Comparative Study of Ethanol and Kerosene Propellant for Gas-generator Fed Upper Stage Application, Using EcoSimPro

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This paper presents a cycle analysis of LOx/Ethanol LRE based on gas-generator cycle using EcoSimPro for steady-state operation as well as a simplified analytical tool for different heat transfer models and its comparison with LOx/RP-1 with same class and design requirements for performance evaluation.

Despite its low C* and specific impulse when compared with LOx/RP-1, the specific characteristics of LOx/Ethanol combination for its cooling capability, combustion gas properties and energy provided at mixture ratio for temperature range of gas-generator application makes its performance comparable of RP-1 in a large range of operational conditions, resulting in an equal global performance in equivalent designed conditions. The use of external tools makes possible a more precise evaluation of entire cycle taking into consideration factors that are not fully implemented in the EcoSimPro tool with ESPSS library.

Key Words: EcoSimPro, Ethanol, Cycle Analysis

Nomenclature

C^*	:	Characteristic exhaust velocity
η_{C^*}	:	C-Star efficiency
η_{FP}	:	Fuel pump efficiency
η_{OP}	:	Oxidizer pump efficiency
η_T	:	Turbine efficiency
P_e	:	Chamber exhaust pressure
P_i	:	Pump inlet pressure
P_{te}	:	Turbine exhaust pressure
Subscripts		
k_gg	:	Gas-generator combustion parameter
e	:	Exhaust condition

1. Introduction

During the evolution of LPRE, since its first studies around 1930 until middle of 1950, Ethanol was used as fuel in combination with Liquid Oxygen. This combination was deeply explored with the development of RD-100 Engine family in Russia and XLR71 program in USA. However, the performance was limited by the propellant itself as well as the turbine driver media as an open cycle.

With limitation of the steam generator temperature by the hydrogen peroxide concentration, the solution from XLR71 program to increase performance led to the bi-propellant gas-generator, which initially was powered by combustion of Ethanol at 92,5% with decomposed hydrogen peroxide.[1] At the same time, RP-1 was been tested as a more powerful fuel on engine RD-103K.[1] The last improvement came with gas-generator operating with same propellant as the chamber in G38, and RD-0105 family for upper stage[1, 2]. As result, studies of LOx/Ethanol gas-generator cycle engines was abandoned, resulting in a lack of information about this propellant combination, especially for upper stage application.

The use of RP-1 as propellant became possible with improvements in the cooling capability since it characteristic as coolant has shown disadvantages. Despite studies to reduce the Sulphur derivatives content, which results in strong incompatibility with Copper alloys as well as ways to increase the coking temperature which led to the development of much more expensive RP-2[2], RP-1 is more preferable choice for Kerosene family fuels.

Recently, studies with LOx/Ethanol start to receive more attention as a possible alternative for NTO/MMH in Space shuttle's OMS[3] and designed propellant of Lockheed RS-88PAD system[4], which are both pressure fed engines. Also, since 2011, the Brazilian LPRE development, in common works with German Space Center (DLR) switch the L75 gas-generator engine fuel from Kerosene to Ethanol.[7]

In this frame, the cycle analysis becomes a fundamental tool to perform a comparison between propellants, taking into account the major characteristics of both fuels in the same system requirement with equivalent specifications. Thus, multiple tools are used to perform a detailed system evaluation and provide a comparison in order to estimate the engine performance. A simple mathematical model for gas-generator cycle engine coupled with a program for chemical equilibrium[8] and fluid properties (REFPROP) is initially connected into a Gas-generator combustion model for LOx/Ethanol[5] and LOx/RP-1 combustion properties as well. The evaluation of optimum combustion chamber mixture ratio for a wide range of combustion chamber pressure make possible estimate an initial configuration for a hypothetical engine according to its expansion ratio. The next step consists in thermal analysis in order to achieve the main requirements for the chamber and propellant according to imposed restriction and will result in a regenerative combustion chamber design. The final step is the detailed cycle simulation by using EcosimPro with European Space Propulsion Systems Simulation (ESPSS) library developed by Empresarios Agrupados on the side of the European Space Agency (ESA). The combination of those tools allows the cycle performance prediction with more fidelity making an important combination for system analysis group in DLR Lampoldshausen.

