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Holistic Modelling of European Reusable Staged-Combustion Rocket Engine SLME

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Abstract

In the high-speed propulsion industry, even minor errors can have catastrophic consequences. While engineers typically excel at designing and modelling individual components such as turbines, pumps, and tanks in isolation, failures often occur at the interfaces between these subsystems. Therefore, the ability to model all system components – considering both expected and extreme operational conditions – can significantly improve performance predictions, enhance system reliability, and facilitate optimization across the entire system. This paper demonstrates the advantages of holistic modelling through a practical case study of the European Reusable Staged-Combustion Rocket Engine SLME. By simultaneously examining the interactions between the rocket cycle, propellant supply systems, turbines, and pumps, we show how integrated modelling enables engineers to identify potential issues, ensure proper operation, and optimize performance across the entire propulsion system. This approach not only improves the accuracy of system simulations but also allows for more efficient design iterations, ultimately contributing to the advancement of high-speed propulsion technologies. This study builds upon previous work published on the digital modelling of SLME engine and aims to demonstrates how integrating all major subsystems – such as the rocket cycle, propellant supply, turbines, and pumps – enables engineers to predict performance more accurately and identify potential failure points.

Keywords: *integrated modelling, rocket engine, staged-combustion, subsystem interaction, propulsion reliability.*

Nomenclature

ESA – European Space Agency
FADEC – Full Authority Digital Engine Controls
FFSC – Full-Flow Staged Combustion
FR – Fuel Rich
HPFTP - High-Pressure Fuel Turbopump
HPOTP - High-Pressure Oxidizer Turbopump
Isp – Specific Impulse
LH2 – Liquid Hydrogen
LOX – Liquid Oxygen
LPFTP – Low-Pressure Fuel Turbopump
MR - Mixture Ratio
OFR – Oxidizer to Fuel Ratio
OR – Oxidizer Rich
RLV – Reusable Launch Vehicle
SLME – Space Liner Main Engine

1. Background

The global revival in space exploration has created a high demand for advanced propulsion systems, with reusable launch vehicles (RLVs) appearing as a critical enabler for cost-effective and sustainable access to space. Over the past decade, the launch industry has experienced a transformative shift driven largely by private entities such as SpaceX and Blue Origin, which have introduced innovative reusable systems and high-performance rocket engines. Among those technologies, closed-cycle

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propulsion concepts such as the expander cycle, staged combustion cycle, and full-flow staged combustion (FFSC) cycle, have gained advantage for their higher efficiency, high thrust, and improved overall engine performance.

More specifically, the FFSC cycle offers strong advantages for RLV applications, including higher specific impulse, reduced environmental impact, and reliable operations for various conditions. While the United States already leverages such technology, Europe currently lacks an operational staged-combustion engine, creating a strategic technology gap that must be addressed to maintain competitiveness in the space sector.

A study at Staged Combustion literature (e.g. SNECMA, SCORE-D [·], RD-0120 [2], Space Shuttle Main Engine [3], etc.) reveals several combinations of pre-burners (PB) and turbopump configurations resulting from either single or dual shaft and either an Oxidizer Rich (OR) pre-burners or Fuel Rich (FR) pre-burner. Without doubt, the design of staged-combustion engines is a complex multidisciplinary challenge. While individual components such as turbines, pumps, and propellant systems can be optimized in isolation, real-world failures often arise at the interfaces between subsystems. Therefore, integrated modelling approaches that capture the interactions among all major subsystems are essential for accurate performance prediction, improved reliability, and optimized system-level design.

This work utilizes the SLME [4] engine to demonstrate how simultaneous consideration of the rocket cycle, propellant feed system, turbines, and pumps, secondary systems enables engineers to predict performance more accurately, identify potential failure points, and enhance overall system efficiency. By leveraging integrated simulations under both nominal and extreme operating conditions, this study highlights the critical role of holistic modelling in advancing the design and reliability of next-generation reusable propulsion systems.

2. Methodology

Historically, rocket engine design has relied heavily on component-level modeling. Using cycle analysis level boundary conditions, engineers design and analyze individual turbines, pumps, injectors, and cooling systems in isolation, typically employing specialized tools tailored to each subsystem. The results are then exchanged—most often in the form of performance characteristics—to enable further integration. However, the shared data are generally obtained under simplifying assumptions, since it is not feasible to capture all variables that vary under off-design conditions (e.g., variation of working fluid extraction value due to bleeds or leakages, as well as fluid composition linked to different oxidizer to fuel ratios used throughout a given mission).

Although component-level modeling with assumptions has enabled progress, it also carries inherent limitations. Performance maps, while widely used by engineers, often lose accuracy beyond the initial design stage because they rely on simplifying assumptions made during their creation.

Specifically, in the design and analysis of the SLME, the following assumptions are of biggest concern, as they directly influence overall engine performance and mass–dimensional characteristics:

- Utilization of pumps performance maps for real fluid and with fixed extraction values When real fluids are employed in the simulation, it is not possible to generate performance maps in corrected coordinates to cover the variation in boundary conditions. Existing approaches yield only partial similarity of operating modes when boundary conditions are varied.
- Assumption of constant fluid composition for turbines instead of a variable one based on oxidizer to fuel ratio.
- Film cooling influence is based on assumptions of wall temperatures along the combustion chamber vs. one determined based on actual geometry and local fluid properties.

To overcome these limitations, this work adopts a holistic (co-simulation) modelling approach using the AxSTREAM® software platform [5] in which all major subsystems of the propulsion system are modeled simultaneously; the performance of each component is evaluated in real time at every iteration of the simulation. This enables more consistent interaction among subsystems and improves the accuracy of system-level predictions. Instead of treating pumps, turbines, tanks, and preburners as standalone entities, the methodology emphasizes the flow of mass, energy, and information between components, capturing the coupled thermodynamic and mechanical dynamics of the system as a whole, therefore allowing to determine all turbomachine parameters for current boundary conditions in real time and take into account all possible phenomena mentioned earlier.

