure and total energy respectively. *"qn"* is the artificial dissipation term. *"A"* is the variable flow-area and *"v"* the velocity. *"h"* is the total enthalpy (= $u + P/\rho$).

Valves/Orifices formulation:

The following momentum equation dynamically calculates the valves' mass flow per unit of area:

$$(I_1 + I_2)\ (A \cdot \frac{dG}{dt} + G \cdot \frac{dA}{dt}) =$$
$$(P + 0.5\rho v^2)_1 - (P + 0.5\rho v^2)_2 - 0.5(\zeta + \zeta_{crit})\frac{G|G|}{\rho_{up}}$$

where,

- P_1 , P_2 = static pressure at valve ends, calculated by the connected fluid volumes
- $(0.5\rho v^2)_{1\text{-}2}$ = dynamic pressure at valve ends,
- I_1 , I_2= half inertia of the connected ends
- A = actual valve area
- G = mass flow per unit of area
- ζ= pressure drop coefficient (-)
- ρ_{up}= upstream gas/liquid mixture density.

ξ_{crit} limits the mass flow to be less or equal to (≤) the critical flow per unit area. It is calculated in such a way that if the flow attempts to be greater than the critical flow, the following extra term will limit the flow to the critical value:

$$\zeta_{crit} = \max\ (\ (G_{st}/G_{crit})^2 - \zeta, 0)$$

where

$$G_{st} = \sqrt{2\rho_{up}((P + 0.5\rho v^2)_1 - (P + 0.5\rho v^2)_2)}$$

and "Gcrit" is the critical (sonic) flow per unit of area $(\rho c)_{crit}$ calculated from empirical correlations based on real gamma values calculated at the upstream capacity component.

Heat Exchangers' formulation:

Heat exchanger components are built topologically by two 1D fluid veins (one for the cold side, one for the hot side), and three arrays of diffusive nodes with the same dimension as the tube nodes number, simulating the fins and plates. Fluid veins uses the equations previously stated at each fluid node.

Heat, mass storage and pressure losses are taken into account, *the efficiency being calculated as a function of the geometry and transient inlet/outlet conditions, not imposed*.

For the plate and fins type HX, after applying symmetry, the basic connections between the fluid veins and the thermal diffusive nodes are:

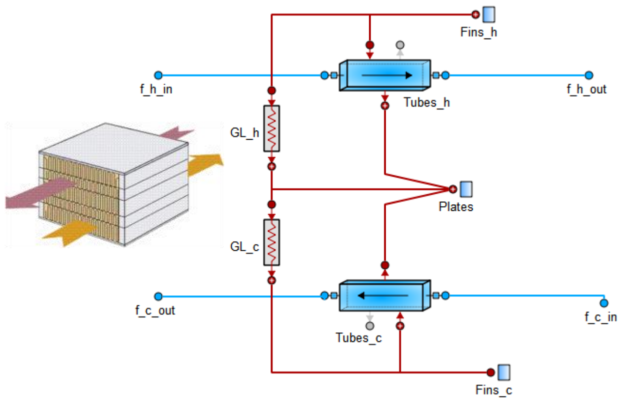


Figure 3 ***Plate & Fins HX topology***

Turbo-machinery formulation:

Turbo-machinery components include additional equations to the general set of equations of the transient *fluid volumes* stated before. These equations are relative to the "source" terms for the pressure drop and mechanical work, applied to the equivalent compressor or turbine fluid volume:

- The power W is obtained by using generalized maps that estimate the efficiency as a function of the reduced speed and pressure ratio, see *Figure* ***4***.c below.
- The axial speed is calculated dynamically as $I_{mech} \cdot \omega' = T_{shaft,port} - T$, where ω is mechanical speed and T is torque, equal to W/ω.
- The mass flow is expressed dynamically in accordance with the pressure rise/drop, estimated again with generalized maps. The following momentum equation is added:

$$I \cdot m_{in}' = (P + 0.5\rho v^2)_{Compr,\,inlet} - (P + 0.5\rho v^2)_{Compr,\,vol} + (\Pi_{nom} - 1) P_{in} \cdot dp\_rel$$

where

m_{in}: inlet mass flow

P: static pressures

I: fluid inertia (1/m)

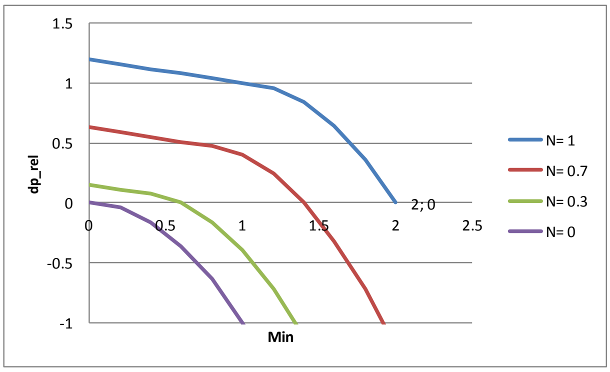
dp_rel is the non-dimensional pressure drop/rise, see *Figure* ***4***.a,b below where:

N: Actual to nominal reduced speed,

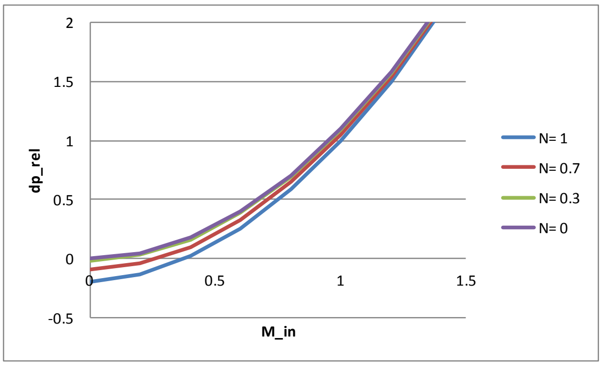
M_in: Actual to nominal inlet Mach number

