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Utilization of LOx/LCH4 for Expander-Bleed Cycle at Upper Stage Engine Application

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Abstract

Although the utilization of Methane or Expander cycle configuration has been performed only in the close scheme, expander-bleed configuration allows a good compromise between performance and system simplicity. This paper presents the cycle analysis of a LOx/LCH4 Expander-bleed configuration for upper stage application using EcoSimPro/ESPSS, for steady-state performance as well as the expected transient behaviour when coupled with the expected performance deviation from an injector dependent model, resulting in an off design operational condition for the system requirement.

1. Introduction

During ignition process, LE-5 rocket engine has used the thermal inertia from its subcomponents to start the engine in order to avoid a separated pyrotechnic starter system which could lead to an increase of system complexity [1]. This system improvement resulted in the LE-5A, LE-5B upper stage engines and eventually LE-9 development as first stage option for H3 rocket family [2].

The expander bleed engine cycle is thermodynamically dependent to be feasible, since the energy to drive the power-pack come from the heat transfer from combustion process to coolant through the cooling jacket. This technique requires an improved knowledge of the heat transfer models in order to provide reliable information for the engine design. Since the cooling side heat transfer model is a function of fluid in use [3], the choice of liquid methane or eventually LNG requires more precise models for a more precise design. In the combustion heat transfer evaluation, the standard model provides an initial evaluation of total heat release for the cooling jacket.

Since the cycle analysis yields the necessary boundary conditions for the design of the engine's sub systems, the injector processes also have impact in the cycle design, since great proportional amount of total available enthalpy increase can be overestimate by simplified models such Modified Bartz [4], Pavli [5] and Ievlev[6].

As the injector heat release is an axially dependent function which results in an energy balance divergence since it doesn't provide the full power from the beginning, the injector models must be implemented in order to provide a more realistic cycle prediction and this way, be able to predict the transient behaviour which can lead to uncertainties in the power available for the expander bleed cycle in analysis.

1.1 LUMEN Demonstrator

Within framework of LUMEN project (**L**iquid **U**pper stage de**M**onstrator **EN**gine), which consist in an engine demonstrator to be developed and tested at DLR Lampoldshausen within the capabilities of P8 [7] test bench, the requirements were defined in order to fulfil the design needs and estimate the detailed design constrains for the cycle prediction and its transient evaluation based on a defined architecture.

For the LUMEN demonstrator, the utilization of liquid methane aims for system simplification, its provides advantages over LH2, as higher specific density, minimum temperature difference between fuel and oxidizer,

However, methane elevated molar mass compared to LH2 system represent a negative point for performance resulting in a fluid with adiabatic specific work in lower range than a gas generator driven system with maximum turbine driven temperature limited by the thermal design of a regenerative cooling subsystem.

The initial design based on a viability matrix [7] allows us to evaluate a parallel flow for double turbine as a good candidate without a split cooling system.

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2. Cycle Analysis

This model was created within LUMEN project, where its mains requirements [7] was adopted in order to fulfil the cycle design and parameters bound, while new tools was created, as well as the already existing ones are being improved from cycle analysis group. In this frame, the cycle analysis has a fundamental importance to provide a correct comparison and realistic investigation of system in studies, aiming for more precise tools as well as the techniques for models validation. To evaluate the initial expected behaviour of expander bleed cycle using methane as fuel, a 0-D model was created [8] to investigate the thermodynamic process in which the energy source to fulfil the engine power requirement is produced by the cooling system. Thus, an improved cooling jacket model was implemented and its main geometry optimized in order to match the maximum enthalpy increase with geometrical bounds and manufacture limitations constrains. The total adiabatic specific work after the cooling jacket was maximized while keeping the maximum wall temperature at combustion chamber hot gas side at 900K as standard requirement.

In a simplified design using straight cooling channels, the cycle available energy was evaluated with initial estimated turbomachinery efficiency while the inter-component pressure drop was evaluated based on mass flow dependence and pressure level available.

The first iteration using the initial parametric output for 0-D tools leads to more detailed turbomachinery evaluation, which takes into consideration a geometrical design as well as the off-design performance based on components intrinsic characteristics as turbine blade geometry, pump profile, sealing systems and others.

For turbomachinery components, the design of OTP were initially evaluated due it low dependence of cooling jacket performance optimization. Thus, the energy balancing was iterated within FTP design, where the power requirement is directly dependent of the cycle performance itself, while the main design parameters was performed in an iterated process taking into consideration the power optimization regarding the cooling jacket design.

Finally, the first information of heat transfer model and available energy for each subcomponent for an expander bleed cycle was performed, while providing dynamic dependent parameters for more advanced 1-D and quasi-2D tools as EcosimPro, which operate with European Space Systems Simulation (ESPSS) library developed by Empresarios Agrupados on the side of European Space Agency (ESA). The coupling between those cycle analysis tools allows the cycle performance prediction with increase of precision making an important combination for system analysis group in DLR Lampoldshausen.

