OBJECT ORIENTED STEADY STATE ANALYSIS AND DESIGN OF LIQUID ROCKET ENGINE CYCLES

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Abstract

The usage of system design tools for liquid rocket engines is necessary during the feasibility study; their flexibility makes them a fundamental instrument along the entire design period including prediction and validation of experimental tests. For this purpose these tools have to be reliable and fast, in order to perform iterative engine design loops, including parametric studies, in a reasonable time. Moreover, they should be able to perform off-design studies and detailed analyses. The Steady State library presented within this paper enables to realize these purposes. Its object oriented structure ensures maximum flexibility and allows for studying any liquid rocket engine thermodynamic cycle (open or closed).

The entire library has been implemented within the existing analysis software EcosimPro, designed to model various kinds of dynamic systems. The already available propulsion library ESPSS can be used to study both stationary states and transients of a propulsion system. Unfortunately its use for steady state applications is not trivial because of the complexity of the transient models there implemented. Therefore, simplified pre-design and parametric studies are difficult and time-consuming. The library shown hereafter was designed specifically for steady state purposes, providing a helpful and fast tool for the pre-design phase (feasibility analysis) allowing for parametric studies.

To this aim, the available fluid properties and combustion modelling functions of ESPSS have been implemented in an adequate form into new libraries. Additionally, fluid dynamic, combustion and heat transfer models have been developed to simulate the physical steady state behaviour of the main components of a propulsion system, as pipes, valves, turbines, pumps, orifices, combustion chamber and nozzle. These components are suited for both launcher and spacecraft applications.

After the description of the main components of the Steady State library, their integration and validation will be presented through an example of liquid rocket engine cycle design.

Nomenclature

A	Area, m^2
D	Diameter, m
fr	Friction factor, -
H	Enthalpy, J/kg
$\dot{m}$	Mass flow rate, kg/s
$\dot{q}$	Heat flux, $\mathrm{W/m^2}$
u	Internal energy, J/kg
v	Mean velocity, m/s
γ	Isentropic coefficient, -
ΔP	Total pressure drop, bar
η	Efficiency, -
ζ	Distributed pressure drop coefficient, -
ρ	Density, $\mathrm{kg/m^3}$
Subscript	
i	Node number
th	Throat conditions
cc	Combustion chamber
ch	Cooling channel
gg	Gas generator
is	Isentropic
p	Pump
t	Turbine

1 Introduction

The European Space Propulsion System Simulation libraries (ESPSS) have been developed by Iberespacio in the frame of two ESA contracts in the last 3 years, and enable the modelling and analysis of propulsion systems for both spacecraft and launcher applications.

A new library has been developed to enable EcosimPro steady state design and off-design analysis of liquid propulsion systems. The models in this library represent a first attempt to develop a complete set of steady state components for design and parametric analysis of liquid propulsion systems. The final aim of this study is to obtain a library able to perform design and parametric analysis, whose components can act as seamless replacements for the transient ESPSS ones.

2 Models

The Steady State library is based on the following libraries of EcosimPro and ESPSS:

- **EcosimPro:**
  - MATH library
  - CONTROL library
  - PORTS_LIB library

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  - THERMAL library
- **ESPSS:**
  - FLUID_PROPERTIES
  - FLUID_FLOW_1D (partially)
  - COMB_CHAMBERS (partially)
  - TURBO_MACHINERY (partially)

In particular, the fluid properties functions and the chemical equilibrium functions for combustion are taken from ESPSS, as they serve the same purpose we need for the steady state. The fact that they are more complex (enabling the use of two fluids at the same time, for instance, which is not needed in the Steady State library) just adds some complexity to the readability of the code, but brings no compatibility issues nor noticeable slowdowns of the simulations. Figure 1 gives an overview of the components developed specifically for the Steady State library. The main components are described hereafter.