The methodology is structured around three principles:

- Subsystem Integration: Each component model is embedded within a larger system framework so that its performance is determined not only by local design parameters but also by upstream and downstream conditions.
- Boundary Flexibility: Operating points are defined across both nominal and extreme conditions, including off-design mixture ratios, temperature variation for both pre-burners and main combustion chamber. This ensures that most loaded modes are included.
- Iterative Coupling: The system is solved iteratively, balancing the requirements of cycle thermodynamics, turbomachinery power, propellant feed stability, and combustion chamber operation.

This approach was applied to the present SLME case study. The next section shows a direct comparison of traditional vs. holistic modelling outcomes, illustrating how subsystem integration can change design conclusions.

A schematic of the iteration process is provided below.

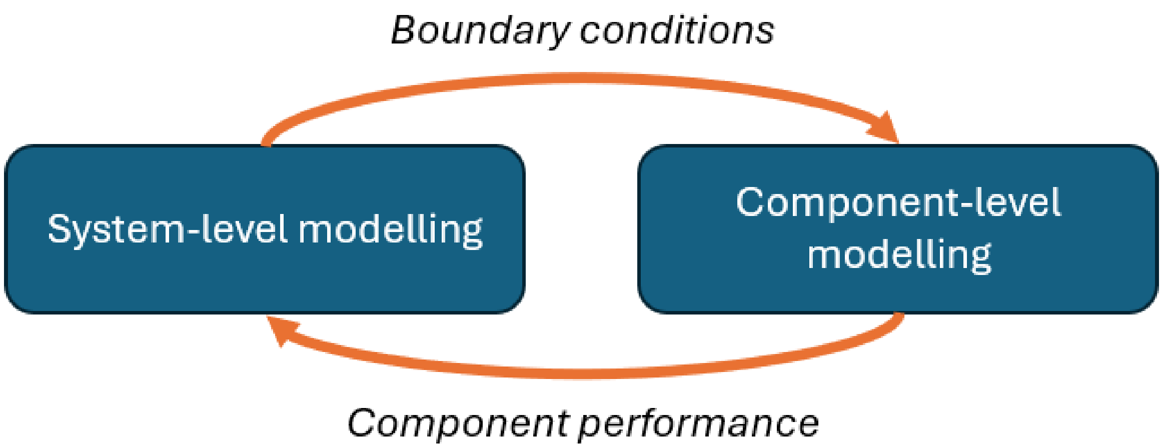


Fig. 1. Iteration process for holistic modeling of staged-combustion rocket engines. The flow of mass, energy, and feedback between subsystem solvers (turbopumps, cycle analysis, cooling circuits, and combustion chamber) is shown, illustrating how convergence is achieved at system level.

Such approach allows accounting for critical system-level effects, including coupled instabilities between turbines and pumps, cavitation or flow mismatch due to transient feed-system dynamics, startup and shutdown transients causing thermal and structural stress beyond design limits, control authority limitations when subsystems interact differently than expected, influence of variable secondary flows on the main flow, and more.

3. SLME Holistic Engine Model

Engine configuration and holistic modeling strategy

The SLME represents one of the most advanced LOX-LH_2 FFSC (Full-Flow Staged-Combustion) concepts currently under European study. Its architecture, shown in the figure below, includes:

- Two preburners: one fuel-rich driving the hydrogen turbopump, and one oxidizer-rich driving the oxygen turbopump.

- A main combustion chamber operating at ~16 MPa nominal pressure.
- Regenerative cooling circuits using hydrogen to manage thermal loads on the chamber and nozzle.
- Multiple turbomachinery elements, including a boost pump and high-pressure fuel turbopump (HPFTP), as well as a high-pressure oxidizer turbopump (HPOTP).

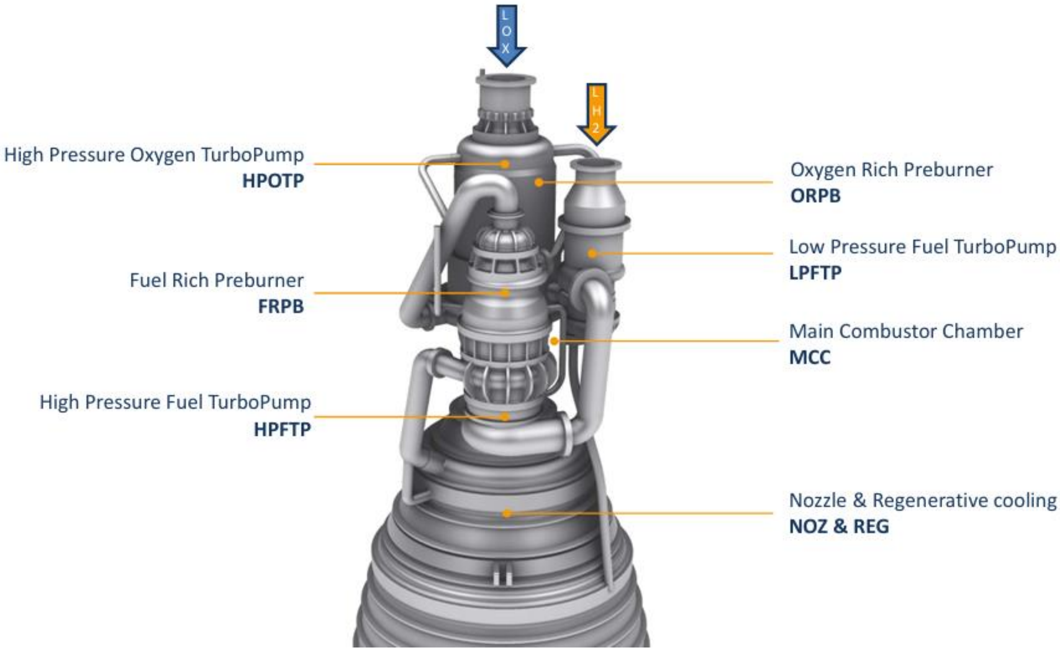


Fig. 2. Main components of the SLME full-flow staged-combustion engine, including dual preburners, turbopumps, regenerative cooling circuits, and main combustion chamber. The schematic highlights the high complexity of the engine.

