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Transient Thermal-Fluid Network Modeling for Throttling Control in Full Flow Staged Combustion Cycle Engines

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ABSTRACT: *Throttling control in liquid rocket engines is a key requirement for modern reusable launch systems, enabling precise trajectory corrections, soft landings, and optimized fuel consumption.*

However, modelling this process presents fundamental thermal and hydraulic issues. Rapid coolant flow reduction during throttling causes local wall overheating, thermal shock, and fatigue in regenerative cooling channels [1], while cavitation and boilout in turbopumps and feed lines lead to severe mechanical damage. These effects can drastically shorten engine life or trigger failures. Past tests showed that boilout in a high-pressure fuel turbopump can destroy blades within 10 to 20 seconds [2], as well as a deviation of ~5 % in wall temperature estimation may lead to a 50 % error in predicted engine life [3].

Analytical errors often arise from applying steady-state models to rapid throttling, overlooking inertial effects and system response, which makes them unreliable for throttling analysis.

This work presents the development of a full transient 0D–1D thermal-fluid network model for a full-flow staged combustion cycle engine [4], incorporating dynamic phenomena. The model enables detailed analysis of transient thermal and hydraulic behaviour during throttling, supporting the design of reliable control strategies for engine management. Special attention is given to evaluating wall temperature distributions, turbopump operating margins, and overall system stability under different control laws. The results provide guidance for optimizing control logic, improving prediction accuracy, reducing test time, and enhancing safety and service life in reusable propulsion systems.

NOMENCLATURE:

FRPB – fuel-rich pre-burner
ORPB – oxidizer-rich pre-burner
LPFTP – low-pressure fuel turbopump
HPFTP – high-pressure fuel turbopump

HPOTP – high-pressure oxidizer turbopump

MCC – main combustion chamber

MOV – main oxidizer valve

MFV – main fuel valve

FPFV – fuel pre-burner fuel valve

OPFV – oxidizer pre-burner fuel valve

FPOV – fuel pre-burner oxidizer valve

OPOV – oxidizer pre-burner oxidizer valve

CCV – chamber coolant valve

D_s – nozzle throat diameter

A_s – nozzle cross-sectional area

A – local cross-sectional area

c^* – characteristic velocity

μ – dynamic viscosity

r_c – throat radius of curvature

C_p – specific heat at constant pressure

Nu – Nusselt number

Re – Reynolds number

Pr – Prandtl number

T_w – wall temperature

T_0 – stagnation temperature

T_f – fluid temperature

T_s – surface temperature

ε_s – surface emissivity

ε_f – fluid emissivity

ε_{CO_2} – CO_2 emissivity

ε_{H_2O} – H_2O emissivity

β – correction factor for H_2O emissivity calculation

depending on partial pressure p_{H_2O} and multiplication pL (p – partial pressure, L – effective path length of the beam);

M – Mach number

γ – ratio of specific heat heats

Δp^* – pressure drop

ρ – density

MFR – mass flow rate

Δt – time step

p_1, p_2 – inlet and outlet pressures

T_1, T_2 – inlet and outlet temperatures

h_1, h_2 – inlet and outlet enthalpies

prc – pressure recovery coefficient

Q – heat flow

ξ – resistance coefficient

F_{exit} – external forces

S_e – energy source (could be heat flow because of convective and radiation heat exchange with solid structure)

S_q – heat source
 α – heat transfer coefficient
 C – specific heat capacity
 C_v – valve constant
 K_p – proportional gain
 K_i – integral gain
 K_d – derivative gain
 SP – set point
 err - error between set point and inlet signal

1. INTRODUCTION

Modern liquid rocket engines (LREs) are capable of delivering high levels of specific thrust and specific impulse while maintaining stringent requirements for maneuverability, reliability, and operational stability under conditions of repeated reuse [6,7]. These performance characteristics are achieved through proper design methodologies and detailed analysis of the engine's operating regimes [6].

A careful consideration of the physical phenomena occurring during LRE operation enables the identification of potentially critical effects already at the design and computational stages, significantly reducing the scope of experimental testing and the associated time and financial costs [9,11].

One of the key engine control capabilities is throttling, which is employed to enable spacecraft maneuvering and to reduce structural loads during flight [12]. However, operation at reduced thrust levels may be accompanied by several adverse effects, particularly those related to the thermal state of the cooling jacket [8,10].