Generalized non-dimensional maps

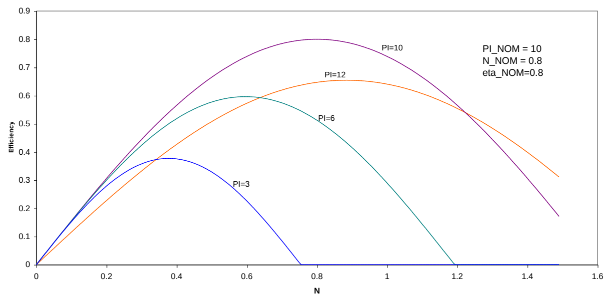
Generalized non-dimensional maps (off-design conditions) obey to *simplified* "physic" equations, giving nominal performances at nominal conditions:



(a)



(b)



(c)

Figure 4 ***Non-dimensional generalised maps for (a) compressor pressure rise, (b) turbine pressure drop and (c) efficiency***

There are four possible cases of operation distinguished, depending on ΔP and mass flow values, the model covering in all zones of operation including zero or negative mass flows and axial speeds (startup process):

- $P_{out} > P_{in}$ (Compressor)
  - I. If the mass flow is negative, the power is calculated as: $W = -eta \cdot m \cdot (h_{out} - H_{ise,in})$.
  - II. If the mass flow is positive, the power absorbed is: $W = m \cdot (H_{ise,out} - h_{in}) / eta$.
- $P_{out} < P_{in}$ (Turbine)
  - I. If the mass flow is positive, the power taken from the fluid is: $W = eta \cdot m \cdot (H_{ise,out} - h_{in})$.
  - II. If the mass flow is negative, the power absorbed is: $W = -m \cdot (h_{out} - H_{ise,in}) / eta$

The isentropic enthalpy $\Delta H_{ise,in-out}$ is calculated using ideal expansions at the local c_p value.

Combustor formulation:

Combustors represent non-equilibrium, non-adiabatic combustion processes for liquid or gaseous propellants.

The transient conditions (gases composition, pressures, temperatures, mass flows and heat exchanged with the walls) are derived from general 1D, area-varying, transient conservation equations as stated before, adding the necessary source terms for propellant injection and burned gases production.

The equilibrium composition of the burned gases is calculated using the Minimum Gibbs energy method, function of the instantaneous molar fractions, pressure and enthalpy of the mixture. Two cases are possible (see [1] for more details):

- Rate models or case of previously burned gases. In this case, the actual (reactant or product) chemicals mass fractions are available since they are dynamic variables.
- Pure fluid reactants. In this case, the reactants mixture composition is calculated from the injected reducer/oxidizer mixture.

DESIGN MODEL INPUT DATA

As stated before, the design model needs the nominal operating conditions and some design parameters as part of the components' input data. The following table summarizes the main input data for the design model:

Turbo-machinery

	eta_nom	*N_nom*	*PI_tt_nom*	*rpm_nom*
T1	0.9	0.4	4	8000
T2	0.9	0.4	3	10000
C1	0.9	0.6	Calculated	8000
C2	0.8	0.2	P_he	10000

Heat exchangers

	dP_hot (%)	*dP_cold (%)*	*Efficiency (-)*
HX2	7	10	0.9
HX1_1	5	5	0.8
HX1	5	5	Calculated

Combustion Chambers

	Pchamber	*Tc/MR_o*	*L_conv*	*Dthroat*	*L_diver*
PB	Calculated	1800 K	5*Dair	Dair	--
CC	P_ch	MR_ch	5*Dth	Dth	50*Dth

The following design variables are considered. They can be easily modified in the EcosimPro experiment without modifying the model:

- *P_ch* (thrust chamber pressure), *MR_ch* (thrust chamber mixture ratio),
- *Dair* ("air side" diameter, used for the throat diameter of the preburner),
- *Dth* (throat diameter of the thrust chamber, 0.4 m)
- *P_he* is the imposed helium pressure (150 bar) at "C2" compressor outlet.

For the Powel's hybrid method (EcosimPro solver) to resolve the complex system of equations, it is necessary to provide a coherent initial value for the model variables, not necessarily close to the actual solution. The variables that are asked to be initialized include mass flows, temperatures and pressures, the rest being automatically initialized by the libraries.

DESIGN RESULTS

Based on the input data described above (see previous section), the EcosimPro experiment consists of a parametric analysis where the operating conditions of the cycle are obtained at various values of pressure and mixture ratio of the thrust chamber.

Figure ***5*** and *Figure* ***6*** collect the results for two flight conditions:

- *Altitude = 20,000 m; Mach = 3.5*
- *Altitude = 10,000 m; Mach = 2.0*

In both cases the helium pressure *P_he = 150 bar* and pre-burner temperature *T = 1800 K*.

The plots show

- *(a) fuel mass flow and preburner MR,*
- *(b) air mass flow and helium mass flow,*
- *(c) efficiency of "HX1",*
- *(d) outlet air temperature of "HX1",*
- *(e) outlet helium temperature of "HX1_1",*
- *(f) outlet helium temperature of "HX2"*
- *(g) gross thrust.*

All variables plotted versus Chamber pressure (parameter) and chamber MR (abscise).

Main conclusions extracted after observing these results are:

- If high MR values (low hydrogen consumption) would be desired to obtain, the required efficiency at "HX1" had to be higher than 1, which has no physical meaning. The limit is smaller for higher chamber pressures.
- Flight conditions have a strong influence on the design conditions. At lower flight Mach number (lower air temperature downstream the intake), the pre-burner has to increase the fuel consumption to compensate the lower air energy.
- Two solutions can be possible given the same temperature in the pre-burner, both of them with the same global LH2 consumption. This makes a change in the pre-burner MR tendency.