Holistic modelling can be applied to both design and analysis tasks. For design, the goal is to ensure that each component is created in such a way that the entire system (accounting for accurate individual and collective performance) is optimized while historically, the cycle is optimized and then each element is designed in a silo for these "optimized" conditions with little to no refinements for improvement, therefore resulting in a sub-optimum complete system. For analysis, the main goals of holistic modelling include ensuring that all the components will work together (vs. separately) and that the complete system may be operated at its best point (which ideally should be the design point but may deviate from it, especially in non-holistic design methodologies).

Using cycle-wide simulations can reveal how a slight deviation in turbine inlet temperature propagates into altered chamber pressures, which in turn shift cooling margins and affect material stress levels. The system-level view provides engineers with early warnings of such cascading effects.

This approach contrasts strongly with the traditional method, where each subsystem would be declared "stable" in isolation, only for integration tests to uncover unforeseen oscillations, pressure drops, or thermal excursions. Validating and highlighting the benefits of this revolutionary modelling approach vs. historical technology is the main purpose of this paper.

Specifically, the current paper continues the work performed in "System Aspects of European Reusable Staged-Combustion Rocket Engine SLME" presented by DLR and SoftInWay at the 2024 Space Propulsion [4], see figure below. In that paper, the work focused on jointly performing a de-risk study under contract to the European Space Agency (ESA) to preliminarily consolidate a staged combustion engine design using the AxSTREAM® software platform. This involved, in part, doing a conceptual design of the turbomachinery, pre-burners and main combustion chamber regenerative cooling to determine consolidated size, mass, and performance data. Performance data of the engine was computed using performance maps for each of the turbomachines, as it has been done historically by engineers for decades. The current paper looks towards more modern modelling techniques available thanks to better computing technologies in terms of hardware and dedicated software which allows solving components for the exact conditions at which they are operated at in their environment (system): holistic modelling.

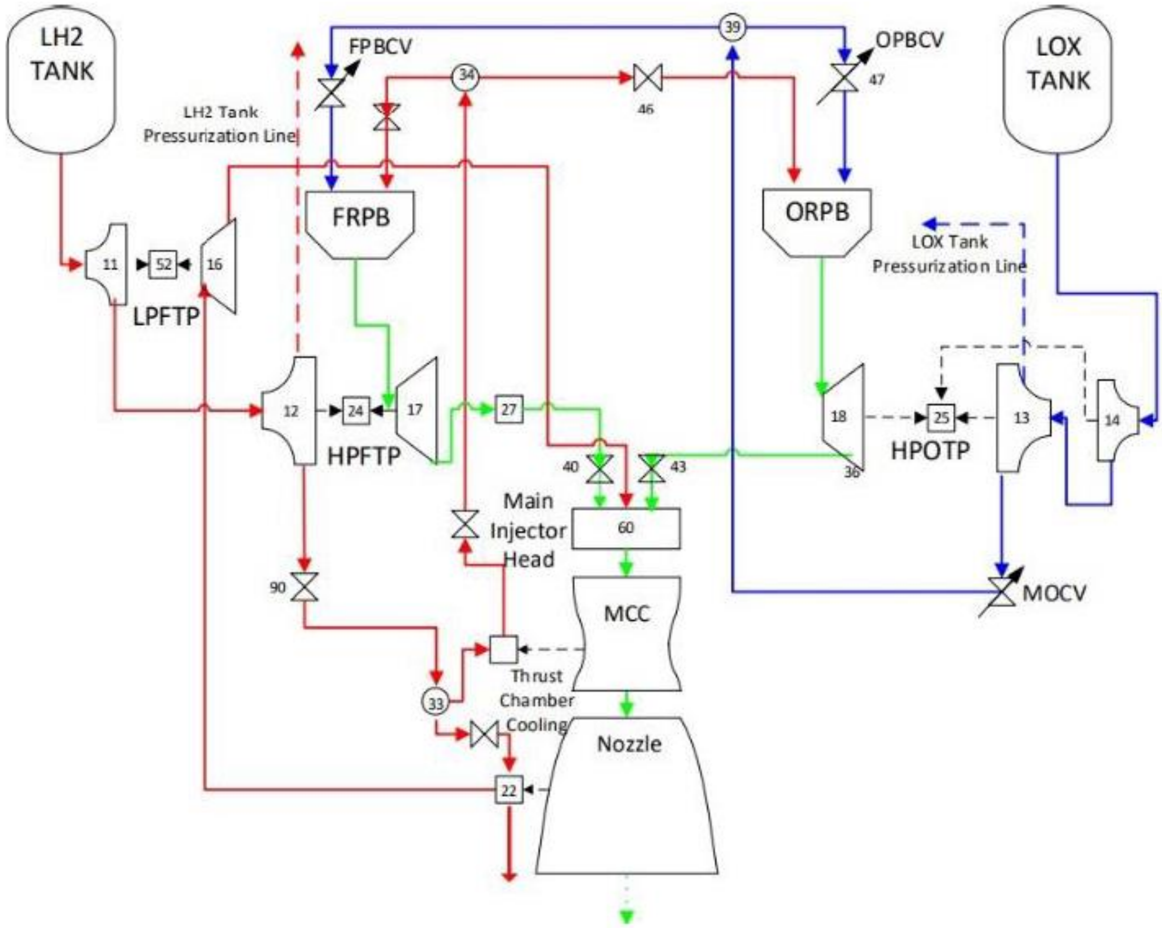


Fig. 3. SLME internal flow schematic showing propellant distribution through turbopumps, preburners, cooling loops, and main chamber. The diagram emphasizes the multiple feedback loops critical for stability and performance [4].