During throttling, heat fluxes redistribute, reducing temperature uniformity and potentially causing local increases in wall temperature within the combustion chamber and nozzle [8]. The deterioration of cooling conditions, combined with changes in combustion behavior, contributes to the formation of temperature gradients that induce additional thermal stresses [10,13]. As a result, the structure's thermal state becomes less stable, increasing the risk of fatigue damage accumulation and potential structural failure, even at reduced thrust levels.

To prevent wall overheating, a properly designed control system is required to maintain temperatures within allowable operational limits [9,14].

This work investigates the throttling process in a full-flow staged-combustion engine. Particular attention is given to the analysis of thermal stresses in the cooling jacket under reduced-thrust conditions. Furthermore, the design and evaluation of a control system for throttling management is presented, aimed at reducing structural loads during engine operation in vacuum conditions.

2. MODEL

2.1 AxSTREAM System Simulation tool description

AxSTREAM System Simulation™ tool developed by SoftInWay Inc. [16] is a comprehensive software program for 0D-1D system design, modeling, and optimization across various engineering applications. This software offers a unified environment for simulating thermodynamic cycles, secondary flow, and other multidisciplinary systems based on a component-network approach.

Each component in the scheme is a computational model with a set of equations to calculate its variables and a set of procedures to calculate its parameters. Each connection between components is also a computational model with its own set of equations and procedures to describe how data must be exchanged between components.

Each equation is pushed by a computational model into a corresponding system of equations. Each procedure is also pushed by a computational model into a corresponding place in the solver algorithm where it is invoked to update the necessary parameters.

A system of equations is solved implicitly using the Newton-Raphson method.

2.1.1 Cycle library elements

In this work, elements from the Cycles library were used to create the engine circuit. These components represent 0D or quasi-1D computational models, each of which contains a system of equations linking the thermodynamic parameters characterizing the component.

There is a mathematical model of a generalized pipe component from this library (Fig.1):

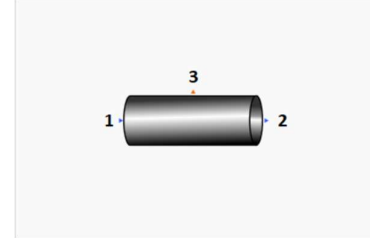


Figure 1 – Example of 0-D model from Cycle library

The computational model that will be processed by the solver as described above:

$$\begin{cases} \sum MFR_i = 0 \\ MFR_1(h_1 - h_2) + Q_3 = 0 \\ \Delta p^* = p_2 - p_1 \\ p_2 = p_1 \cdot prc \end{cases} \quad (1)$$

Where index 1 corresponds to the inlet port, index 2 – outlet port, index 3 – heat port.

2.1.2 Thermal-fluid network approach

The thermal-fluid network method is used to model fluid and heat flow utilizing a one-

dimensional abstraction. The main idea behind the method is to represent different sections of a fluid path and different parts of a solid structure as one and zero-dimensional components, which are then connected with each other in order to form a thermal-fluid network (Fig.2) and to simulate fluid and heat flow through these components.

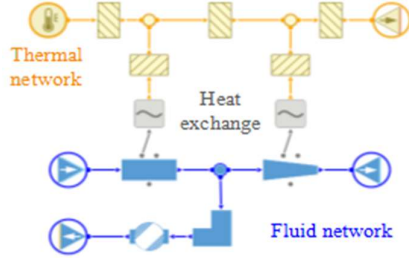


Figure 2 – Example of thermal-fluid network

Each component may consist of one or several elements, which can be branches and nodes. Branches are used to describe different resistances to fluid and heat flow, while nodes are used to connect branches and set up boundary conditions (Fig.3).

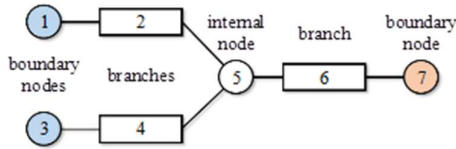


Figure 3 – Nodes and branches

Fluid branches utilize the momentum equation to calculate mass flow rate through a section of fluid path, which could be written in the following form:

$$\Delta p = 0.5 \cdot \xi \cdot MFR^2 \rho \cdot A_2 + F_{exit} A \quad (2)$$

This equation describes the total pressure drop between the inlet and outlet of a branch due to fluid flow resistance and external forces for a given section of the fluid path. Here, external forces could be gravity or inertial forces due to the rotation effect.