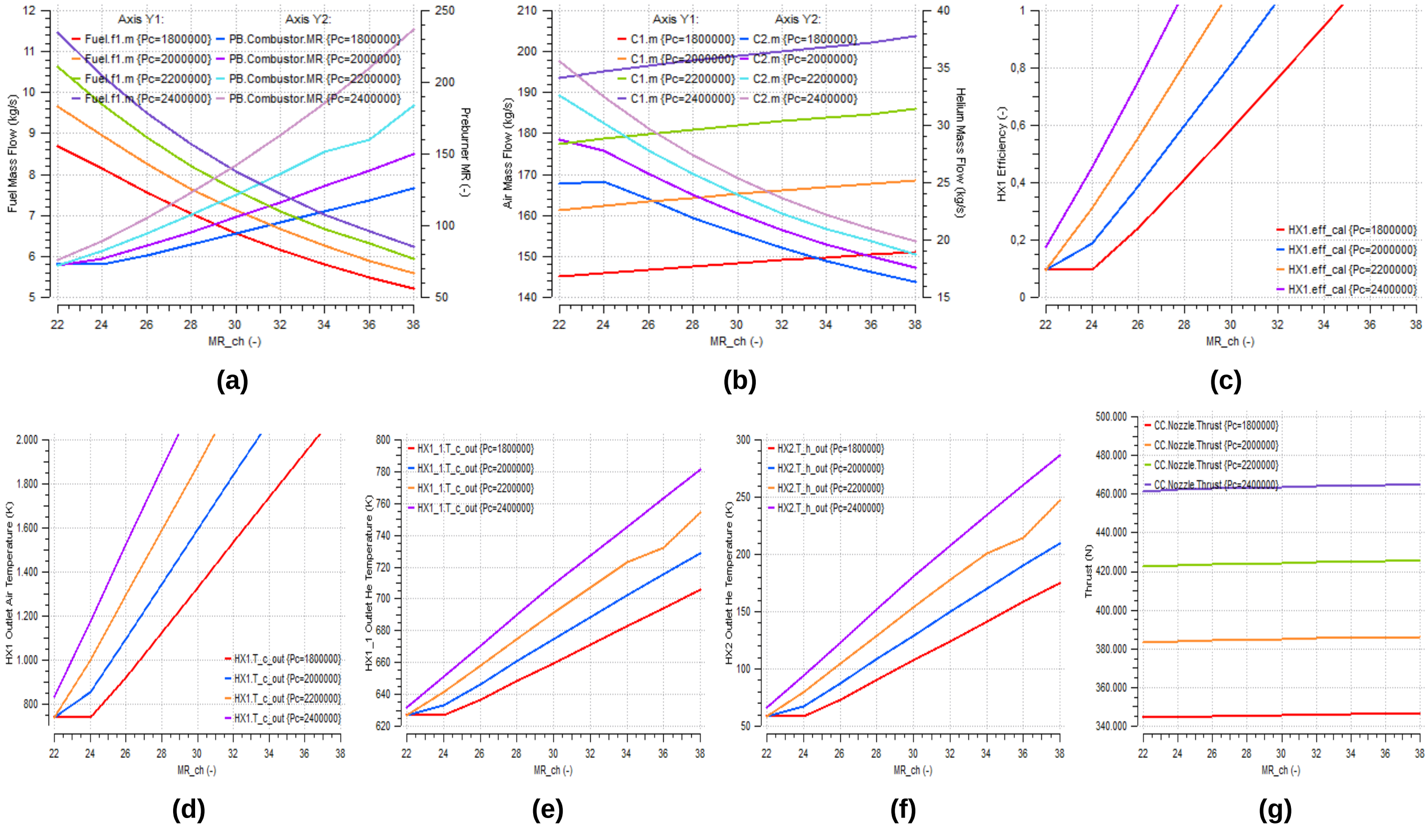


Figure 5 ***Design results at Altitude = 20,000 m; Mach = 3.5.***

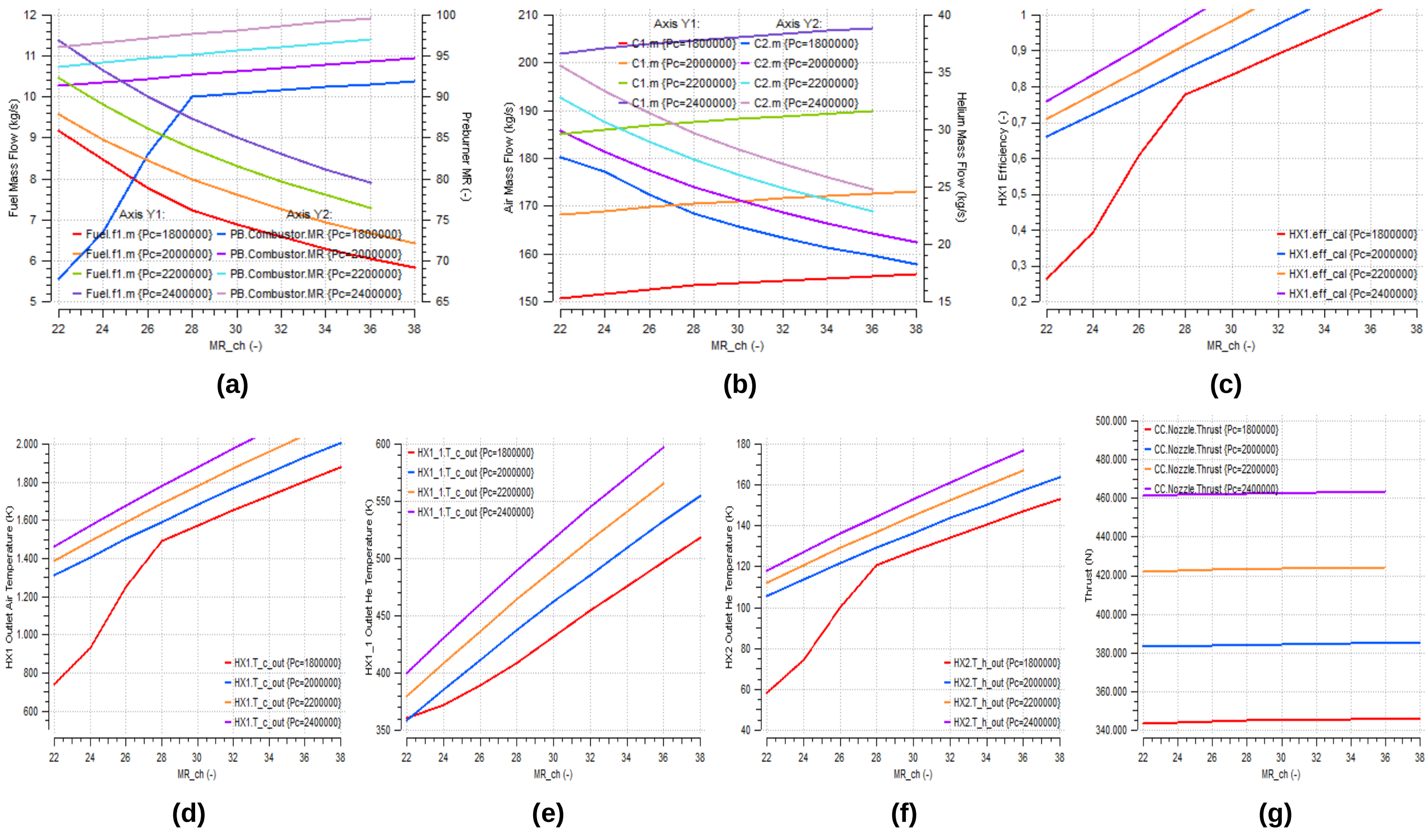


Figure 6 ***Design results at Altitude = 10,000 m; Mach = 2.0.***

In view of the previous results, the selected conditions to calculate the nominal working point are:

- Flight conditions: *Alt = 20 km; Mach = 3.5*
- Thrust chamber pressure *P_ch = 20 bar*
- Nozzle diameter *D_th = 0.4 m*
- Thruster mixture ratio *MR_ch = 31*

Using these values the resulting nominal working point is:

Turbo-machinery

	Mass flow (Kg/s)	*Inlet Pres. (bar.)*	*Inlet Temp. (K)*	*Inlet flow area (m2)*	*Radius (m)*
T1	21.56	135.4	1716	0.005829	1.174
T2	21.56	33.84	1061	0.01832	0.734
C1	165.6	3.61	601.7	1.011	0.350
C2	21.56	10.49	139.6	0.16	0.134

Heat exchangers

	Outlet hot side		*Outlet cold side cond.*	
	(k)	(bar)	(K)	(bar)
HX2	139.6	10.49	652.2	90
HX1_1	601.7	3.605	681.6	142.5
HX1	1280	20.4	1716	135.4

Combustion Chambers

	A_inj_oxy (m2)	*A_inj_red (m2)*	*Valve area (m2)*	*GH2 flow (kg/s)*	*Noz. T (KN)*
PB	0.2912	0.002757	0.0003987	1.49	-
CC	0.3643	0.01071	0.001443	5.39	385.1

OFF-DESIGN RESULTS

The transient model considers off-design behavior in combustors and turbo-machinery, and a detailed calculation of the pressure drop and heat exchange in the different HXs. This feature is of great importance in such a system in view of the compromise needed to achieve high thermal efficiency and low pressure losses, both depending on the detailed geometry of the heat exchanger passages.

HXs input data

The input data of the transient model are based upon the results (nominal operating conditions, turbo-machinery geometry, characteristic radius and inter-blade area) obtained from the Design Model (see previous table).