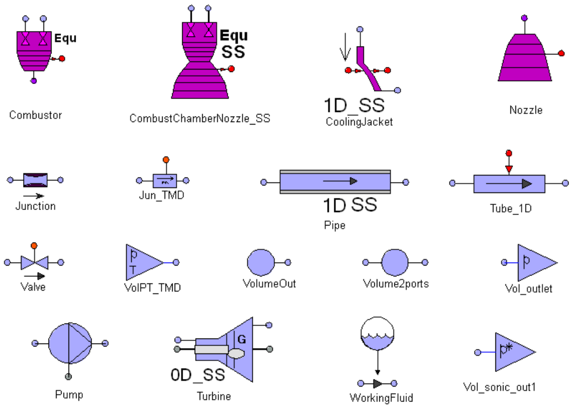

Figure 1: Components in the Steady State library

2.1 Ports

Ports are used to connect a component to another one or to different ones, in order to guarantee the propagation of the variables. Two new ports have been created: the Steady State *fluid* port, that represents the basis and the rationale on which the whole library is coded, and the *nozzle* port, to better manage nozzle connections, similarly to the transient nozzle port.

Each port can connect two or more components at once. SUM variables, such as mass flow rate, will be summed at the ports to ensure mass flow conservation; EQUAL variables, such as stagnation pressure, will be propagated to all components connected at the same port. A standard flow component should have two ports, one IN and one OUT, thus defining the mass flow direction. IN ports ensure calculation of the enthalpy flow mh, while enthalpy h is computed in the OUT ports.

Similarly to the original ESPSS fluid port, the Steady State fluid port can propagate the molar fraction of chemical species to allow the correct evaluation of fluid flow of combustion products in systems where this makes sense (e.g. staged combustion cycles).

2.2 Functions

Several functions present in ESPSS are used in the Steady State library. The authors would like to point to [3] and [5] for the details of the ESPSS implementation. Nevertheless, some functions had to be modified or rewritten; this is the case of the *FL_state_vs_ph* function. This function is the modified version of the *FL_state_vs_ru* function, and calculates the fluid properties using pressure and enthalpy. This function is mainly needed for the Steady State tube component, where the independent state variables are pressure and enthalpy, instead of density and internal energy.

2.3 Tube, pipe and cooling jacket components

The tube component is able to evaluate a one-dimensional flow in steady state conditions. The tube takes into account the enthalpy variation due to external heat fluxes and the pressure drop due to the friction along the pipe. As for the transient version of the component, the Steady State tube is divided in volumes and junctions. Pressure drops and enthalpy variations are calculated at the end of each volume, on the junction. The governing equations are the following:

Mass conservation

$$\dot{m}_{in} = \dot{m}_{out} = \rho v A \tag{1}$$

Momentum conservation

$$P_{i+1} = P_i - \Delta P_i \tag{2}$$

where, for each node i,

$$\begin{aligned} \Delta P &= \frac{1}{2}\zeta\frac{\dot{m}^2}{\rho A^2} \qquad (3) \\ \zeta &= \frac{\Delta L_i}{D_h} fr \qquad (4) \end{aligned}$$

and where the friction factor *fr* is a function of Re and relative roughness, as defined in [5]. In order to ensure numerical stability, *fr* is limited in the range $[10^{-2}, 1]$, enabling flows with Reynolds numbers between 64 and 10^8.

Energy conservation. For each node i:

$$\dot{m}\Delta H_i = \dot{q}_w\,\Delta A_{wet,i} \tag{5}$$

The heat flux is evaluated using the thermal port and connecting the component with all components inside the EcosimPro THERMAL library. It has been decided to use the original transient EcosimPro THERMAL library, but still allowing to be interfaced with the Steady State library. This choice enables a relaxation in the overall steady state model stiffness thanks to the first order differential equations present in the THERMAL components. Of course, due to the specifications of the Steady State library, the time variable will have no physical meaning anymore, and it must rather be regarded as an integration constant.

The pipe component is inherited from the tube. Additionally it features a 1D wall model for the evaluation of the heat fluxes and heat capacities. As in the corresponding transient component, it includes a material pipe thermally connected to the tube, and permits simple convection with the ambient by using a constant convective coefficient h_c.

The cooling jacket components are inherited from the tube component as well. They permit the modelling of a combustion chamber regenerative circuit. Since the direction of the flow in the Steady State library must be given at the schematic design stage, two components are foreseen: a co-flow and a counterflow cooling jacket. They are constructed by aggregation of one tube representing the channels and a simplified 3D geometry (built by means of several bars around the channels) around them (see Figure 2).