Conservation of mass and total enthalpy equations are used to model fluid flow separation and mixing in internal fluid nodes. They can be written as follows:

$$\frac{\partial}{\partial t}(m) = \sum_{branches} MFR_i \quad (3)$$

$$\begin{aligned} \frac{\partial}{\partial t}(m \cdot h_0 - p \cdot V) = \\ = \sum_{branche} MFR_i h_{iupstream} + S_e, \quad (4) \end{aligned}$$

Equation (3) describes the rate of fluid mass change in a node due to fluid flows through connected fluid branches.

Equation (4) represents the rate of energy change in time through the change of total

enthalpy and pressure in a fluid node due to total enthalpy transfer from upstream nodes through connected fluid branches and an energy source. Thermal branches utilize an equation of heat flow due to the temperature difference between different places in a solid structure and between a solid surface and a fluid flow, which can be written in the following form:

$$Q = \alpha \cdot (T_1 - T_2) \cdot A \quad (5)$$

The energy conservation equation is used for a thermal node and can be expressed as:

$$\frac{\partial}{\partial t}(m \cdot C \cdot T) = \sum_{branches} Q_i + S_q \quad (6)$$

This equation describes the rate of energy change in time through the change of temperature within the mass of the substance (solid or fluid) with a specific heat capacity due to the heat flows through connected branches and a heat source.

Time derivatives in the left-hand side (LHS) of conservation equations (3), (4), and (6) are approximated using the fully implicit scheme of the first order as follows:

$$\frac{LHS^{new} - LHS^{old}}{\Delta t} = RHS^{new} \quad (7)$$

which gives an unconditionally stable solution for any time step.

Momentum equation (2) and mass conservation equation (3) for all fluid nodes and branches form one system of equations, while energy conservation equations (4 and 6) for fluid and thermal nodes and heat flow equation (5) for thermal branches form another system of equations. These two systems are solved using the Newton-Raphson method sequentially in iterations, while both systems are converged with a given tolerance.

As a result of the calculation, the solver computes fluid flow properties (such as pressures, densities, velocities) for fluid components and heat flow properties (such as heat fluxes and temperatures) for thermal components.

Despite implementation differences, all programs for thermal-fluid network modeling deal with the same governing equations, some of which were briefly presented in this section. These equations describe conservation of mass, momentum, and energy, and supplemented by the equation of state, allow to perform steady state and transient analysis of fluid and heat flows. The use of these equations in a one-dimensional formulation allows for the modeling of complex thermal-fluid systems and reduces computational time compared with 2D-3D CFD.

2.2 Engine cycle

The subject of this study is the SLME (Space Liner Main Engine), designed by SoftInWay

Switzerland and DLR-SART, funded by GSTP with the European Space Agency (ESA) for reusable heavy launch applications [4]. The SLME operates on a full-flow staged combustion cycle.

A schematic of the cycle is shown in Fig.4.

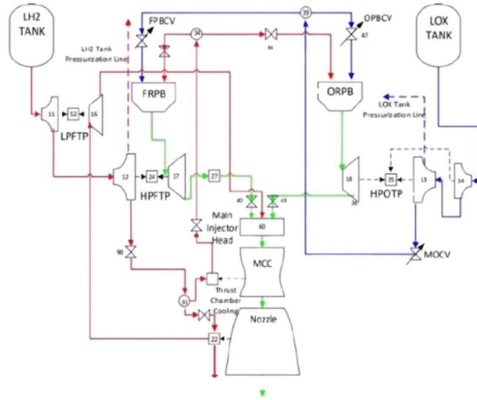


Figure 4 – SLME cycle scheme, extracted from [4]

Before entering the main combustion chamber, the fuel and oxidizer are injected into two pre-burners: the oxidizer-rich pre-burner (ORPB) and the fuel-rich pre-burner (FRPB). The resulting combustion products are then directed to the turbines (HPFTP turbine and HPOTP turbine), which drive the corresponding pumps (HPFTP pump and HPOTP pump), thereby increasing the pressure of the propellants before their injection into the pre-burners.

To prevent cavitation, the fuel is initially pressurized by a low-pressure fuel turbopump (LPFTP). Before combustion, the fuel passes through the regenerative cooling jacket, removing heat from the chamber walls and nozzle. Subsequently, the flow is split: one portion is directed to the pre-burners, another drives the LPFTP turbine, and the remaining fraction is discharged from the main cycle to avoid excessive thermal loading in the cooling channels.