Since the design model does not calculate HX geometry, the following detailed heat exchanger dimensions have been determined to best fulfill the required efficiencies from the design calculations.

Several tests were done, and finally, the following geometrical data giving reasonable weights were selected:

Plate&Fins	**HX2**
n_plates	150
Fins per plate	200
Length	4
Width	1.0
Hot & cold fins' height	0.005 0.002
Plate thick.	0.0003
Fin thick.	0.0002
Material	Alum.
Weight	***945***

Shell&tube	**HX1**	**HX1_1**
No. tubes	2000	2000
No coils	10	10
L_coil	4	4
D_tube	0.0065	0.0065
Tube thick	0.0003	0.0003
Fin area	10	10
Fin thick	0.0002	0.0002
a_shell	1.7	2.1
b_shell	1.7	2.1
L_shell	5	5
Mat.	Alum.	Alum.
Weight.	***1597***	***1644***

Note: Units are in (m) and (kg).

Engine start-up and throttle setting simulation

The following simulation consists on a startup until the steady conditions are reached. The ignition of the pre-burner occurs at time *t = 1 seconds*, whereas the combustor ignites at *t = 20 s*.

To allow the startup, "C2" compressor is mechanically driven by an external torque during the first 12 seconds.

The set point for the "T1" inlet temperature (first PI controller) is maintained to 1720 K while the pre-burner MR is higher than 15.

Once the steady conditions are reached at time *t = 50 s*, *a new throttle condition is calculated* setting "HX2" Helium outlet temperature (second PI controller) to 90 K instead of 60.

Figure ***7*** and *Figure* ***8*** show the cycle and heat exchangers performances respectively at *Altitude = 20.000 m* and *Mach = 3.5*.