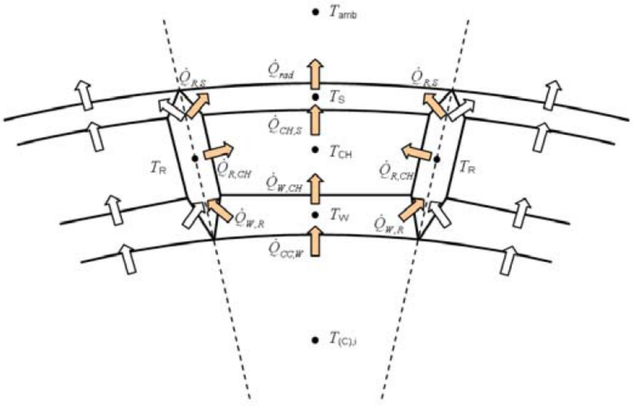

Figure 2: Cooling jacket channels wall mesh [5]

2.4 Thrust Chamber

The thrust chamber is composed by two different components following the same idea developed in the transient library. A combustor component and a nozzle component are linked together to create the thrust chamber.

2.4.1 Combustor

This component represent a non adiabatic 1D combustion process inside a convergent chamber (up to the throat section). It is a steady state, one dimensional, isoenthalpic combustion chamber with constant mass flow rate. The equilibrium combustion products are calculated using the minimum Gibbs energy method [6] as a function of the propellant's mixture molar fractions and enthalpies and of the chamber pressure.

The chamber geometry allows for precise chamber contour definitions and non homogeneous node discretisation.

The component evaluates the equilibrium composition in the first section, to obtain thermodynamic and transport properties, and in the throat, to evaluate the chamber pressure and the mass flow rate by an iterative loop. Thermodynamic properties along the chamber sections are evaluated using isoenthalpic correlations in frozen conditions. Heat fluxes are calculated with the Bartz correlation in closed form [2]. The chamber works only in "ignited" mode, as it is not required for a steady state model to show transitions between burning and non burning state.

The compositions of both fuel and oxidizer are evaluated from the injected fluids. It is possible to use either pure fluids or combustion products from a previous combustor (preburner).

The mass flow conservation is written as:

$$\dot{m} = \frac{\rho_{th} v_{th} A_{th}}{\eta_c} \tag{6}$$

where the subscript th refers to throat conditions, and η_c is the combustion efficiency. This equation is actually used in the overall loop to determine the chamber pressure P_c implicitly. The ideal gas equation is written twice, for stagnation chamber and for throat conditions. Isentropic throat conditions are calculated iteratively assuming shifting equilibrium conditions and variable isentropic coefficient γ.

For each node i, the relevant characteristics (Mach number M_i, P_i, T_i, ρ_i, sound speed $v_{sound,i}$, v_i) are calculated assuming isentropic flow conditions. This simplification is tolerated since these variables are only needed for assessing the heat transfer coefficient with the Bartz equation.

2.4.2 Nozzle

The component represents a 1D supersonic nozzle in steady state conditions. The choked throat conditions (P_{th}, T_{th} and v_{th}) are evaluated in the combustor component and communicated through the nozzle port. Stagnation conditions are calculated from the throat conditions. Static conditions are evaluated in each section using isoentropic correlations and assuming frozen chemistry. The heat flux in each section is evaluated using the semi-empirical correlation of Bartz in a closed form.

2.5 Pump

The pump component features a simple model using isentropic relations and constant, user-given efficiency to calculate pump conditions. The isentropic enthalpy rise is calculated assuming an isentropic transformation between inlet and outlet pressure. The shaft rotational speed ω and torque τ are then linked with the isentropic enthalpy rise by the power balance equation:

$$\omega\,\tau = \dot{m}\frac{\Delta h_{is}}{\eta_p} \tag{7}$$

In order to enable the component to work in both dimensioning design mode and in off-design analyses, a switch has been implemented as a "construction parameter" DP. This switch decides whether the pump pressure rise is user-assigned (with calculated specific speed N_s) or calculated (with assigned specific speed N_s); it must be carefully set depending on the user needs. A rule of thumb is that in a pre-design phase, when the N_s is unknown, the user can set DP = TRUE. This setting works best in a subsystem, rather than in a complete engine cycle. On the other hand, if the pump specific speed N_s is known, the user can rely on it and set DP = FALSE. This setting can be used on a complete engine cycle.