For numerical analysis, a system model of the SLME was developed using the AxSTREAM System Simulation platform (Fig.5):

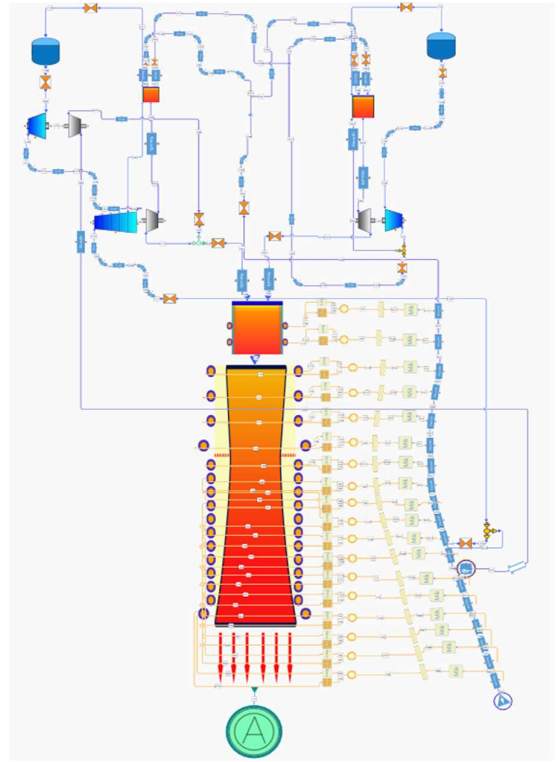


Figure 5 – SLME model in AxSTREAM System Simulation

The model is implemented as a 0D–1D thermo-fluid network, where:

- Propellant tanks, valves, and pre-burners are represented as zero-dimensional (0D) components
- Turbomachinery performance is defined using characteristic maps, enabling accurate representation of pump and turbine geometries
- Flow passages are modeled as one-dimensional (1D) ducts of varying geometry, accounting for hydraulic resistance, compressibility, inertia, and other relevant fluid dynamic effects
- The combustion chamber and nozzle are treated as quasi one-dimensional models.
- Thermal interactions are modeled through dedicated components that simulate heat transfer between hot combustion gases flowing through the nozzle and the hydrogen coolant circulating in the regenerative cooling channels:
 - Heat flux on the hot-gas side is calculated using the Bartz correlation [15]:

$$h = \frac{0.026}{D_*^{0.2}} \left(\frac{\mu^{0.2} C_p}{\text{Pr}^{0.6}} \right)_0 \left(\frac{p_c}{c^*} \right)^{0.8} \cdot \left(\frac{D_*}{r_c} \right)^{0.1} \left(\frac{A_*}{A} \right)^{0.9} \sigma, \quad (8)$$

where σ is the dimensionless factor accounting for the variation of density and viscosity values across the boundary layer, and is expressed by:

$$\sigma = \frac{1}{\left[\frac{1}{2} \frac{T_w}{T_0} \left(1 + \frac{\gamma-1}{2} M^2\right) + \frac{1}{2}\right]^{0.8-(w/5)}} \cdot \frac{1}{\left[1 + \frac{\gamma-1}{2} M^2\right]^{w/5}}, \quad (9)$$

supplemented by a radiative heat transfer component accounting for CO₂ and H₂O mole fractions [16]:

$$q = \frac{\varepsilon_s + 1}{2} \cdot \sigma \cdot (\varepsilon_f \cdot T_f^4 - A_f \cdot T_s^4), \quad (10)$$

$$\varepsilon_f = \varepsilon_{CO_2|T=T_f} + \beta \cdot \varepsilon_{H_2O|T=T_f}, \quad (11)$$

$$A_f = \varepsilon_{CO_2|T=T_s} \cdot \left(\frac{T_f}{T_s}\right)^{0.65} + \beta \cdot \varepsilon_{H_2O|T=T_s} \cdot \left(\frac{T_f}{T_s}\right)^{0.45}, \quad (12)$$

- Heat transfer on the coolant side is evaluated using the Mikheyev equation:

$$Nu = 0.021 \cdot Re^{0.8} \cdot Pr^{0.43}, \quad (13)$$

- Environmental conditions are defined using an Ambient component. In this case, the process of throttling an engine in a vacuum will be considered.