2. Gas-generator Cycle Evaluation Model

The initial assumption for the gas-generator cycle model evaluation takes into account the propellant combination, on the thrust level and exhaust pressure specified for main design parameter comparison. At this stage, the numerical tool also adopts a transition between H.C.O. and Z.R.H. models[5] for gas-generator and a polytropic compression for pumps by using the real fluid properties. Each step for the iteration is calculated according to the flow presented in Fig. 1.

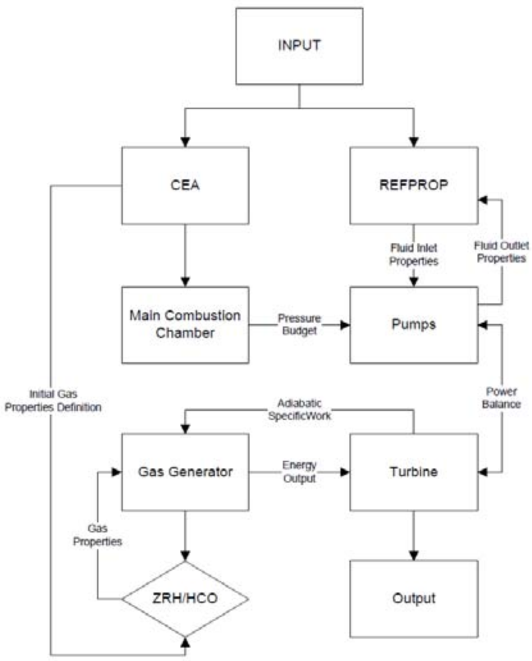

Fig. 1. Calculation logic for the optimization tool used to generate the initial condition for gas-generator cycle analysis.

This allows matching a cycle power balancing according to specified turbine and pumps efficiency as well as the desired gas-generator combustion temperature for a wide range of specified Main Combustion Chamber Temperature and Mixture ratio in a program structure as presented below.

2.1. Major Consideration about GG Calculation.

For this evaluation, the initial constrains for a performance comparison was chosen a thrust level of 100kN with an exhaust pressure of 5kPa, which is in accordance with an upper stage requirement for a medium size class launcher as Ariane 5.[9] This definition is also in accordance with a range from L75 Engine class [7] to a RD-0110 upper stage for currently Soyuz 2-1a versions.[10] The gas-generator combustion temperature was aimed for 900K and all pumps and turbine efficiency initially defined as the same range of 50%. In the Table 1 is shown the main parameters specifications according to design rules estimated from existing engines.[11]

Table 1. Initial Parameters.

Parameter	Values	Unit
Thrust	100	kN
P_e	5	kPa
η_{OP}	0,5	---
η_{FP}	0,5	---
η_T	0,5	---
P_{in} **Oxidizer**	400	kPa
P_{in} **Fuel**	400	kPa
P_{te}	300	kPa

Since the main aim of this work is a comparison of cycle, the design solutions as detailed turbopump as omitted in order to verify similar requirement performance from the propellant itself in the cycle. Thus, TPA performance shift evaluation will not be part of this investigation.

2.2. Gas-Generator properties

In a range of GG combustion temperature, Chemical equilibrium tools as CEA[8] fail to predict the expected parameters. This can be seen in LOx/RP-1 as presented in the graph of Fig. 2. Thus, the Z.R.H. and H.C.O.[5] method was used in order to provide a more reliable result for the relation between mixture ratio and combustion properties for such component.

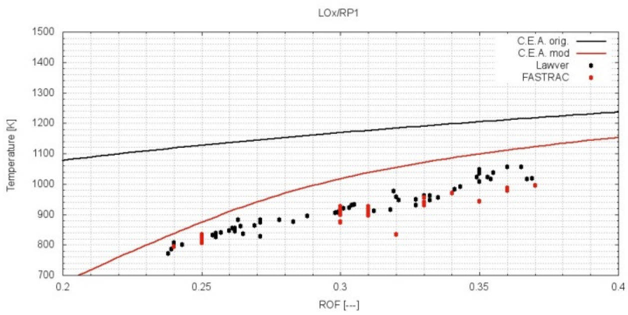

Fig. 2. Original and modified CEA equilibrium conditions to match the literature available information about mixture ratio and combustion temperature with corrected pressure dependence.