In the near future the off-design mode (with assigned specific speed) will be upgraded with the capability of using performance maps for efficiency and pressure head.

2.6 Turbine

The turbine component is a simple component using isentropic relations and constant, user-given efficiency to calculate turbine conditions. The isentropic enthalpy fall is calculated assuming an isentropic transformation between inlet and outlet pressure. The shaft rotational speed ω and torque τ are then linked with the isentropic enthalpy rise by the power balance equation:

$$\omega\,\tau = \dot{m}\,\eta_t\,\Delta h_{is} \tag{8}$$

This component is able to operate in two different modes. The construction parameter PI decides whether the total to total turbine pressure ratio Π is user-assigned or calculated from the rest of the model. This switch must be carefully set depending on the cycle studied. For open cycles (gas generator), the pressure ratio should be given by the user (PI = TRUE), and the model will find the mass flow that equilibrates the pump power. For closed cycles, in most cases, the mass flow is determined by the preburner (staged combustion) or by bypass valves (expander), therefore the pressure ratio should be calculated in the turbine component (PI = FALSE). These considerations must be taken as guidelines and depend on the particular system in study.

3 Results

Several test cases have been performed in order to evaluate the reliability of the Steady State library. Following a step by step approach, it was decided to validate first each component singularly and then more complex systems.

3.1 Pipeline test case

The purpose of this test case is to validate the Steady State pipe component and demonstrate its proper function compared to a transient component. The schematic shown in Figure 3 has been also built to check the correct behaviour of Steady State components in long pipelines. A long pipeline is modelled twice, with standard ESPSS transient components and with Steady State components. Pressure drop distribution along the pipeline and mass flow rates are compared between the two models.

Please note the absence of the volume between two junctions. Purely capacitive components are not needed in the Steady State library, and it is possible to chain multiple resistive components in series.

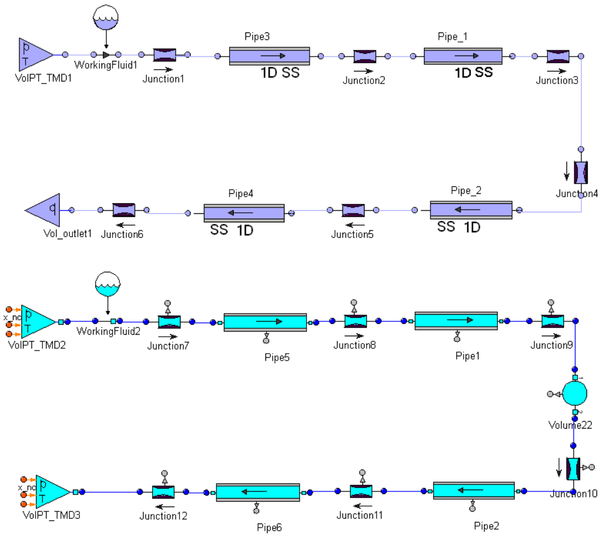

Figure 3: Schematic of the Pipeline test case

The schematic describes a series of pipes linked together by junctions. A pressure difference has been imposed between inlet and outlet. The input data shown in Table 1 represent the inputs implemented in each component (steady or transient). The initial conditions have been taken equal for each pipe, with atmospheric pressure and low initial mass flow. These conditions are quite distant from the solution, and the convergence of the steady state code in this case is an indicator of its robustness.

The simulation results are summarized in Table 2, showing a very accurate mass flow calculation and pressure drop distribution.

3.2 Combustion Chamber

The purpose of this test case is to calculate the main characteristics of combustion chamber and nozzle components. Its schematic is shown in Figure 4 for both steady state and transient models.