The present holistic model is shown below and relies on accurately solving the following components and subsystems:

The system-level modelling (thermodynamic cycle and the thermal-fluid network) is performed using AxSTREAM System Simulation™ [6] through 0D and 1D elements. This allows solving for engine thrust, combustion temperature, nozzle cooling, etc. It includes components such as tanks, propellant supply system, turbomachinery, pre-burner and main combustion chamber, nozzle (for which the regenerative cooling system is modeled by discretizing the flows of heat and fluid along the nozzle length), valves, and more.

The turbine and pump components are solved using the industry-leading turbomachinery solver, - AxSTREAM Flow Path™ [7] -, through the use of 1D or 2D (meanline/streamline) solvers relying on well-published empirical correlations for performance quantification

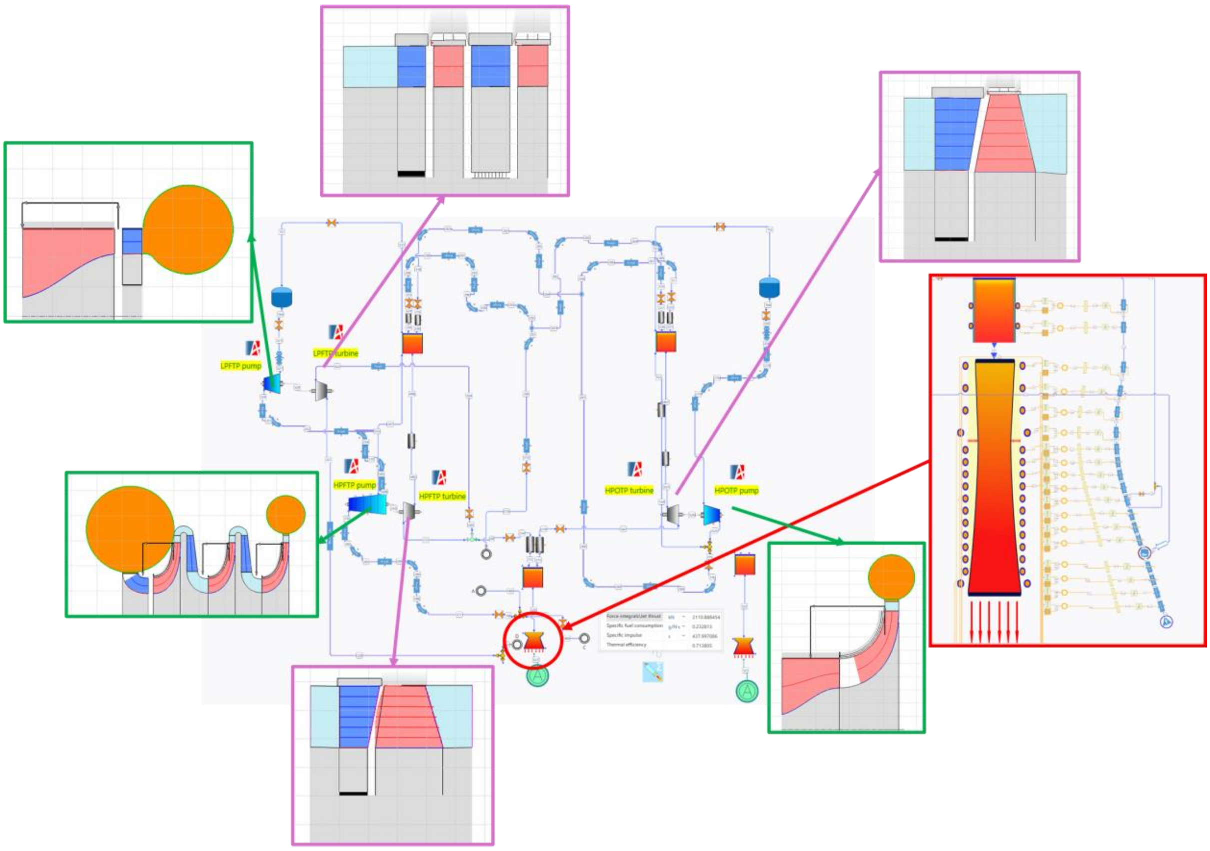


Fig. 4. Holistic system model of the SLME, combining thermodynamic cycle analysis, 1D/2D streamline-based turbomachinery solvers, and 1D thermal-fluid modeling of regenerative cooling. The model demonstrates integration of geometry-based solvers into a system-level framework.

In the presented model, the OFR and combustor outlet pressure are fixed inputs used to maintain the required thrust and Isp while the rest of the system finds balance which includes finding the joint point of operation of the oxidizer and fuel pumps and turbines (6 in turbomachines in total) accounting for their performance at the appropriate cycle conditions. The input data for the turbomachine calculations comes from the rocket engine cycle to determine performance parameters which are returned to the cycle and iterated until convergence is achieved across system and component solvers. Specifically, the pumps determine the rotation speed (angular velocity) and efficiency for known mass flow rates, inlet temperatures, inlet and outlet pressures while the turbines calculate inlet pressures and efficiencies for given mass flow rates, inlet temperatures, outlet pressures and angular velocities. All returned (output) parameters are fixed and act as boundary conditions for the cycle, ensuring proper data transfer and complete system convergence. For clarity, the data used and obtained in the process of calculating turbomachines is given in the table below. It is to be noted that thanks to the one-dimensional modeling of the piping system, the pressure losses between and at each component are computed at each solver iteration instead of assuming they are constant throughout the mission.