3. EcoSimPro/ESPSS Model

To provide a more reliable information regarding the thermal evaluation with coupled power consumption from its subsystems, the transient EcoSimPro model using ESPSS library was created using non-steady library in order to taking into advantage the more sophisticated components as such the cooling jacket and the thermal capacity of its lines. The possibility to perform a quasi 2D investigation [9] in the cooling jacket component becomes interesting for the required precision in the thermodynamic cycle analysis. The model presented in

Figure **1** takes into account initially a simplified expander bleed scheme, while using a separated turbopump and no split-cooling, as proposed in [11].

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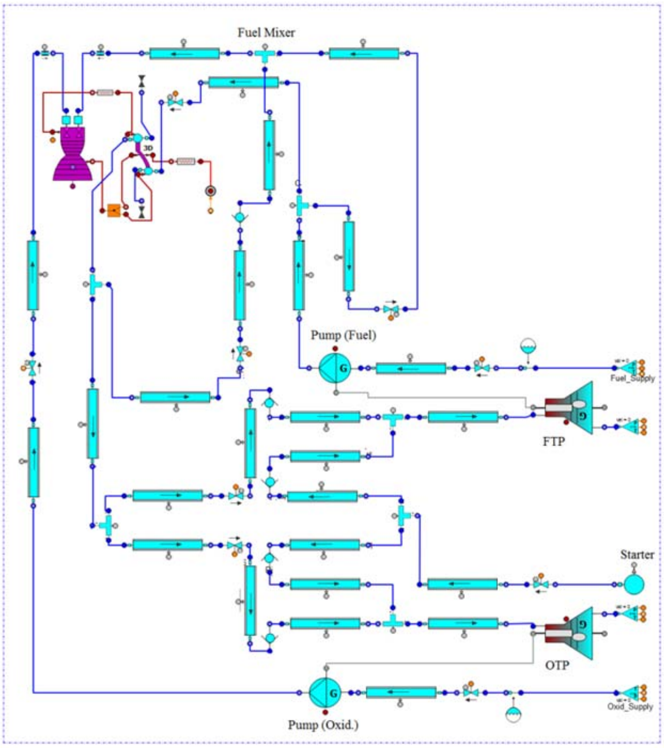

Figure 1: EcosimPro model of an expander-bleed cycle with two separated turbopump

The main modification of such cycle schematic when compared with standards models consist in a cold gas starter based on the same propellant as used to initially drive the turbopump.
The initial evaluation was performed at steady-state conditions, where the thermodynamically dependent parameters, especially from cooling jacket system, were unchanged along time.

3.1 Transient model at steady-state condition without injector dependence

In the initial evaluation, the main difference was verified in the relation between pressure drop and outlet temperature for the same required maximum wall temperature in the combustion chamber hot gas side. Different models were initially evaluated, as Ievlev [6][10], Modified Bartz [4] and Pavli [5], being adopted the standard modified Bartz methodology for simplified evaluation of the results.
The main difference between 0-D tools and EcosimPro can be related to quasi-2D possibility in 3D cooling jacket component, while a non-dimensional model is based initially in the average bulk temperature for cooling channels and the heat transfer for coolant approached from rib efficiency hypothesis [10] from a double-shell method.
The standard model for thermal evaluation shows no significant change of heat transfer coefficient in the cylindrical section as presented in the bar graph of Figure **2**, where each axial node correspond to the value for axially spaced 30mm distant apart.

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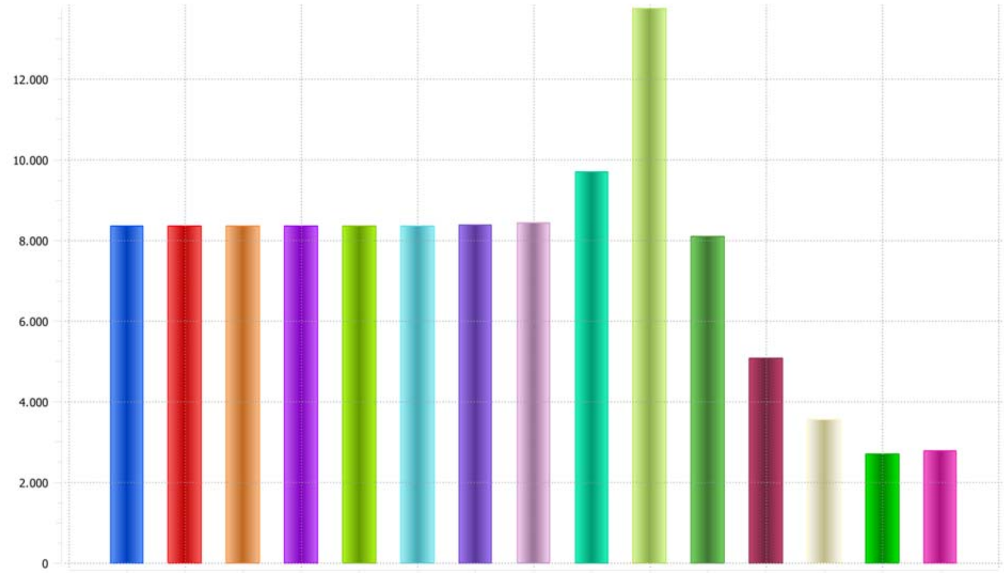

Figure 2: Standard heat transfer coefficient along axial nodes

3.2 Transient model at steady-state condition with injector dependence.

The injection system dependence can lead to a lower than expected heat transfer to the cooling jacket, resulting in degraded efficiency for the expander-bleed cycle. Thus, the standard model was initially compared with already available injector behaviour for heat release from EcosimPro. The model takes into consideration a propellant droplet size in order to provide initial evaluation for evaporation and consequently the heat release modelled by the time-dependent variables.