The only difference between the two models (besides the different modelling approach) is the absence of the injector

Table 1: Pipeline input data

Name	Description	Value	Units
P_{in}	Total Pressure at inlet	50	bar
T_{in}	Total Temperature at inlet	300	K
P_{out}	Total Pressure at outlet	30	bar
P_o	Initial Total pressure in the pipe	1	bar
T_o	Initial Total temperature in the pipe	300	K
m_o	Initial mass flow in the pipe (guess value)	0.2	kg/s
rug	Roughness	5e-05	m
L	Pipe length	1	m
D	Pipe internal diameter	0.01	m
nodes	Pipe nodes discretisation	5	-
Ao	Junction area	7e-05	m^2
ζ	Loss coefficient	1	-
fluid	Working fluid	Real H2O	-

Table 2: Pipeline output data

Name	Value Transient	Value Steady State	Error
m [kg/s]	1.109	1.109	0.006%
ΔP_1 [bar]	3.110	3.110	0.002%
ΔP_2 [bar]	3.111	3.111	0.002%
ΔP_3 [bar]	3.112	3.112	0.002%
ΔP_4 [bar]	3.112	3.112	0.002%

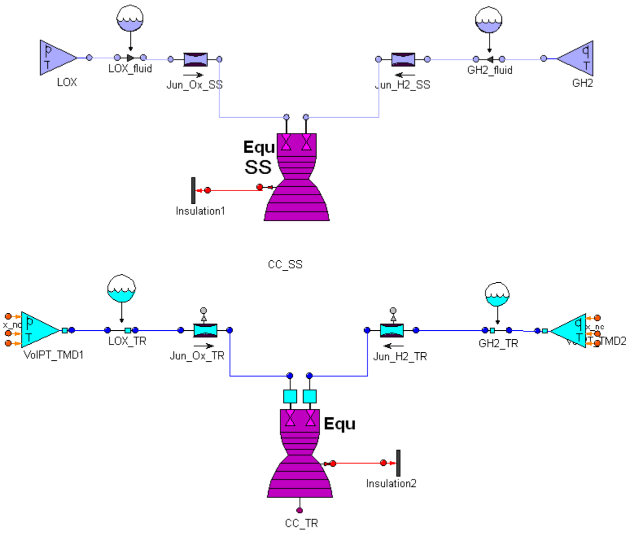

Figure 4: Schematic of Combustion Chamber test case

capacity inside the Steady State combustion chamber injection plate.

Relevant input data are listed in Table 3. The initial conditions are the same for the steady state and the transient components.

Table 3: CC input data

Name	Description	Value	Units
$P_{in,ox}$	Ox. Total Pressure at inlet	70.8	bar
$T_{in,ox}$	Ox. Total Temperature at inlet	94.7	K
$P_{in,fu}$	Fu. Total Pressure at inlet	71	bar
$T_{in,fu}$	Fu. Total Temperature at inlet	208.9	K
N_{sub}	Number of subsonic nodes	5	-
N_{sup}	Number of supersonic nodes	5	-
L_{cc}	Chamber length of subsonic part	0.5	m
D_{th}	Nozzle throat diameter	0.10	m
P_{cc}	Initial Chamber pressure	1	bar
T_{cc}	Initial Chamber temperature	300	K

The test compares the propellant mass flows and the chamber pressure and temperatures between the two models. Other important characteristics as heat fluxes, wall temperatures and adiabatic wall temperatures have been evaluated as well, but are not reported here for simplicity.

The output data from the two models are compared in Table 4. It is evident that the steady state results are very similar to the respective transient results.

Table 4: CC output data

Name	Transient Value	Steady State Value	Error
m_{ox} [kg/s]	18.72	18.53	1.0 %
m_{fu} [kg/s]	3.14	3.11	1.0 %
m_{tot} [kg/s]	21.86	21.64	1.0 %
MR [-]	5.959	5.956	0.04 %
P_{cc} [bar]	64.97	64.27	1.1 %
T_{cc} [K]	3518	3514	0.11 %
Mach [-]	2.887	2.762	4.5 %

3.3 HM7B Turbopump subsystem

This test case was using during the ESPSS Industrial Evaluation from Astrium Bremen to validate the ESPSS library for liquid rocket engine cycles [4].

The schematic shown in Figure 5 represents the turbomachinery power pack of the upper stage engine of the Ariane 5 launcher, the HM7B engine, including the gas generator and both turbopumps.

Figure 6 shows the equivalent schematic implemented with Steady State components. They are very similar to each other. Only volume components and non condensable fluid lines are absent. The first ones are not needed for the same reasons stated in Section 3.1; the latter have been eliminated since there is no need to model the Helium purging phases in a steady state simulation.