Table 1. Input and output data for turbomachine calculations

Components	Input data	Output data
Pumps	• Mass flow rate • Inlet temperature • Inlet Pressure • Outlet pressure	• Efficiency • Angular velocity
Turbines	• Mass flow rate • Inlet temperature • Outlet pressure • Angular velocity	• Efficiency • Inlet pressure

For example, the calculation of the HPFTP pump (element 12 in Fig. 3) will dictate its efficiency for a given calculated angular velocity. This affects the amount of power needed to be produced by the HPFTP turbine (element 17 in Fig. 3) therefore requiring more or less fuel being burnt in the fuel-rich pre-burner, affecting system performance, amount of fuel to bring on-board, tank volume (and therefore mass), and so on. Similarly, different pressure levels in the system between the expected and the real values experienced by the hardware, lead to varying pipe thicknesses to withstand the calculated stresses. Having a more accurate estimation of these pressures allows reducing confidently the stress margin on these pipes, therefore lightening up and shrinking the engine.

Operational Domain

As stated in [4], the SpaceLiner requires a take-off thrust of approximately 2000 kN per engine at sea level. During ascent, the nominal mixture ratio (MR) varies between 6.5 and 5.5, starting at MR = 6.5 in the early flight phase and throttling down to MR = 5.5 later in flight. By contrast, other investigated RLV applications often operate at a single fixed MR throughout the mission.

For the ascent reference mission, the engine cycle times are defined as follows:

- Booster engine: 245 s nominal operation, with ~122 s at MR = 6.5 followed by ~122 s at MR = 5.5 (or earlier cut-off).
- Passenger Stage engine: 463 s nominal operation, with ~336 s at MR = 6.5 and ~127 s at MR = 5.5.

The target lifetime for each engine is 25 missions with minimal refurbishment. This translates into a total accumulated operating time of ~6100 s (1.7 h) for the Booster engine (SLB) and ~11,600 s (3.2 h) for the Passenger/Orbital Stage engines (SLP/SLO), including over 2 h 20 min at the demanding MR = 6.5. These requirements highlight the significant technical challenges of achieving both safety and cost efficiency in the engine design.

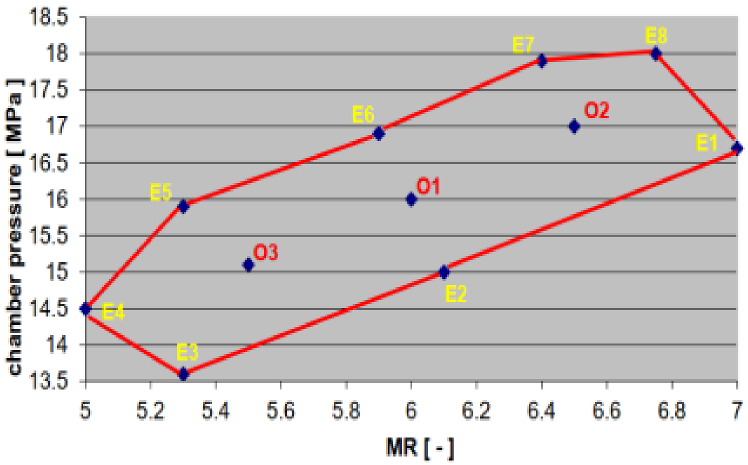


Fig. 5. Calculated SLME Operational Domain showing the chamber pressure and MR

The newly calculated SLME operational domain is shown in Figure 5 [4]. Its boundary points (E1–E8) define the safe operating limits for the engine and its subsystems. The MR range extends from 5.0 to 7.0, achieved mainly by varying the LOX flow by up to ±18%, while LH_2 mass flow variations remain below ±8%. This represents a preliminary design choice that may be refined in future analyses.

The SLME operational envelope now reaches a maximum chamber pressure of 18 MPa, a value that is moderate compared to earlier LOX–LH_2 engine developments such as the SSME and RD-0120.

Thermal analysis of Combustion Chamber and Nozzle

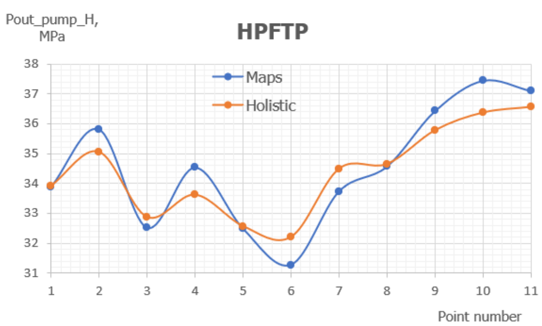
Thermal analysis of the SLME has been performed as part of the system performance in this holistic model. Since AxSTREAM System Simulation™ offers 1D Thermal Modelling Capabilities that include Conduction, Forced and Free Convection, Radiation and Film Cooling, it is possible to couple the thermal analysis of the combustor and nozzle with the rest of the system at each solving iteration for each operational point, - meaning that combustion chamber and nozzle thermal performances are accurately determined (instead of being assumed) dynamically during the convergence process, at each engine condition of interest. Hot gas properties are calculated based on quasi-one-dimensional subsonic and supersonic flows models allowing a direct data exchange between hot gases, walls and cold supercritical Hydrogen coolant.

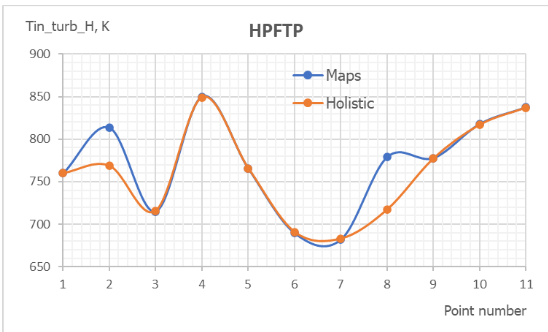
The benefit of usage of current 1D-quasi model is direct integration into the project. Given approach reduces possibility of manual errors and requires minimum inputs such as Combustion Chamber and Nozzle Profile Geometry and thermodynamic inlet conditions that come from the system.