Such model is not realistic since it doesn't evaluate the supercritical behaviour of injected propellant as well as the interaction between combustion products, injector type and others parameters which doesn't take part of this investigation.

For this investigation an initial value for droplet size and time constant was adjusted to provide an axially dependent heat release similar to the expect behaviour from a API injector type [11][12]. The initial heat transfer coefficient using the injector correlation model is shown in the Figure **3**, where is possible notice the axially dependent thermal release in the first 3 nodes.

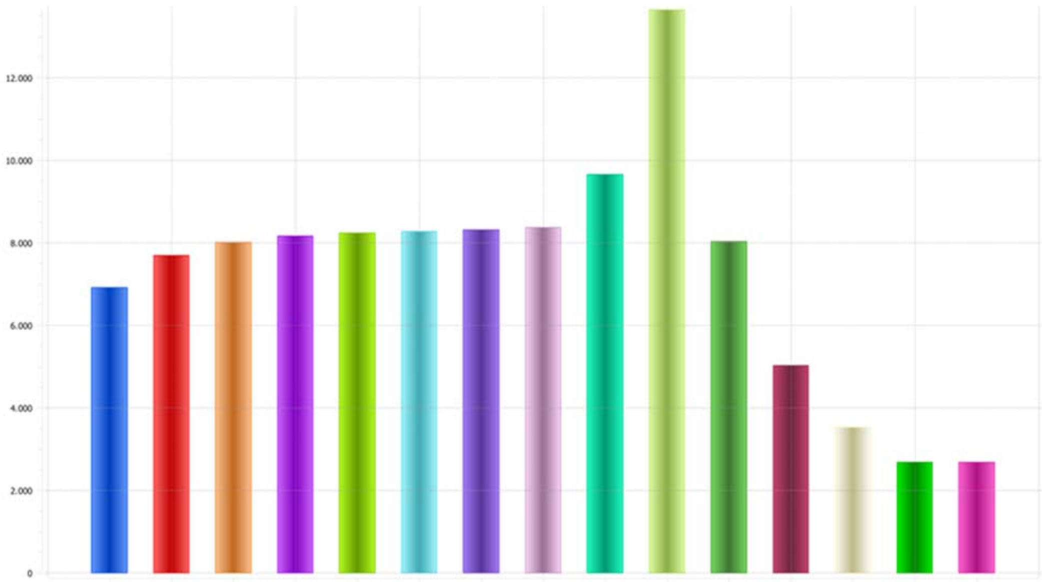

Figure 3: Heat transfer coefficient considering injector contribution along axial nodes

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When compared to the standard model as presented in the Figure **2**, the injector contribution shows a drop of around 17% in the heat transfer coefficient near to the injector head, as shown in the Figure **4**. The progressive increase of heat transfer coefficient ratio achieves it maximum close to section 8, which represent the end of cylindrical section.

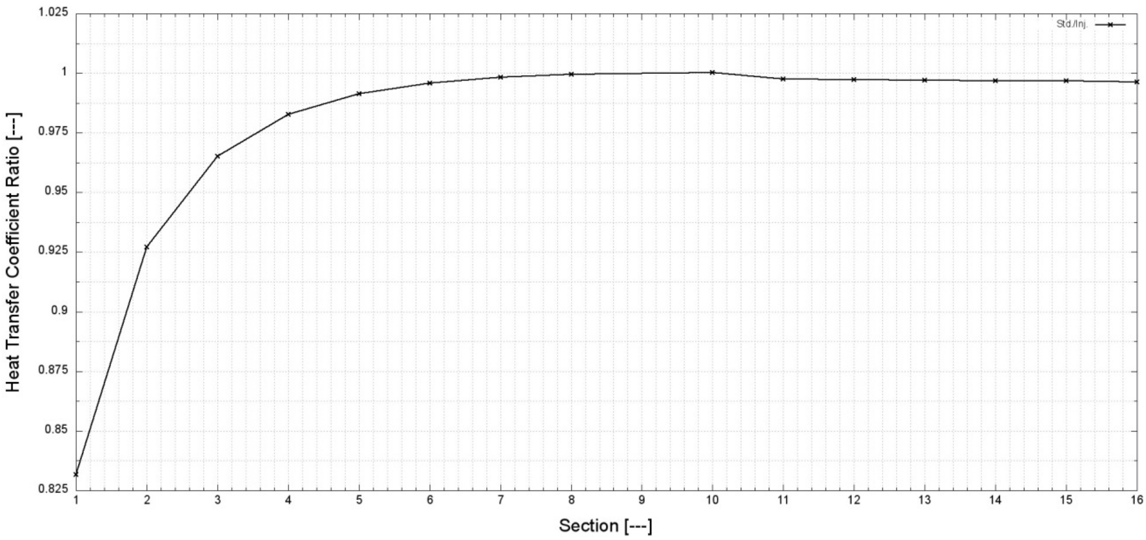

Figure 4: Ratio between standard heat transfer coefficient and injector dependent heat transfer coefficient according to axial dependent section

The local pressure according to the axial position is also changed for injector dependent model, indicating flow acceleration due to combustion process. The ratio between the standard model and the injector dependent model is shown in Figure **5** and is possible to correlate with experimental behavior of an injector head, as an example the API type [11][12]. The model also allows identifying a pressure ratio below 1 at the critical section, defined as position 10 in the graph previously mentioned. These results allow correlating the injector model with maximum possible combustion efficiency when compared with standard models.