2.3 Modeling of the throttling process

Throttling allows a liquid rocket engine (LRE) to vary thrust over a wide range, helping it adapt to changing flight conditions and structural load limits [12]. One of its most important functions is limiting acceleration loads during the final stages of ascent, especially in near-vacuum conditions as vehicle mass decreases.

A well-known example is the RS-25 (SSME) engine [14], which is throttled near the end of flight to about 67% thrust to keep vehicle acceleration close to 3g (Fig.6).

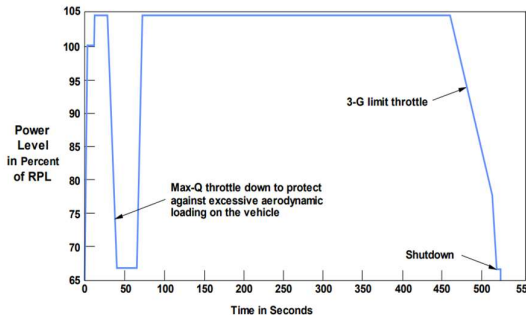


Figure 6 – RS-25 (SSME) typical throttling profile, extracted from [14]

In this study, the throttling behavior of the SLME is investigated over a range from 100% down to 67% thrust, corresponding to a similar mission scenario focused on acceleration control under near-vacuum conditions.

Thrust reduction in the SLME is achieved by decreasing the mass flow rates through the pre-burners. At the same time, the engine control system maintains the mixture ratio (MR) at its nominal value and ensures that the nozzle wall temperature remains within allowable limits.

System throttling is realized using the control valves FPOV (fuel pre-burner oxidizer valve), OPOV (oxidizer pre-burner oxidizer valve), and CCV (chamber coolant valve), whose positions directly influence the aforementioned parameters by regulating propellant mass flow rates.

To investigate the intrinsic system behavior in the absence of active control laws, throttling was simulated by imposing a linear reduction in the oxidizer and fuel mass flow rates through the FPOV, OPOV, and CCV valves, proportional to the instantaneous thrust level. The thrust is reduced uniformly over a period of 44 seconds, corresponding to a throttling rate of 0.75% per second.

3. COMPARISON OF THE STEADY-STATE AND TRANSIENT MODELS

3.1 The transient approach justification

As noted earlier, throttling of a liquid rocket engine may introduce both thermal and hydraulic challenges [1]. One of the critical issues is localized overheating of the nozzle cooling jacket walls, caused by a mismatch between the rate of decrease in the coolant (hydrogen) mass flow and the heat flux from the hot combustion gases. Inaccuracies in predicting nozzle wall temperatures can significantly reduce engine lifetime and may even lead to structural failure [10].

Undesirable effects of this kind often remain undetected when using steady-state models, as such models neglect system inertia and are therefore inadequate for capturing transient behavior [3,9]. To identify and subsequently mitigate issues arising during throttling, a transient modeling approach is required.

3.2 SLME transient model

The AxSTREAM System Simulation tool provides transient thermo-fluid network modeling capabilities across various levels of complexity. When operating in transient mode:

- Tank components simulate propellant depletion over time
- Pipe elements account for flow dynamics and time-dependent effects
- To represent the inertial effects arising from flow delays, a time delay of 1 second was introduced between

changes in pre-burners' mass flow rates and the corresponding response in the main combustion chamber flow.

This adjustment compensates for the use of zero-dimensional pre-burner models, which do not account for finite volume effects or combustion dynamics, and 0D valve models.

Fig.7 illustrates the distribution of wall temperatures at 100%, 80%, and 67% thrust levels, calculated using the steady-state model.

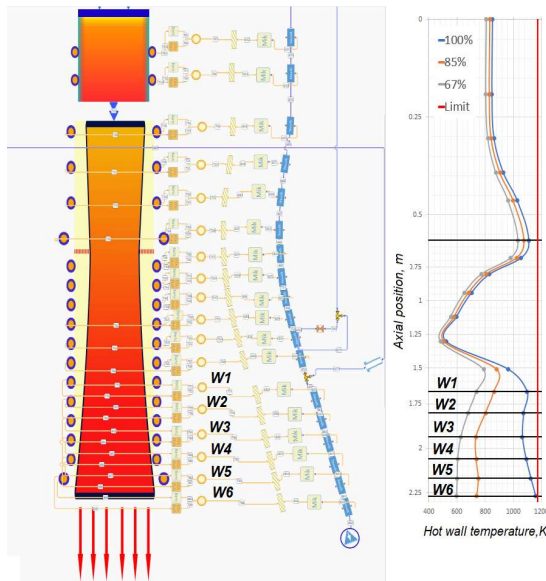


Figure 7 – Hot wall temperature distribution at different thrust levels

It can be observed that throttling has the most pronounced effect on the temperatures of walls W1–W6, which are cooled by the hydrogen flow discharged from the main cycle. In contrast, the upstream nozzle wall temperatures exhibit only minor variation.