As mentioned before, LOx/RP-1 have been investigated since middle of 1950 and this way, there is plenty of information about its behavior in far from stoichiometric conditions, as presented in the Fig. 2, from Lawver studies [12] and also available from tests performed during Fastrac engine development.[13] This way was possible to adjust the H.C.O. models to achieve a good agreement between modified C.E.A. conditions according to mixture ratio and combustion pressure for a gas-generator range mixture ratio.

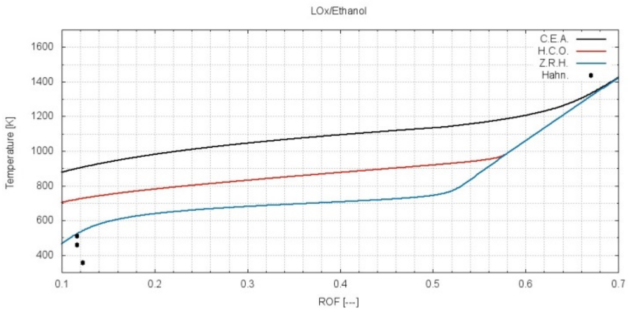

Fig. 3. Combustion temperature in function of mixture ratio according CEA full result, hydrocarbon omission (H.C.O.) and zero reaction hypothesis (Z.R.H.) models. [5)]

In the recent years, studies with LOx/Ethanol gas-generator become available, which result in the possibility to estimate the combustion properties with acceptable agreement with experimental results as shown in Fig. 3.[5)] With such models taken into consideration, the comparison between LOx/RP-1 and LOx/Ethanol for gas-generator cycle increases its precision.

The selected methodology was implemented in the software and the iteration provides a good approach to estimate the required power to drive the turbopump. Thus, the global specific impulse according to chamber pressure for various mixture ratio is presented in the graph of Fig. 4 for LOx/Ethanol.

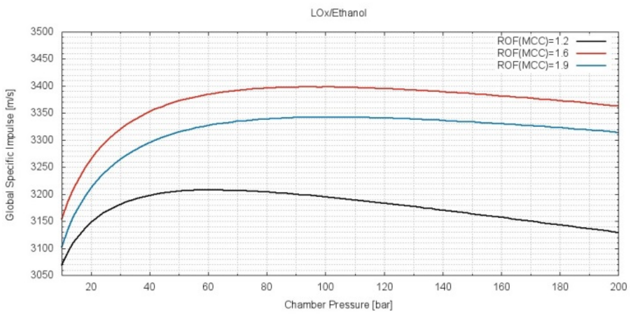

Fig. 4. Global specific Impulse for LOx/Ethanol in function of main combustion chamber pressure for different mixture ratio adopting 5kPa of exhaust pressure.

The same methodology was used to estimate the global specific impulse for LOx/RP-1 combination as presented in the Fig..

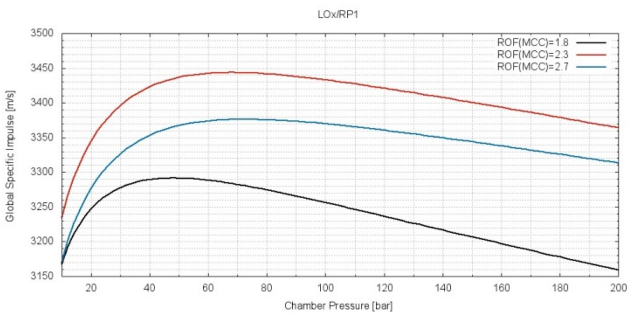

Fig.5. Global specific Impulse for LOx/RP-1 in function of main combustion chamber pressure for different mixture ratio adopting 5kPa of exhaust pressure.

The maximum global specific impulse according to the required Mixture ratio can be verified in Fig. 6 for Ethanol and in circumstance of different exhaust pressure, showing a negligible change in the mixture ratio for the optimum point.