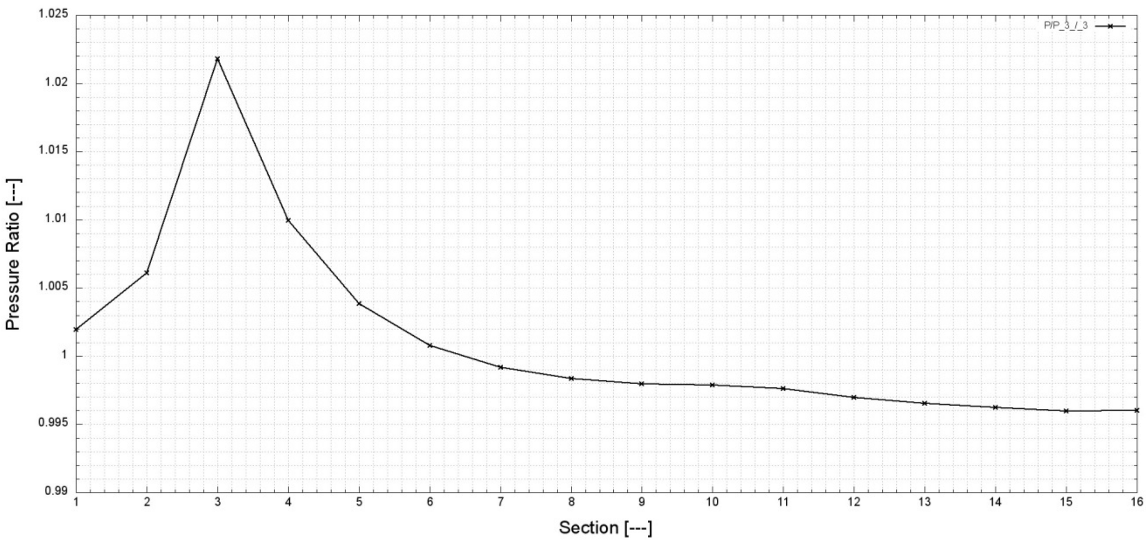

Figure 5: Ratio between local chamber pressure for standard model and injector dependent model, according to axial dependent section.

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Since the thermal release have direct impact on the combustion temperature, the local combustion temperature in the region of first node for the injector dependent model shows an initial value drop of around 35% when compared with standard model described before, as shown in Figure 6.

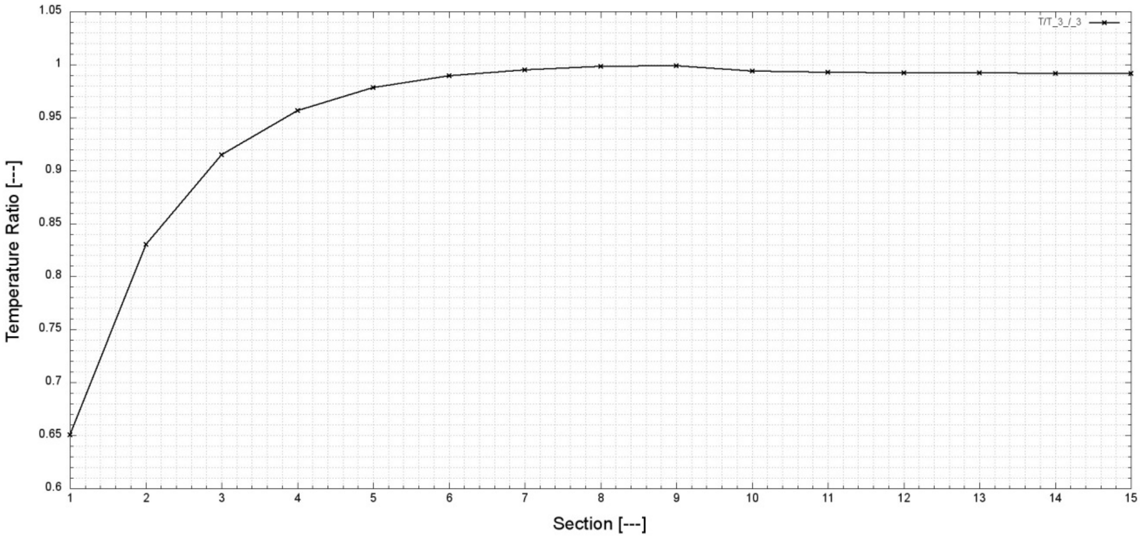

Figure 6: Ratio between adiabatic combustion temperature for standard model and injector dependent model, according to axial dependent section