Figure ***9*** and *Figure* ***10*** have been obtained for *Altitude = 10.000 m* and *Mach = 2.0*.

Variables represented are

Cycle performances:

- *(a): Turbo-machinery pressure ratios.*
- *(b, c): H2, He and Air mass flows.*
- *(d): Turbo-machinery powers and nozzle thrust.*
- *(e, f): Air P/T evolutions.*
- *(g): Axial speeds.*
- *(h, i): He loop P/T evolutions.*

HXs performances:

- *(a, b, c): Inlet/outlet temperatures of HXs.*
- *(d, e, f): Inlet/outlet pressures of HXs.*

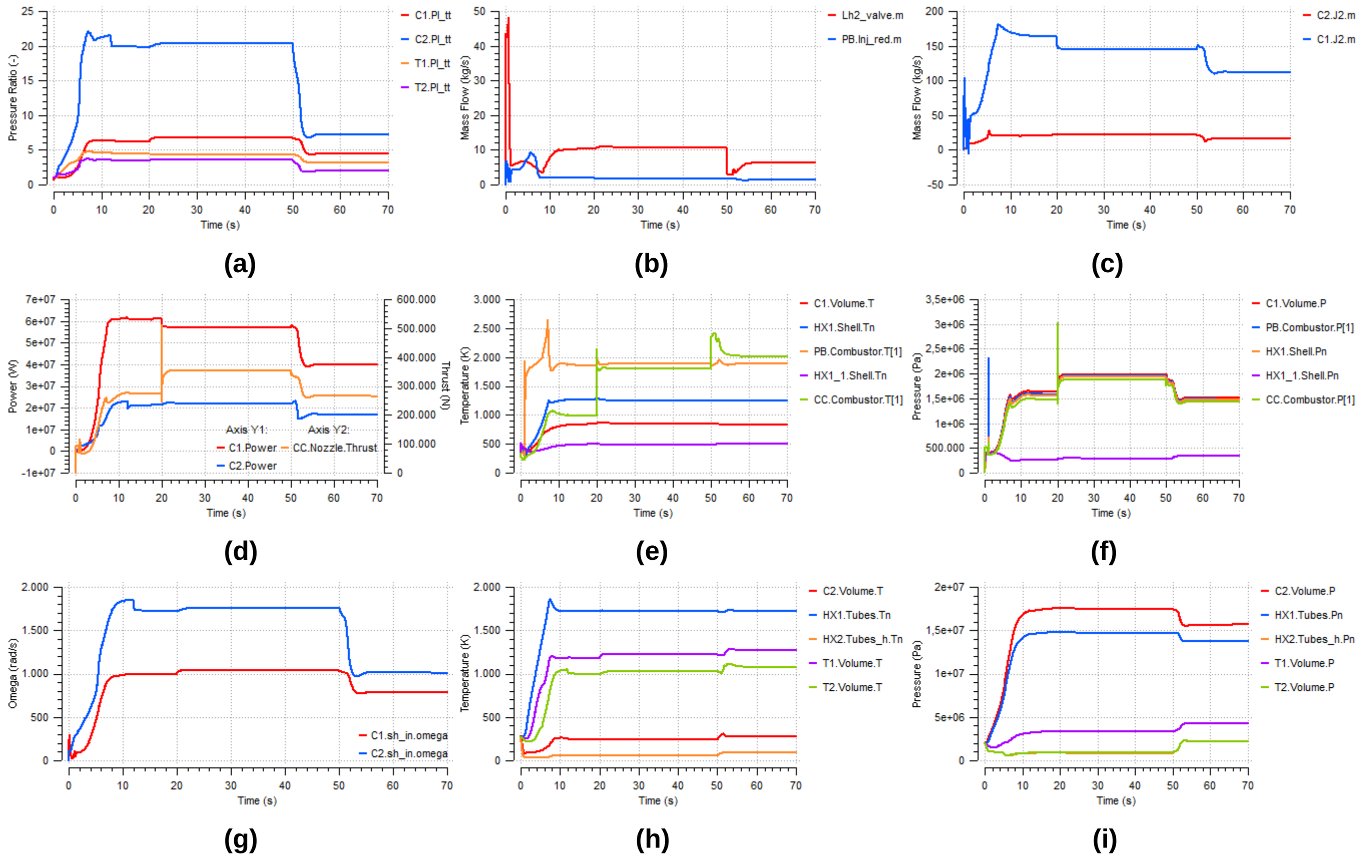


Figure 7 ***Off-design results at Altitude = 20,000 m; Mach = 3.5. Start-up and throttle setting (cycle performances)***