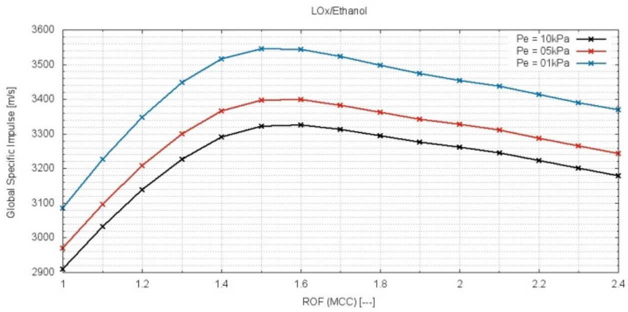

Fig. 6. Maximum global specific impulse in function of mixture ratio considering three different exhaust pressure for LOx/Ethanol application.

The result for RP-1 as fuel, however present a more distinctive change in the global specific impulse according to the specified exhaust pressure. However, the mixture ratio for the optimum performance is unchanged as presented in Fig. 7.

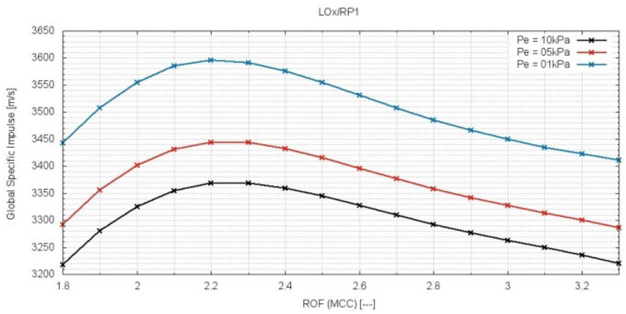

Fig. 7. Maximum global specific impulse in function of mixture ratio considering three different exhaust pressure for LOx/RP-1 application.

With the given optimum mixture ratio for LOx/Ethanol combination as approximately 1,6 (O/F), is possible correlate the maximum global specific Impulse with the chamber pressure, as stated in the Fig. 8 for the distinctive exhaust pressure.

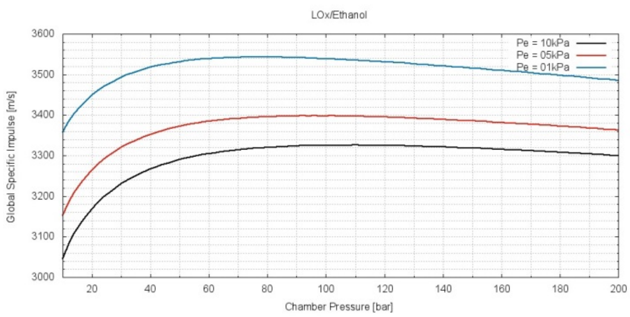

Fig. 8. Global specific impulse for different main combustion chamber

pressure for the optimum mixture ratio in three different exhaust pressure when operating with LOx/Ethanol.

The same evaluation applied for RP-1 as fuel, presented in Fig. 9, shows an optimum main combustion chamber pressure for the optimum mixture ratio is also dependent to the exhaust pressure.

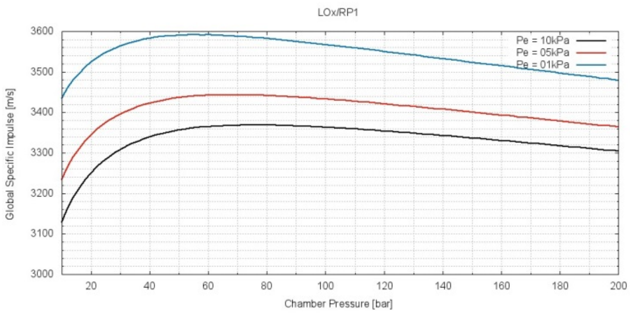

Fig. 9. Global specific impulse for different main combustion chamber pressure for the optimum mixture ratio in three different exhaust pressures when operating with LOx/RP-1.

Using the optimum mixture ratio and an exhaust pressure of 05kPa is possible estimate the maximum performance at around 7,0MPa and 10,0MPa for RP-1 and Ethanol respectively as fuels. Considering the associated error and performance deterioration at main combustion chamber pressure variation, for a design evaluation was selected a Pressure level of 10MPa for both combinations, having the specific impulse difference applied in the combustion efficiency. This procedure makes possible compare the thermal load for both systems without impact in the engine specific impulse.