3.3 Standard transient model

The relative high molecular mass Methane used as coolant and turbine driver shows a negative impact in a transient by thermal inertia when compared to hydrogen engines under the same cycle. Due to limited energy available during start, the thermodynamic process in the cooling jacket does not allow a fast start as presented by the LE-5 and LE-5B [1][2]. Instead, the boiling phenomenon during start-up can create a pressure oscillation in the cooling jacket while pressure and temperature are building up until crossing the transcritical phase. Such behaviour was identified in the initial transient model using EcosimPro and ESPSS library and the graph of Figure **7** shows the transient phenomena mentioned above.
Due to this oscillation behaviour, a longer than expected time to achieve steady-state condition can lead to different FSI coupling, which is not initially evaluated in such analysis. Thus, the alternative to avoid this behaviour was, as previously mentioned, use a high pressure cold gas start fed by the selected fuel itself though a separated pressure reservoir, which is indicated in the Figure **1**.

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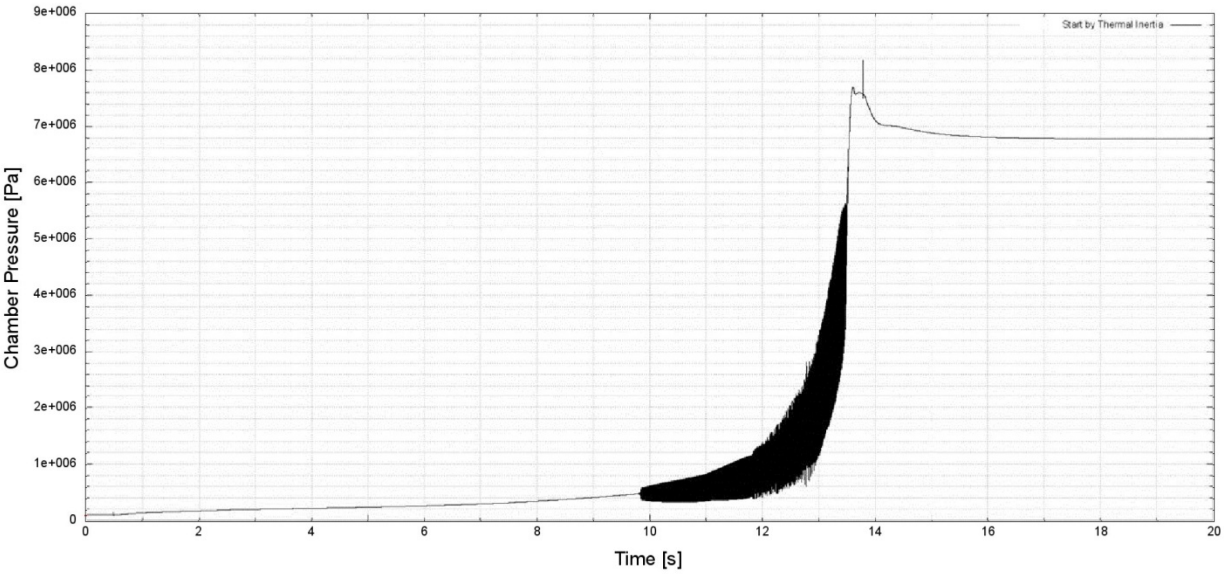

Figure 7: Combustion chamber pressure at first node (30mm from injector face plate)

The model was then modified to withstand a pressure vessel capable to be refilled by the system itself after steady-state operation, with initial pressure of 6MPa, dropping to 5,5MPa after the start. The new chamber pressure build up with adjusted transient model is shown in Figure **8**.

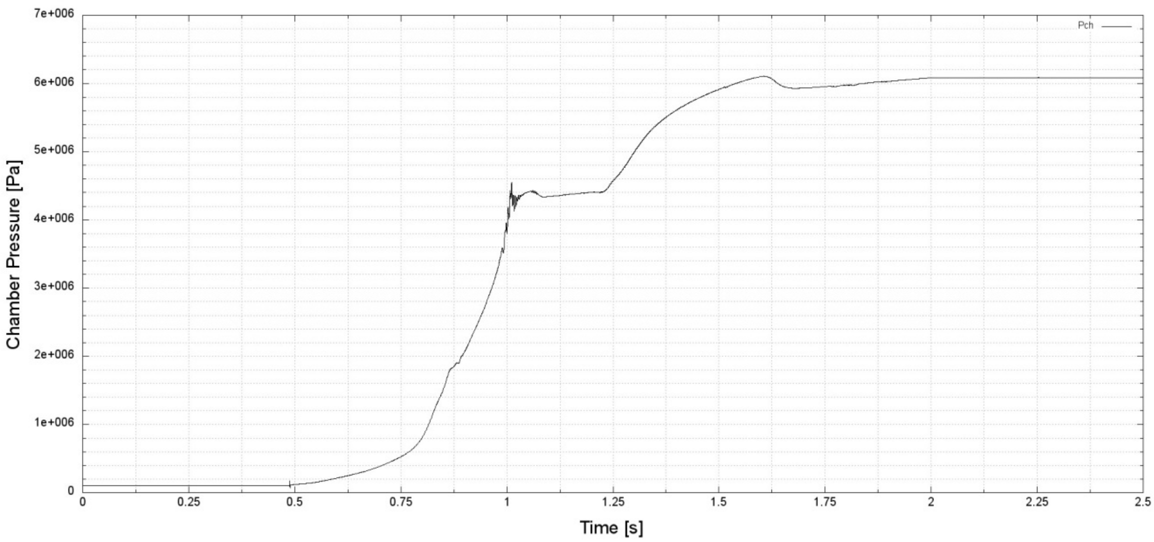

Figure 8: Combustion chamber pressure at first node (30mm from injector face plate)