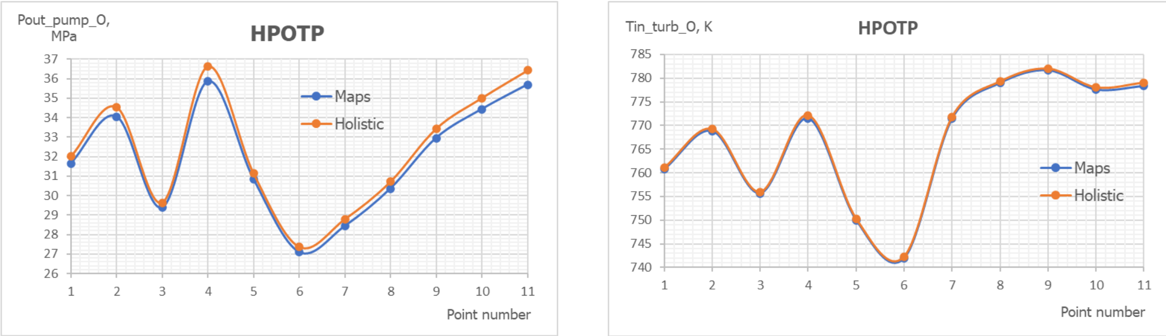
For the current case Conduction, Convection and Radiation Heat Transfers were considered. Heat Transfer Coefficients were calculated using known Barts Correlation [8] for hot side and Mikheev Correlation [9] for cold side. Copper was selected as material for Combustion Chamber while Steel Alloy was used for Nozzle regenerative cooling part. The main part of heated Hydrogen flows to pre-burners and the rest flows to LPFTP Turbine after which it goes to Combustion Chamber for Film Cooling.

4. Results

The eleven points shown in Fig. 5 (O1-O3 and E1-E8) were considered and converged using the presented holistic modelling approach. According to the fact that the thrust and Isp values are maintained constant, the main comparison parameters between the holistic approach and the performance map approach are the inlet turbine temperatures and outlet pump pressures. These values not only influence the engine's performance but also its dimensions, materials used in its constructions and eventually its mass.
The graphs below (Fig. 6) compare the results of calculating using performance maps vs. the holistic approach for the identified relevant parameters.







a) b)

Fig. 6. Comparison of calculation results using performance maps vs. holistic approach for each of the 11 engine conditions investigated, for the following components:

a) Fuel and oxidizer HP pumps outlet pressures

b) Fuel and oxidizer HP turbines inlet temperature

From Fig. 6, it can be seen that for the HPFTP pump outlet pressure the average difference between the results of the performance map vs. the holistic modelling across all 11 engine conditions studied is ~1.5% while the maximum deviation is ~3%. This trend is similar for the HPOTP with values of, respectively, ~1.5% and ~2.5%. Regarding the turbine inlet temperature, the average deviation for the HPFTP is ~1.5% with a maximum deviation above 8% while for the HPTOP the deviation is negligible.

Combustion Chamber and Nozzle Cooling Results

Fig. 7 and Fig. 8 below present the results of the thermal analysis of nozzle regenerative cooling under the engine's nominal operating condition. The Coolant comes at the middle of the nozzle and splits into two directions. The main part of the flow goes towards the Combustion Chamber after which it goes to the Pre-burners. The remaining part of the coolant, after flowing in the opposite direction through a section of the nozzle, then splits again into two streams: one flows to power the LPFTP turbine, while the other continues towards the end of the nozzle, where it is ejected.

The blue curve shows the combustion chamber and nozzle profile. The contour expansion from the chamber through the throat and into the divergent section was designed using the profiling with circular arcs (parabolic with corner entry) [10] since it gives the shortest nozzle with acceptable losses and with minimum mass, and it is included here as a non-dimensional geometric reference to correlate with the thermal distribution.

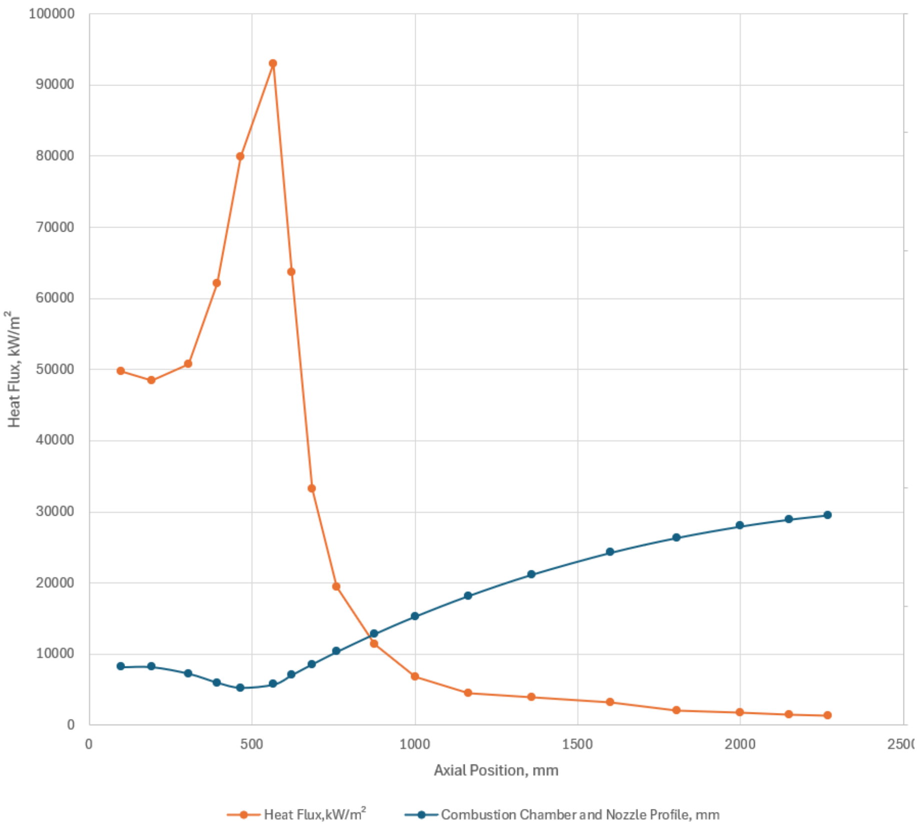


Fig. 7. Heat Flux (orange) as well as combustion chamber and nozzle profile (blue) along the nozzle at the nominal engine conditions