2.3. The Choice of Main Parameters

Initial consideration for this evaluation took into account the main combustion chamber design following a methodology describe in various literatures[14), 15)] with a supersonic profile created by method of characteristics.[15)] For a design simplification, the regenerative cooled section was adopted until an area expansion ratio of 36 (Ae/At) to minimize the total enthalpy increase of chosen coolant.

Based on previous considerations, the MCC of this cycle evaluation was designed to withstand to a maximum Wall temperature of 900K due to the mechanical and thermal degradation copper alloys usually specified for LRE application.[16)] Also, the heat transfer model in the gas side conditions is based on modified Bartz methodology[17)] while the cooling side takes into account the Nusselt-Prandtl correlation for heat transfer in the cooling channels. The initial results for LOx/Ethanol model with previously described restrictions shows a wall temperature profile as presented in the Fig. 10.

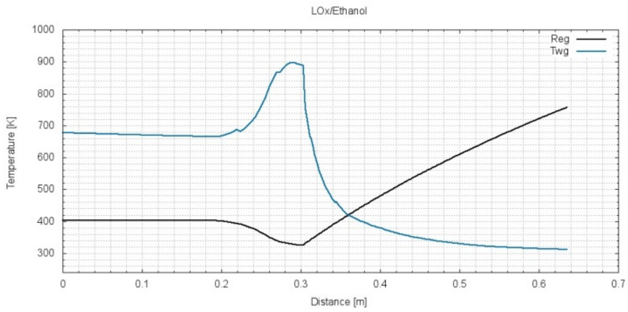

Fig. 10 – Wall temperature for regenerative cooled section of LOx/Ethanol Design.

The cooling jacket design was adjusted in order to provide the lowest pressure drop possible while minimizing the coolant temperature. Those considerations applied to LOx/Ethanol evaluation resulted in a coolant temperature as shown in Fig. 11.

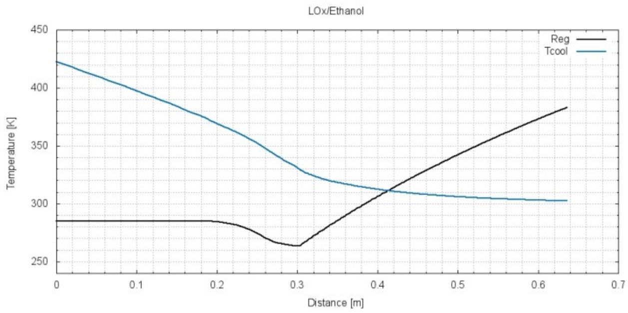

Fig. 11. LOx/Ethanol Coolant temperature

Adopting the same requirements for LOx/RP-1 design, was possible optimize the cooling channel for withstand with a lowest possible wall temperature based on the same volumetric flow in the cooling channels. However, due to the intrinsic RP-1 characteristics, there is need to make use of Fuel Film Cooling in an attempt to decrease the maximum wall temperature as well as limiting the coolant maximum temperature to reduce the possibility of cocking and resin deposition which can often result in cooling channel blockage and thermal failure of combustion chamber.

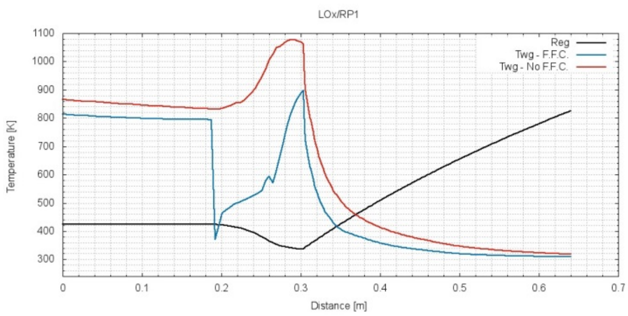

Fig. 12. LOx/RP-1 wall temperature for standard calculation (red) and for fuel film cooling calculation (blue).

The initial iteration based on a methodology presented on

Ref. 15) result in a Fuel film Cooling mass flow of 1,06kg/s injected at the end of cylindrical section in order to reduce the maximum wall temperature at levels below 900K, as presented in Fig. 12.