Thus, a starter model was created by using, as mentioned before, a cold gas in high pressure. The model has no influence in the steady state, but the improvement over the transient is clear. Even a small oscillation related to phase change in the cooling system is shown at time equal 1,0s in the Figure **8**. Until 1,25s the backpressure from boiling and transcritical phase is coupled with feed in the fuel turbopump as well as the mixer mass flow. Close to 1,6s the full power is provided to both turbopump while the starter turned off, achieving the cycle power equilibrium at 2,0s.

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3.4 Transient model with injector correlation

When compared the transient time using the injector model, the main differences from standard model start to be noticeable in the time frame which the main phenomenon appear as well as the evolution of the previously described differences. The thermodynamic parameters, which are the main driver of expander-bleed cycle engines, are also which results in more pronounced deviation.
The simulation shows a temperature at turbine inlet manifold being approximately 8,5% lower for injector dependent model when compared to a standard one, as shown in Figure **9**, which results in 4,2% lower energy to drive the turbopump system, providing lower power than required. To be able to achieve the desired load point, the entire system need to operate in an off-design condition, with once more have a negative impact on its performance.

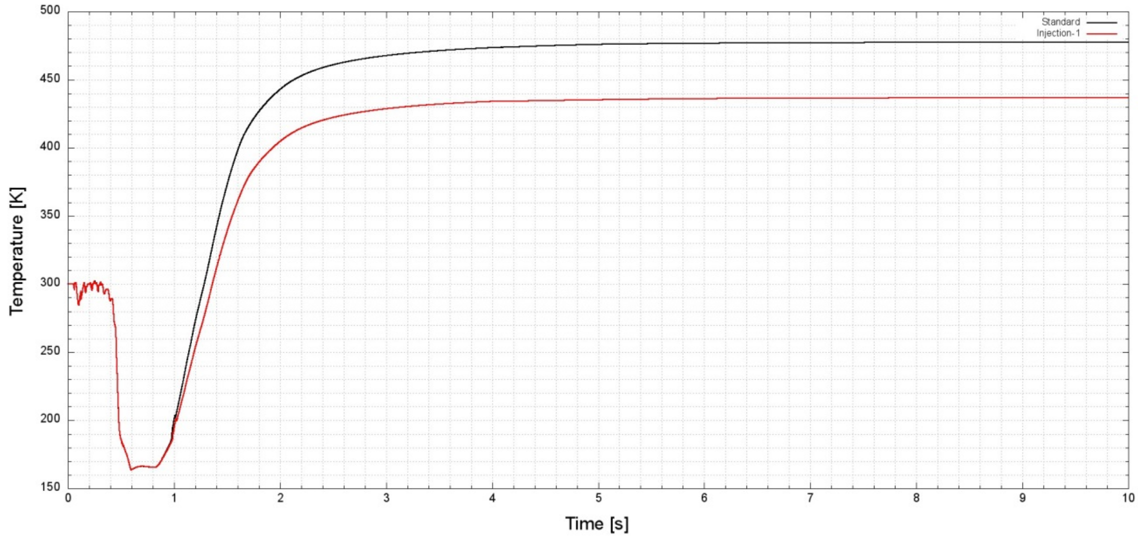

Figure 9: Methane temperature at turbine inlet manifold of fuel turbopump

The temperature difference during the 2s simulated transient, however, is minimal which as result in a not evident impact on the feedback response for turbopump coupling. This deviation is less evident in change of coolant outlet pressure when compared the injector dependent model with the standard design, as presented in Figure **10**.