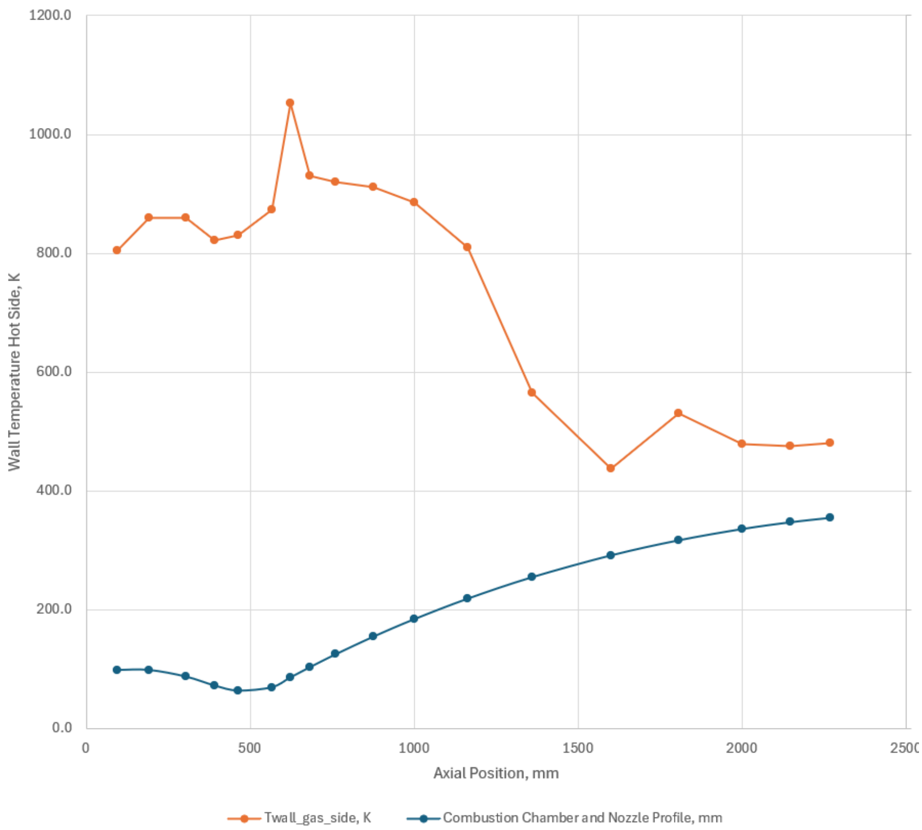


Fig. 8. Hot side Wall Temperature along the nozzle at the nominal engine conditions (without film cooling)

Fig. 8 above shows that the temperature of the wall at hot gases side (orange curve) remains around 800–850 K within the chamber region before rising sharply to a maximum of approximately 1053 K in the vicinity of the throat (~600mm axial location), which corresponds to the zone of highest convective heat flux due to elevated gas velocity and pressure. Although the predicted wall temperature does not appear excessively high, for copper this value is at the critical limit where material failure or melting could occur. To ensure structural integrity and extend nozzle life, especially for reusable engines, film cooling and protective coatings must be implemented in the maximum thermal loads area. Downstream of the throat, the temperature of the wall gradually decreases, dropping to about 450–500 K towards the nozzle exit, with minor local variations. As thermal loads in that area are not so intensive, the copper can be replaced by Steel Alloy to provide better strength, oxidation resistance, and structural durability. This shows how the careful modeling of the system and its components is necessary to ensure both performance and reliability.

5. Future Work

While the current study demonstrates some of the advantages of holistic modelling, further work may be done to expand its scope and fidelity:

- Transient Modelling: Incorporating detailed startup and shutdown sequences, including valve timing and pressure oscillations.
- Controls Integration: Embedding FADEC logic and actuator dynamics to simulate closed-loop operation.
- Uncertainty Quantification: Propagating uncertainties in component performance, material properties, and manufacturing tolerances through the integrated model.
- Digital Siblings/Twins: Linking integrated models with test data to create continuously updated digital siblings for system health monitoring and predictive maintenance.
- Experimental Validation: Ultimately, integrated modelling must be validated against test campaigns. A combined numerical-experimental feedback loop is essential for maturing European staged-combustion technology to operational readiness. The presented approach may be used to model physical testing sites to provide better insights into system performance under testing and real-operation conditions. Such an example is shown below in Fig. 9 where an oxygen-rich subsystem including a pump was used to evaluate the impact of test facility geometric characteristics on the axial thrust and cavitation characteristics of the pump. In fact, SoftInWay, Inc. identified that having longer pipelines could lead to a drop in the inlet temperature which in turn affects the cavitation margin of the pump. In a similar way, such holistic approach can help engineers evaluate the optimum number and location of sensors to be used during test set up as well as come up with early abort protocols in case of (and prior to) failure.