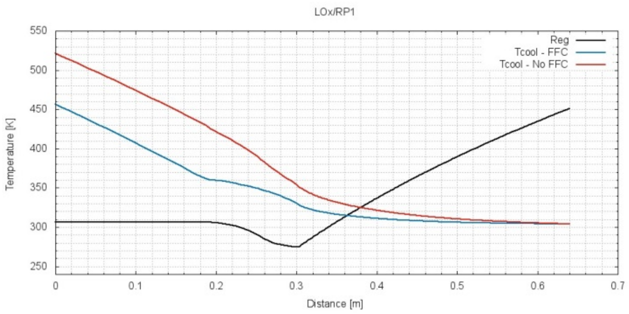

Fig. 13. LOx/RP-1 coolant temperature for standard calculation (red) and for fuel film cooling injected at the end of cylindrical section (blue).

This restriction reduces the maximum coolant temperature shown in Fig. 13 at level in a desirable range for a RP-1 operation[18], with an effect also in the reduction of global specific impulse, since the extra fuel used for film cooling will have a negligible impact in the chamber pressure and effective thrust.

3. EcoSimPro

With aid of EcoSimPro using the ESPSS library, is possible to perform a 0D or 1D model for steady state and transient simulations and results in a great help for cycle evaluation while operating together with basic calculation tools for design optimization as described previously, in order to improve the convergence for the designed model.

3.1. LOx/Ethanol – Steady State Model

For this evaluation was performed a Steady State Library from ESPSS in EcoSimPro using the previously described requirements. The schematic of this model is presented in the Fig. 14 and shows a good agreement with the simplified mathematical model used for parametric optimization previously described. The major difference however, lies in the gas-generator models using Z.R.H./H.C.O.[5] which provides a good agreement with information from data available in the literature.[12), 13), 5)]

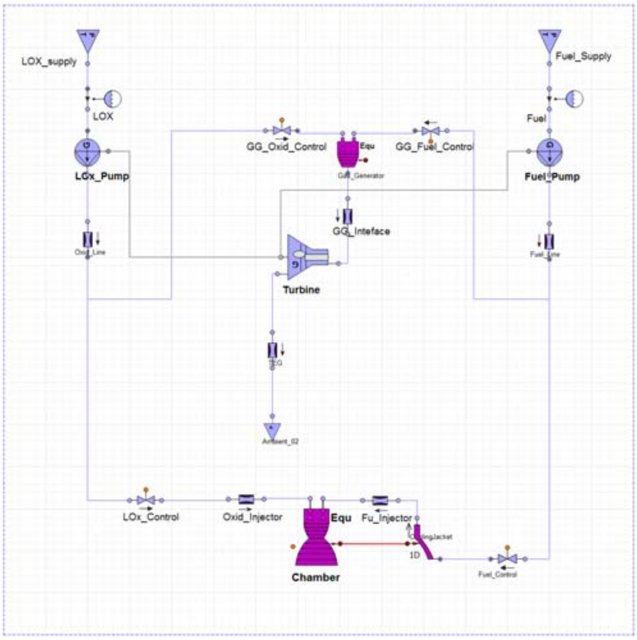

Fig. 14. Steady state model of LOx/Ethanol cycle.

Preliminary results for this model shows difference in global specific impulse of 2,2% due to disagreement in gas-generator conditions. Thermal evaluation of cooling jacket also provides a strong deviation with local temperature range of -6,3%. This deviation is associated to the simplified model of heat transfer for coolant side, due to lack of details on the cooling channel characteristics.

3.2. LOx/RP-1 – Steady State Model

A similar model was created for LOx/RP-1 evaluation using ESPSS library. For this configuration was adopted a calibrated orifice to simulate the fuel film cooling used for such application, as shown in Fig. 15.

The main gas-generator parameter was adjusted according to literature information about this component, which result in a global specific impulse 1,6% higher than provided from previously described cycle optimization tool.