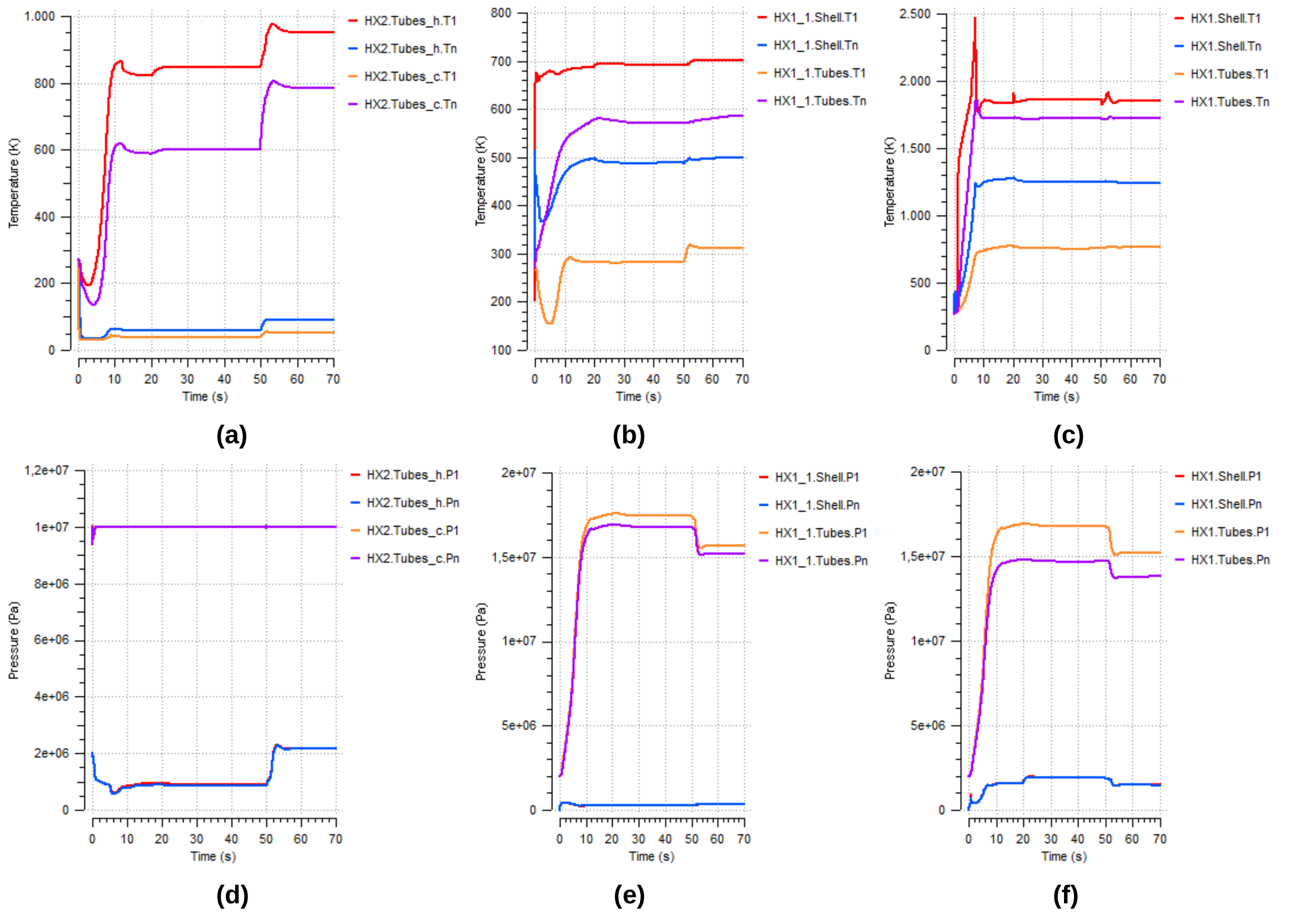


Figure 8 ***Off-design results at Altitude = 20,000 m; Mach = 3.5. Start-up and throttle setting (HXs performances)***

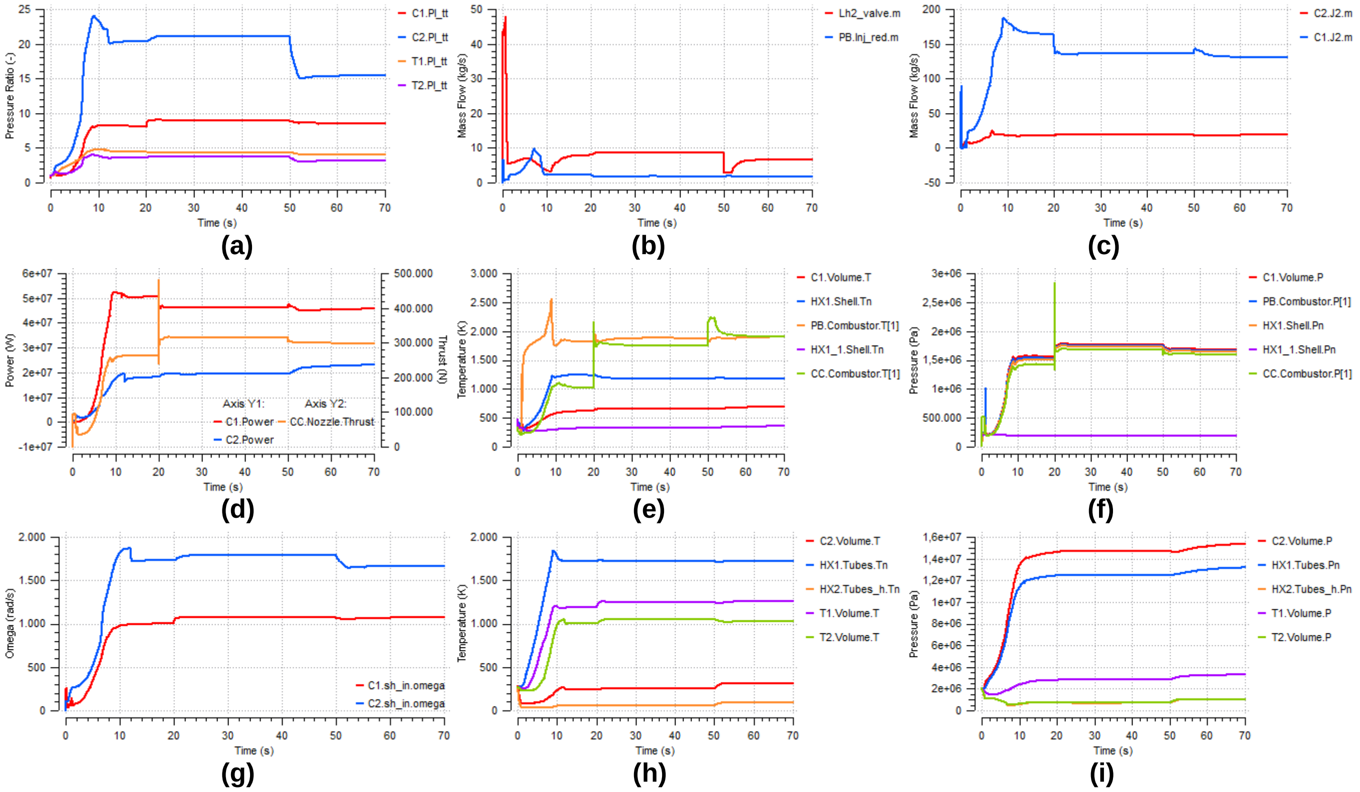


Figure 9 ***Off-design results at Altitude = 10,000 m; Mach = 2.0. Start-up and throttle setting (cycle performances)***