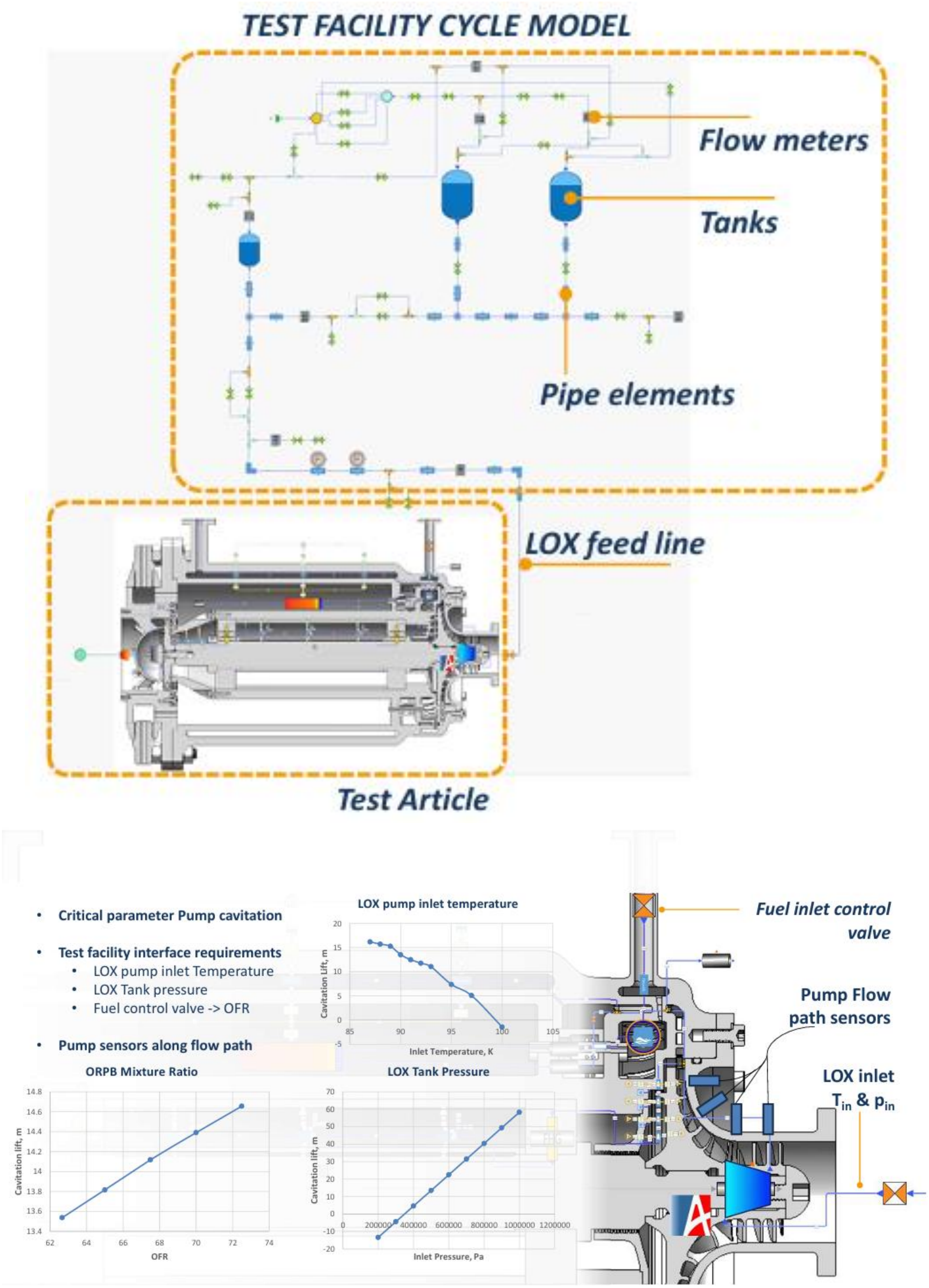


Fig. 9. Application of holistic modeling to experimental test setups. Shown here is an oxygen-rich subsystem with pump and facility feedlines, illustrating how facility geometry can influence inlet temperature, cavitation margin, and measured thrust. This demonstrates how holistic methods extend beyond engine design to test planning and validation.

6. Conclusion

When modeled in isolation several issues may arise once the hardware components are connected together:

- Pumps may appear to meet efficiency targets, but cavitation margins can be insufficient once feed-line pressure drops are introduced.
- Cooling circuits can appear adequate, but integrated modelling may reveal localized overheating during throttling transitions.
- Preburners may seem stable individually, yet coupled operation can create oscillatory conditions leading to combustion instability.
- Holistic modelling exposes these interactions, ensuring that the integrated SLME design is both operable and robust under reusability demands.

Quantitative assessment of the holistic vs. traditional modelling methods of the SLME indicates several benefits over component-level analysis:

1. **Improved Prediction Accuracy:** Holistic modelling aligns predicted performance more closely with real hardware behavior, reducing the risk of over-optimistic efficiency or thrust estimates.
2. **Failure Point Identification:** System simulations highlight critical interface conditions—such as cavitation risk at the pump inlet under off-design pressures or excessive wall temperature spikes during rapid throttling—that may be missed by local models.
3. **Operation and Design Optimization:** By observing the complete system response, designers can trade parameters more effectively. For example, adjusting preburner mixture ratios may alleviate turbine stress but simultaneously reduce chamber efficiency; only a system-level view can quantify the overall effect.
4. **Enhanced Reliability:** Capturing coupled dynamics supports the design of robust engines capable of multiple reuses. Early detection of subsystem conflicts reduces reliance on costly and time-consuming test campaigns to uncover integration failures.
5. **Reduced Iteration Cycles:** Holistic modelling accelerates design convergence by minimizing back-and-forth revisions between subsystem teams. Instead of redesigning pumps after chamber tests or re-sizing cooling circuits post-integration, potential mismatches are revealed early.

In summary, integrated, holistic modelling allows engineers to anticipate the complex interplays that govern safe and efficient operation as well as perform uncertainty quantification on entire systems instead of locally to individual components, hoping the rest of the elements will behave as hoped.

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