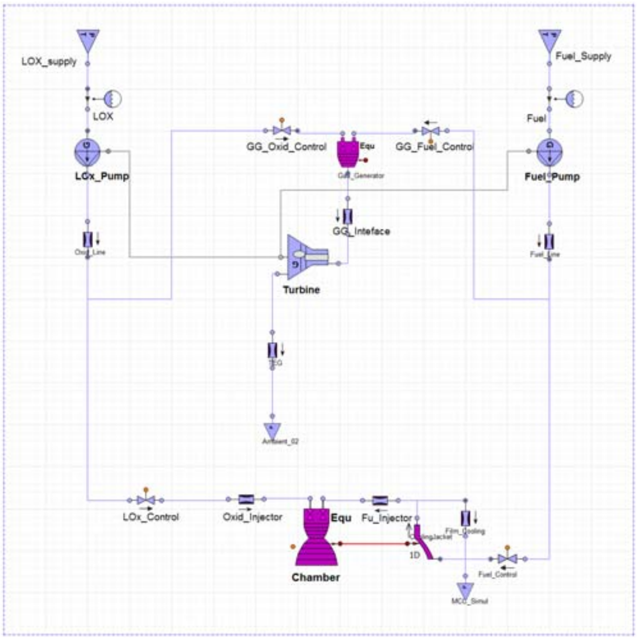

Fig. 15. Steady state model of LOx/RP-1 considering a fuel film cooling section for performance evaluation purposes.

For this steady-state model, the thermal evaluation has shown a strong discrepancy in a range of 48% due to lack of film cooling models implemented in the available library, as well as the impossibility to perform thermal evaluation considering the specific characteristics of a real cooling jacket.

3.3. Transient Models

Due to the Steady-state model limitation for more improved evaluation in specific behalf of thermal properties of cooling jacket, a Transient model was used with inputs generated from previous design tools as well as the result from steady state evaluation. The transient model was adjusted to capture the information after achieve a steady-state configuration. Thus, we can have the following model, shown in Fig. 16, to simulate LOx/Ethanol operation using transient library.

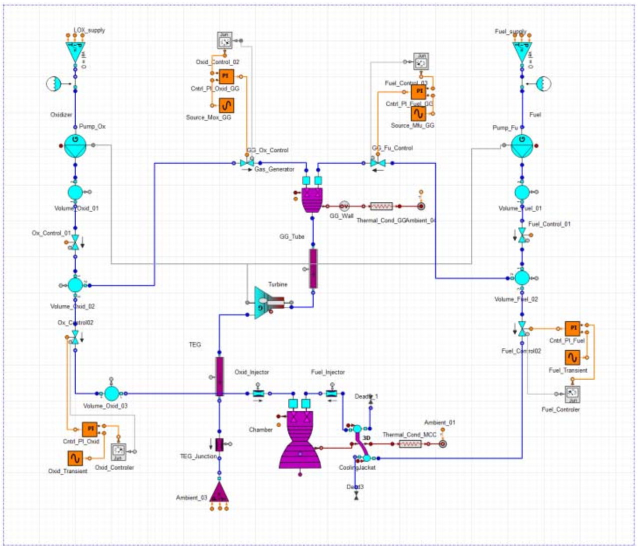

Fig. 16. Simplified transient model for LOx/Ethanol performance evaluation.

The initial considerations show a good agreement with previous results when taking into account a simplified approach for gas-generator calculation as well as the limiting requirements imposed initially. However, the impossibility to perform Fuel Film-Cooling evaluation required a system simplification thus, making the final result for thermal investigation not as precise as could it be with such powerful tool. The Fig. 17 shows the transient model for LOx/RP-1 configuration.

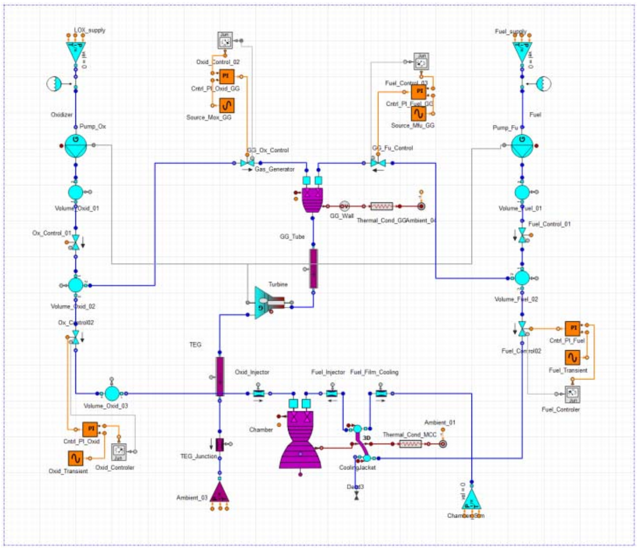

Fig. 17. Transient model of LOx/RP-1 engine using fuel film cooling for performance evaluation.