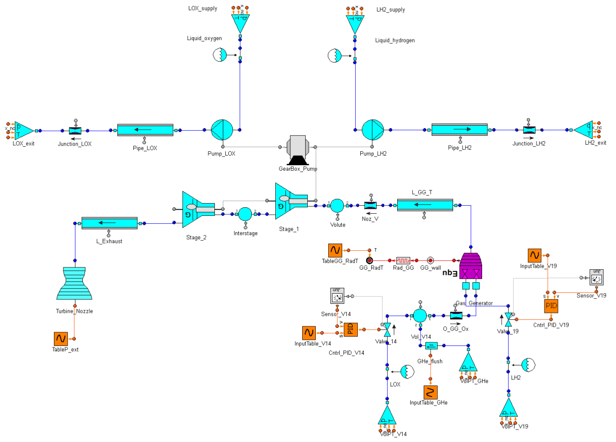

Figure 5: Turbopump test case: HM7B power pack transient schematic

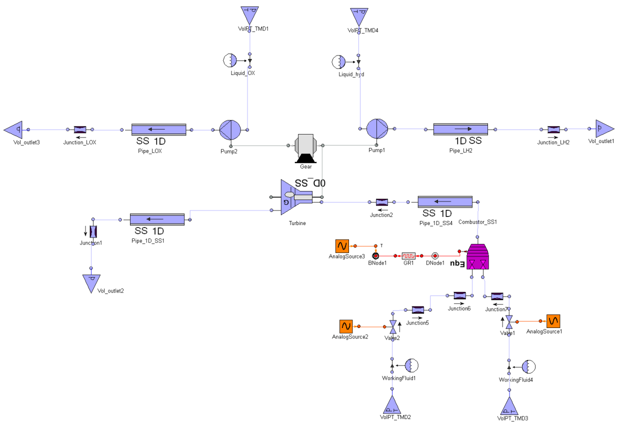

Figure 6: Turbopump test case: HM7B power pack steady state schematic

The chosen input data are collected in Table 5; Table 6 summarizes the main system variables results performed by the transient and the steady state models. The steady state model matches very well the transient one for fluid flow, turbomachinery gas generator main parameters.

3.4 HM7B Chamber subsystem

This test case represents the combustion chamber subsystem of the HM7B engine. The aim of this test case is to validate the behaviour of the combustion chamber and cooling jacket components when they are coupled together in a simulation, by comparing results with the transient model simulation.

Figures 7 and 8 show the schematics of the combustion chamber subsystem using the ESPSS transient library and the steady state model, respectively.

As in the previous test case, described in Section 3.3, the similarity of the two schematics shown hereafter is evident.

Table 5: HM7B Turbopump input [1] and initial data

Name	Description	Value	Units
$P_{in,LOX}$	Total pressure in LOX tank	2.0	bar
$P_{in,LH2}$	Total pressure in LH$_2$ tank	3.0	bar
$P_{out,LOX}$	Total pressure at Pump outlet/Gas Generator inlet	50.0	bar
$P_{out,H2}$	Total pressure at Pump outlet/Gas Generator inlet	55.0	bar
P_{cc}	Initial chamber pressure	20.0	bar
T_{cc}	Initial chamber temperature	900	K
$\omega_{p,ox}$	Initial LOX pump speed	1000	rpm
$\omega_{p,fu}$	Initial LH$_2$ pump speed	6000	rpm

Table 6: HM7B Turbopump output data

Name	Nominal Value [1]	Error Transient/Steady State
$\dot{m}_{gg,ox}$ [kg/s]		0.3%
$\dot{m}_{gg,fu}$ [kg/s]		0.07%
MR [-]		0.5%
P_{gg} [bar]		1.3%
T_{gg} [K]		0.08%
$\dot{m}_t$ [kg/s]		0.3%
ω_t [rpm]	60500	0.8%
τ_t [N·m]	59.98	2.0%
$\dot{m}_{p,LOX}$ [kg/s]	12.4	0.0%
ΔP_{LOX} [bar]	48	1.6%
$\omega_{p,ox}$ [rpm]	13000	0.8%
$\tau_{p,ox}$ [N·m]		10.4%
$\dot{m}_{p,LH2}$ [kg/s]	2.4	0.0%
ΔP_{LH2} [bar]	52	0.8%
$\omega_{p,fu}$ [rpm]	60500	0.8%
$\tau_{p,fu}$ [N·m]		6.0%

The only difference for the steady state model is the absence of non condensable fluid lines and capacitive components such as volumes.