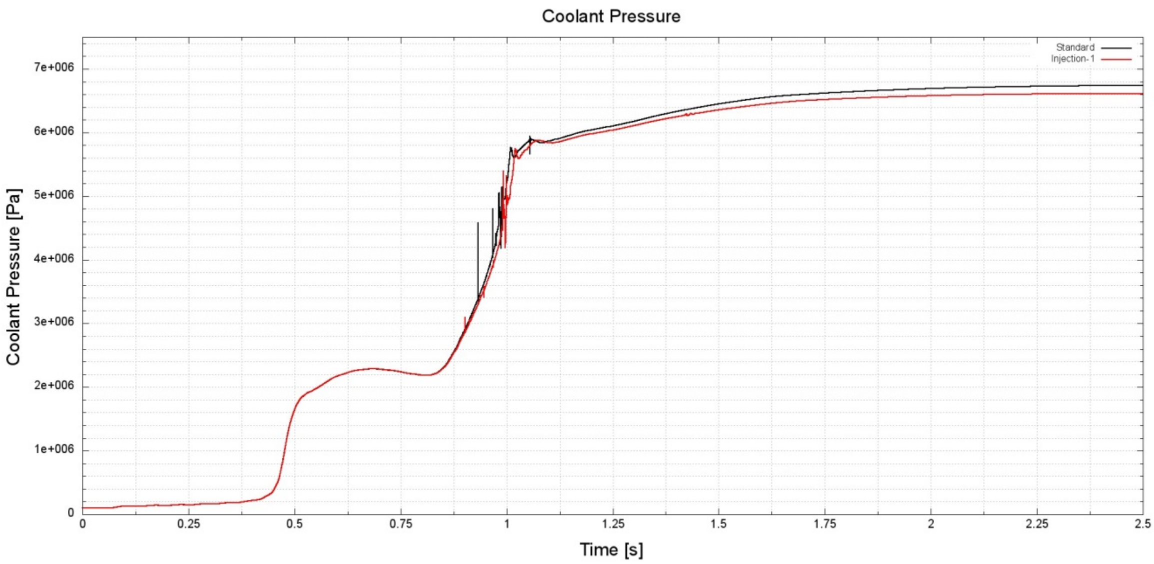

Figure 10: Coolant outlet pressure during transient.

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In the interval between 0,8s and 1,1s is possible identify the pressure oscillation caused by fluid boiling which result in pressure increase and consequently the condensation and drop of back pressure. These phenomena also results in coupling with feed system, creating mixture ratio variation present in the time of 1,05s of resulting temperature profile shown in Figure **11**. In the same graph is possible to verify the combustion temperature of injector dependent model in the first node (30mm from injector face plate) considerably smaller than the values of standard model.

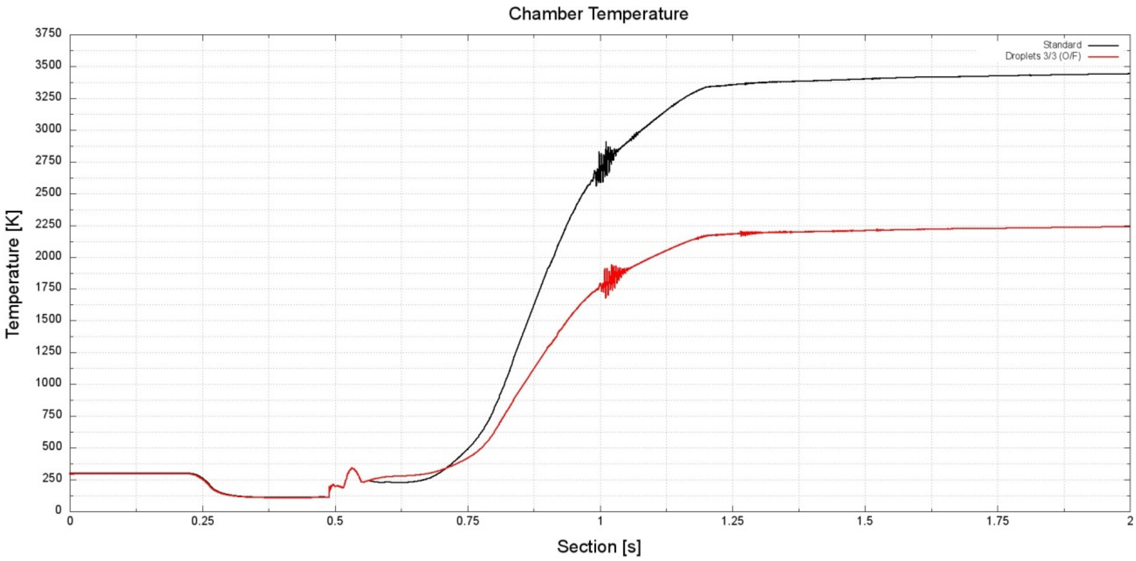

Figure 11: Combustion temperature at first node (30mm from face plate)

This difference has a greater influence on the design upper bounds, creating a lower local gas side wall temperature and resulting in a maximum performance lower than available for the system in evaluation, creating restriction for the cycle optimization.

With the variation of adiabatic specific work provided during transient with injector dependent model and compared with standard model, is possible to verify a small deviation in the time of occurrence for main coupled phenomena in the combustion chamber. The variation starts to be more noticeable after 1,6s, as presented in the graph of Figure **12**. The lower energy difference compared to the total amount is the main responsible for such small deviation in the initial phase of transient.

The turbopump coupling also provides a time delayed feedback which is only identifiable at high power driven region.