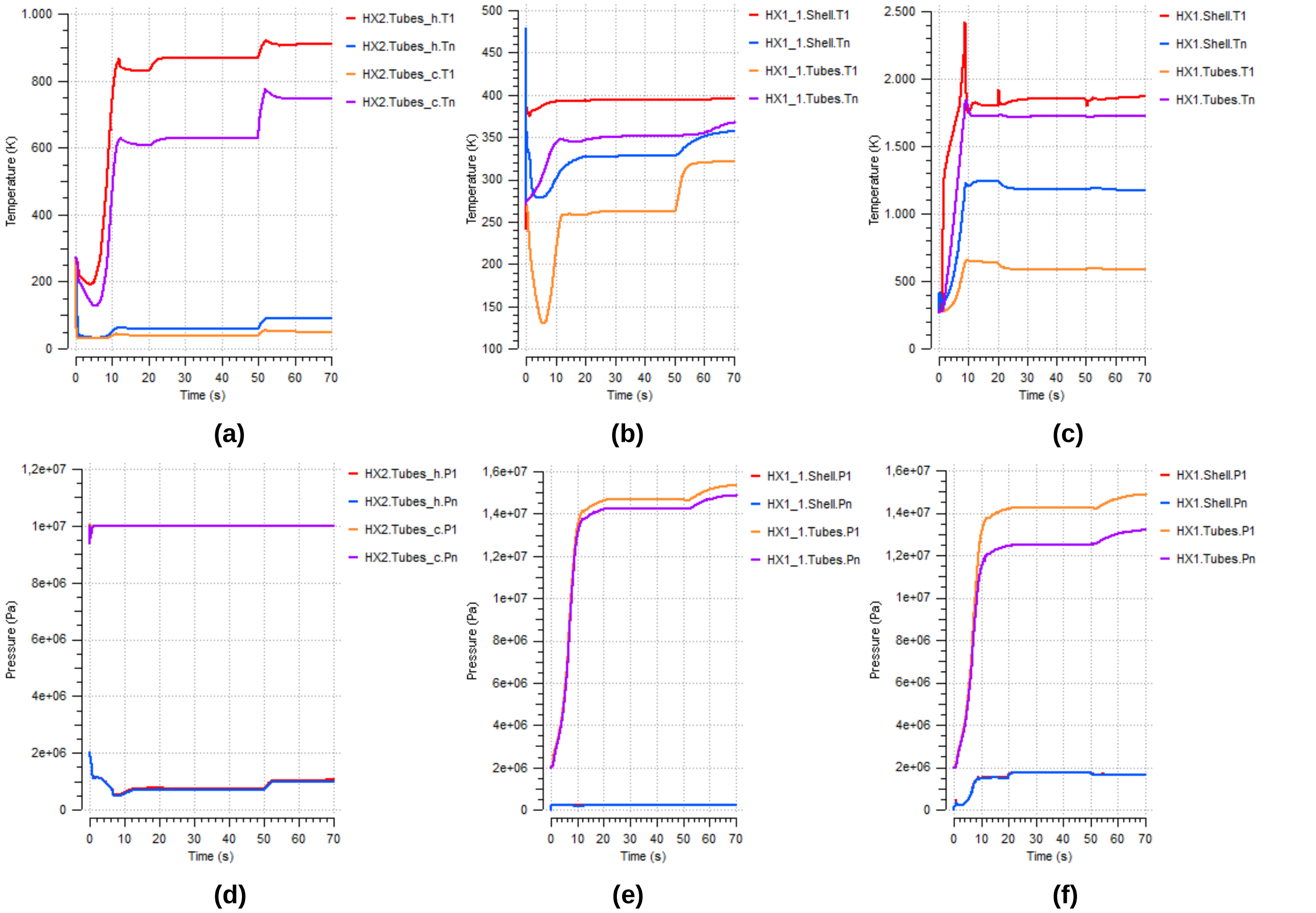


Figure 10 ***Off-design results at Altitude = 10,000 m; Mach = 2.0. Start-up and throttle setting (HXs performances)***

The table below shows a comparison between design (simplified HX) and off-design conditions (higher fidelity HX) at different stabilized throttle positions. (Alt. 20,000 m; Mach 3.5):

	He flow (Kg/s)	Gh2 flow (Kg/s)	Air flow (Kg/s)	Chamber Pres. (bar)	Nozz. Thrust (KN)
Design	21.6	6.9	165.6	20	385
Off design *(throttle 1)*	21.7	12.5	145.1	18.9	353
Off design *(throttle 2)*	16.9	8.0	111.8	14.3	265

Notes:

- *Throttle 1: "HX2" Helium outlet temperature = 60 K*
- *Throttle 2: "HX2" Helium outlet temperature = 90 K*
- *Design conditions: "HX2" He outlet temperature = 140 K (calculated with "HX2" efficiency = 0.9)*

Main conclusions extracted after observing these results are:

- The performances do not reach the exact nominal values computed by the design model due to slightly lower performances of the off-design HXs, which are calculated from their actual geometry.
- As a consequence, the steady thrust of the off-design model is degraded about 10% (chamber pressure reaches about 19 bar instead of 20 bar) with respect to the conditions computed in the design model. The LH2 consumption increases in a more important proportion (in the range 15 - 100% depending on the throttle).
- The required throttle (helium outlet temperature exiting "HX2") should be lower than the calculated by the design model: indeed, higher temperatures (> 90 K) would provide lower consumptions but makes the model unstable for the control scheme chosen.
- The model takes into account the delay produced in the HXs, combustors and turbo-machinery due to the thermal inertia of the materials and fluid mass accumulation. Necessary time to stabilize wall temperatures is about 10 – 20 seconds.
- A pressure overshoot is produced at compressor "C2" during start-up, which could make it cross the surge line. This effect happens as a consequence of the very low values reached by the He outlet temperature before the HXs are stabilized (see Figure 7.a and Figure 9.a).
- Higher HX efficiencies for a better matching of the design hypothesis would require higher weights using current technologies.

SABRE COMPARISON RESULTS

*Figure **11*** shows a comparison of ESPSS uninstalled and specific thrust for the Skylon air-breathing ascent against a simplified off-design SABRE cycle as reported in [2]. The figures are based on the thrust of a single nozzle, disregarding the thrust of the ramjet burners, and one fourth of the fuel and air flows per nacelle.

Both models control the turbine inlet temperature by means of the pre-burner GH2 valve. Second GH2 valve (main thruster) has different controls: the SABRE cycle control is done by regulating the fuel flow across the pump turbine, while in the ESPSS model the control is reduced to maintain "HX2" Helium outlet temperature constant to 60 K in this case.

As a result, the pre-burner total air flow ratio in the SABRE cycle decreases during the vehicle ascent trajectory, whereas the pump turbine to overall fuel flow ratio (χ13) remains fairly constant. In the ESPSS model, a maximum thrust results at Mach = 3 with fixed "HX2" Helium outlet temperature.

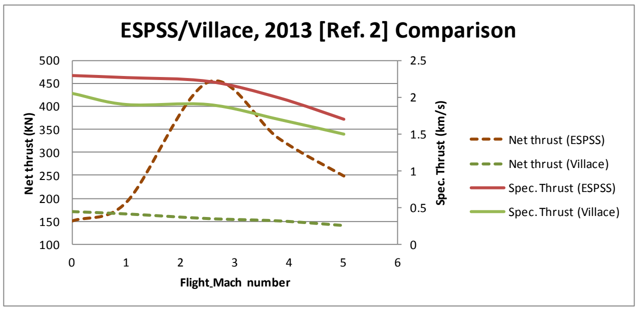


Figure 11 ***Ascent Line performances comparison. (Altitude goes from 0 to 25km at Mach = 5)***

It is pointed out that:

- The comparison is not straightforward since the cycle topologies, the chamber pressure levels and the engine regulation are different.
- ESPSS cycle regulation gives an important thrust overshoot at M=3 with relatively constant Hydrogen consumption. ESPSS cycle has an optimal efficiency at Mach 3 (in that point turbo-machinery and HXs are close to their design conditions).
- The specific thrusts follow more similar evolutions since they are less dependent on the regime. Differences can be explained since the intake is supposed to be ideal (efficiency = 1).

Figure 12 shows the Ascent Line mass flows in the ESPSS cycle:

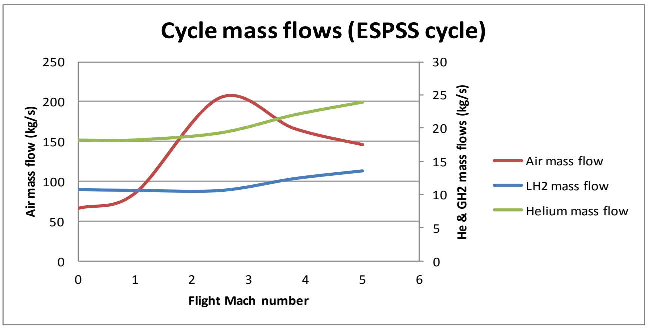


Figure 12 ESPSS Ascent Line mass flows.

CONCLUSIONS

ESPSS models under design and off-design conditions have been successfully tested and compared with SABRE results.

Simulated transient performances including a complete startup reproduce the main physical tendencies that can be expected in these types of cycles, in particular:

- Off-design performances do not achieve the exact nominal values computed by the design model due to the lower performances of the HXs calculated from their actual geometry. Differences in LH2 consumption can reach up to 100% for badly estimated HXs efficiencies.
- As a consequence, the required helium outlet temperature exiting the helium cooler (about 60 K) can be lower than the calculated by the design model with ideal HXs efficiencies: indeed, higher temperatures would provide lower consumptions of LH2 but could make the cycle unstable, especially during the startup.
- This results in a limitation of the throttle capability, since it is not possible to reduce the LH2 mass flow when the He temperature exceeds a particular value (about 90 K in our case) without risking the engine extinction.
- ESPSS models take into account the delay produced in the HXs, combustors and turbo-machinery due to the thermal inertia of the materials and fluid mass accumulation. Necessary time to stabilize wall temperatures is about 20 – 30 seconds.

Turbo-machinery generalized maps have permitted a complete simulation of the off-design conditions including the engine startup and ascent line. More precise results would require the use of turbo-machinery *real* maps if they are known.

Current ESPSS model should be improved with a more realistic engine regulation by including LH2 by-pass valves for example.

REFERENCES

[1] ESPSS: European Space Propulsion System Simulation. EcosimPro Libraries User Manual.

[2] Villace, V. F. (2013). Simulation, Design and Analysis of Air-Breathing Combined-Cycle Engines for High Speed Propulsion - Doctoral Thesis. Von Karman Institute for Fluid Dynamics. ISBN 978-2-87516-067-6.