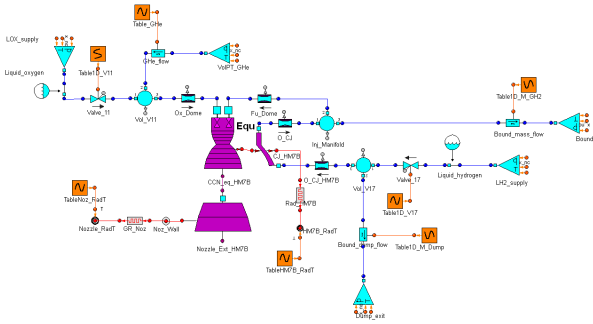

Figure 7: Chamber test case: HM7B Combustion Chamber transient schematic

In Table 7 the main input data for both systems are collected; in Table 8 the main system variables results are summarized, performed by the transient and the steady state models.

As reported in the table the steady state model matches the transient results, showing very good agreement between the values of the combustion chamber, and of the cooling channel model.

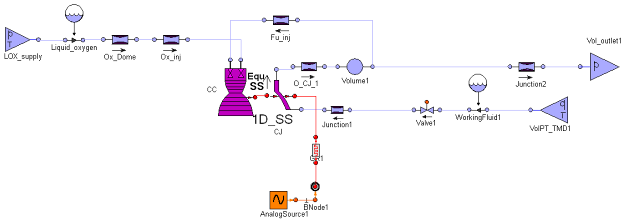

Figure 8: Chamber test case: HM7B Combustion Chamber steady state schematic

Table 7: HM7B CC input [1] and initial data

Name	**Description**	**Value**	**Units**
$P_{in,LOX}$	Total pressure at pump outlet/chamber inlet	50.0	bar
$P_{in,H2}$	Total pressure at pump outlet/chamber inlet	55.0	bar
P_{cc}	Nominal chamber pressure	36.6	bar
n_{ch}	Numbers of channels	128	-
$P_{i,cc}$	Initial chamber pressure	30	bar
$T_{i,cc}$	Initial chamber temperature	1000	K
P_o	Initial total pressure in the channels	49	bar
T_o	Initial total temperature in the channels	30	K
m_o	Initial mass flow in the channels	2	kg/s

4 Conclusion

A new EcosimPro library for steady state applications has been presented in this paper. This library enables to perform in a fast and a reliable way design and parametric analyses of liquid propulsion systems. The work presented here represents a first attempt to develop a complete set of components able to perform dimensioning designs and off-design analyses. A step-by-step approach has been followed in order to validate the reliability of each component developed and the robustness of more complex systems, such as complete thermodynamic cycles systems of liquid rocket engines.

Future improvements of the Steady State library are foreseen. First of all, the importance of differentiating between a “design/dimensioning” and “off-design/analysis” mode has been individuated during this first library development. Therefore, the possibility of adding dedicated switches to most components is being investigated. For example, valves would have pressure drops as inputs in dimensioning mode, and geometric dimensions in analysis mode. Similarly, combustion chambers would have chamber pressure and mixture ratio as inputs in dimensioning mode, and geometric parameters in analysis mode.

A second topic of improvement would be the refinement of the off-design mode for each model, enabling for instance the use of performance maps for turbomachinery components.

Table 8: HM7B CC output data

Name	**Nominal Value** [1]	**Error Transient/Steady State**
m_{ox} [kg/s]	12.4	2.4%
m_{fu} [kg/s]	2.46	0.38%
m_{tot} [kg/s]	14.86	2.0%
MR [-]	5.0	2.9%
P_{cc} [bar]	36.6	0.32%
T_{cc} [K]		0.88%
m_{ch} [kg/s]	2.46	0.37%
ΔP_{ch} [bar]		9.9%
$T_{out,ch}$ [K]		6.7%

Acknowledgments

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