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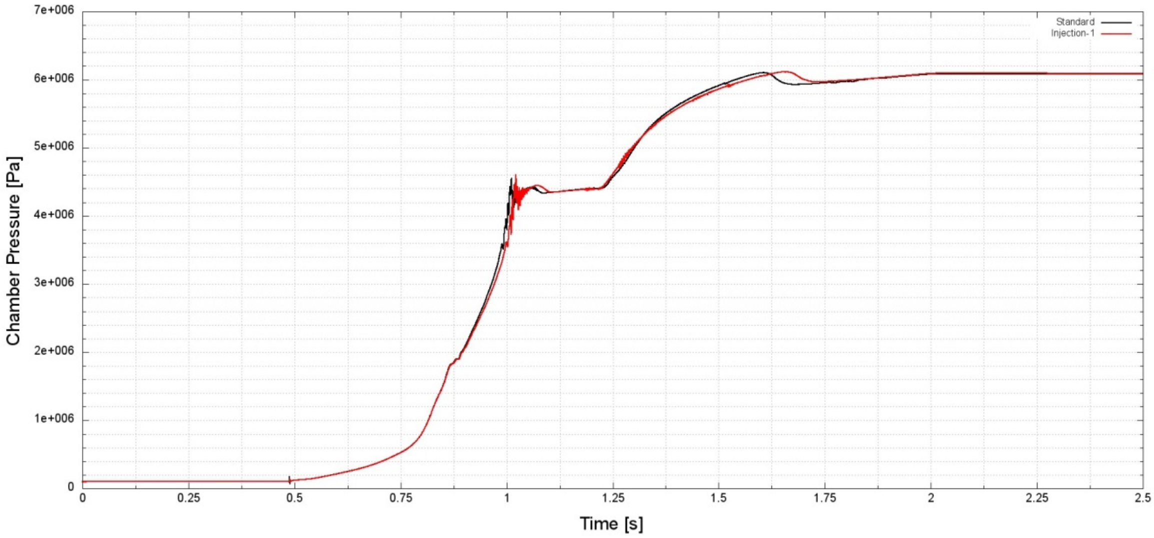

Figure 12: Combustion chamber pressure at first node (30mm from face plate) from standard model in black and injector dependent model in red

4. Conclusion

Design of an expander-bleed cycle engine is critical due to thermal coupling between the required power balance and available energy from cooling jacket system. The main subcomponents optimization gives margin to small improvements despite the limitation imposed by the system requirements as maximum combustion chamber gas side wall temperature and pressure budget.

In this work was possible identify the power dependence with relation to the injection system, creating an energy balance deviation, resulting in lower output power than required, making the cycle possible to work only in off-design conditions. Effects such as combustion efficiency and thermal inertia present a standard limitation, which can be mitigated with detailed information about thermal release coupled with injection system and structural heat capacity loads.

The heat transfer model based on propellant can also increase the cycle analysis precision, specially based on the specific fuel composition, when in use of liquid natural gas (LNG). As pointed in [3], the heat transfer models can differ according to the coolant in use, requiring experimental validation for each particular case. This can lead to a cycle prediction with lower uncertainties, resulting in subcomponents operating as close as possible of its optimum design condition. Improved and validated models for each specific propellant and injector design configuration will be required for more precise system analysis.

In this work, was possible to verify as well the injector dependence for transient is initially negligible, showing only a major impact on the steady-state operation. According to the cycle architecture and engineering solutions adopted, the maximum loads and upper design bounds can be smaller than predicted in case of injector behaviour omission.

Methane shows to be a good candidate to expander-bleed operation, especially for upper stage application, where the split cooling in high expansion ratio for the nozzle section can provide extra energy to increase the cycle performance in matter of adiabatic specific work for TPU as well as the lower bound for turbine and chamber exhaust pressures.

5. Acknowledgement

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References

[1] Yanagawa, K., Fujita, T., Miyajima, H., Kishimoto, K. 1985. High-Altitude Simulation Tests of the LOx/LH2 Engine LE-5. J. Propulsion.
[2] Atsumi, M, *et al*. 2011. Development of the LE-X Engine. Mitsubishi Heavy Industries Technical Review Vol. 48 No. 4.
[3] Liang, K., Yang, B., Zhang, Z. 1988. Investigation of Heat Transfer and Coking Characteristics of Hydrocarbon Fuels. Journal of Propulsion and Power.
[4] Huzel, D. K., Huang, D. H. 1992. Modern Engineering for Design of Liquid-Propellant Rocket Engines; American Institute of Aeronautics and Astronautics.
[5] Di Matteo, F., De Rosa, M., Onofri, M. 2010. Semi-Empirical Heat Transfer Correlations in Combustion Chambers for Transient System Modelling. Space Propulsion Conference.
[6] Ievlev, V. M. 1971. The Methods of Calculation of the Turbulent Boundary Layer for High-Temperature Gaseous Flow. 9th AIAA Aerospace Sciences Meeting. New York.
[7] Deeken, J.,Waxenegger, G. 2016. LUMEN: Engine Cycle Analysis of an Expander-Bleed Demonstrator Engine for Test Bench Operation. DLRK.
[8] Hahn, R. H. S., Deeken, J., Schlechtriem, S. 2017. Comparative Study of Ethanol and Kerosene Propellant for Gas-generator Fed Upper Stage Application, Using EcoSimPro. ISTS. Matsuyama Ehime, Japan.
[9] Di Matteo, F., De Rosa, M., Pizzarelli, M., Onofri, M. 2010. Modeling of Stratification in Coolong Channels and its Implementation in a Transient System Analysis Tool. 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. Nashville.
[10] Vassiliev, A. P., et al. 1993. Theory and Calculation of Liquid Rocket Engine Elements. Federal Program of Publishing. Moscow.
[11] Deeken, J., Suslov, D., Haidn, O., Schlechtriem, S. 2010. Design and Testing of a Porous Injector Head for Transpiration Cooled Combustion Chambers. AIAA.
[12] Deeken, J., Suslov, D., Schlechtriem, S., Haidn, O. 2011. Impact of Injection Distribution on Cryogenic Rocket Engine Stability. 4th EUCASS.