The transient models evaluated in steady state conditions have shown a performance lower than predicted in a range of 1,3% for LOx/Ethanol model and 1,8% for LOx/RP-1 when compared with the steady state model.

Table 2. Result from optimization tool.

Parameter	Ethanol	RP-1	Unit
Optimum mixture ratio	1,6	2,3	---
Fuel film cooling mass flow rate	0	1,06	kg/s
Engine mixture ratio	1,34	1,74	---
Global specific impulse (Vacuum)	3294,4	3284,4	m/s
Outlet coolant temperature	416,1	455,9	K

The final performance results from steady-state and transient library, when compared with the information from optimization tools shown in Table 2, provide an overview of deviation range due to parametric adjustments, as shown in Table 3, for steady state evaluation.

Table 3. Steady state model.

Parameter	Ethanol	RP-1
Global specific impulse (Vacuum)	2,2%	2,6%
C* at main combustion chamber	2,8%	3,0%
Gas-generator pressure	22%	28,7%
Fuel pump outlet pressure	3,8%	4,4%
Oxidizer pump outlet pressure	3,5%	4,1%

Outlet coolant temperature	-6,3	42,6%
Maximum wall temperature	0,2%	38,9%

The results from transient library evaluated at steady state conditions are also compared with results are described in Table 2 and is presented in the Table 4.

Table 4. Transient model at steady-state conditions.

Parameter	Ethanol	RP-1
Global specific impulse (Vacuum)	2,4%	2,5%
C* at main combustion chamber	2,9%	3,1%
Gas-generator pressure	46,0%	52,0%
Fuel pump outlet pressure	-9,2%	-9,5%
Oxidizer pump outlet pressure	78,0%	75,1%
Outlet coolant temperature	20,5%	58%
Maximum wall temperature	39%	78%

Is possible verify also a big deviation in the pump exhaust pressure, which result in a higher turbopump power requirement. This variation is result of more precise piping and valve models from EcoSimPro ESPSS. However, the total required power deviation is proportionally increased in both models, resulting in a power balancing without strong influence in the overall performance.

4. Conclusion

The evaluation using different techniques and mathematical models allows verifying the overall engine performance for upper stage applications operating with LOx/Ethanol have similar global specific impulse to the LOx/RP-1 at the same design specifications. The advantages of using Ethanol, however is starting to be investigated with the new developments[5), 7)], which will be able to fully validate the considerations adopted for a cycle analysis of a gas-generator engine.

EcoSimPro with ESPSS library is a powerful tool which is able to provide valuable data for an engine operation as well as evaluate the cycle performance. The results compared with mathematical models in its simplified forms shows a good agreement between the performance results with different techniques in as acceptable range of deviation.

However, the lack of more specific components such as fuel film cooling and heat transfer models able to be easily adjustable with user specification, as well as gas-generator combustion models capable to provide more precise information about its combustion characteristics makes EcoSimPro also a limited tool to be used alone or without user programming. Thus, the use of external mechanisms for design optimization can be easily connected with EcoSimPro solver, allowing a fast parametric change to achieve the desired specification with required constrains.

Despite show a strong deviation on heat transfer modeling when compared with described cycle optimization techniques, a gas-generator performance will be limited only for the design boundaries, since the overall results shows a similar engine behavior.

Future modifications in the heat transfer models as well as gas-generator design for EcoSimPro models will allows to evaluate thermal cycles as expander and/or expander bleed as well.

With the actual information available about the combustion performance of LOx/Ethanol at Upper stage design conditions, its global performance makes it a good candidate to become an ecologically friend substitute for RP-1. Also, future studies with experimental information will be possible from new developments will make possible validate the assumption for such engine configuration in a simplified open cycle scheme.

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