This trend is consistently observed in both steady-state and transient simulations.

The highest wall temperature is reached at location W6, corresponding to the region where the thermal load is most severe. Therefore, a detailed comparative analysis of the temperature evolution at walls W1–W6 during the throttling process is conducted in the following section.

3.3 Steady-state and transient models calculation results

A comparison of SLME throttling results regarding W1–W6 hot wall temperature values obtained using steady-state and transient models is presented in Fig.8 – Fig.10.

The nozzle walls are assumed to be manufactured from AISI 316 stainless steel, which has a melting temperature in the range of 1643–1673 K [5].

However, its allowable operating limits are significantly lower and depend on exposure time and mechanical loading.

For continuous operation, permissible temperatures are typically in the range of 1073–1143 K, while short-term excursions up to 1173–1198 K (for durations of several minutes at stresses up to 120 MPa) may be tolerated [5].

For the present analysis, a conservative wall temperature limit of 1173 K was adopted.

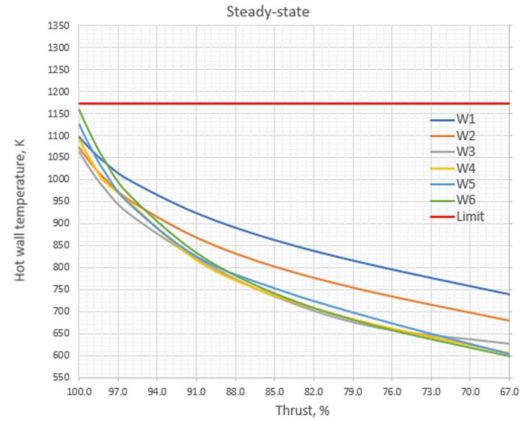


Figure 8 – Changes in the W1–W6 hot wall temperature during the throttling process of the steady-state model

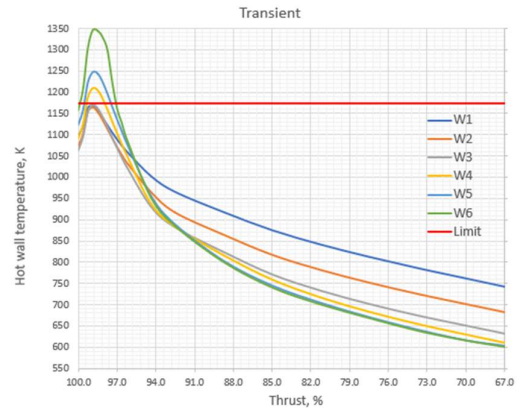


Figure 9 – Changes in the W1–W6 hot wall temperature during the throttling process of the transient model

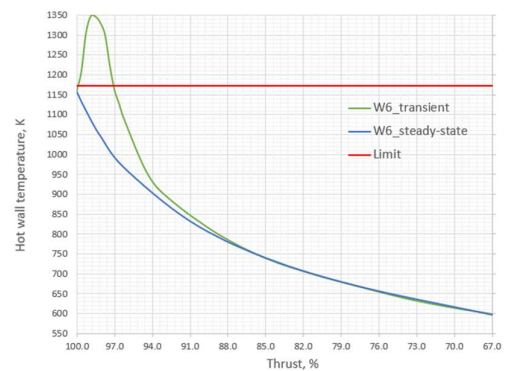


Figure 10 – Comparison of changes in the W6 hot wall temperature during the throttling process of the steady-state and transient model

As shown in the results, the transient model, unlike the steady-state model, predicts a sharp spike in wall temperature caused by the system's inertial response, exceeding the allowable thermal limits. Such behavior may lead to accelerated material fatigue and a substantial reduction in engine service life.

4. ENGINE CONTROL SYSTEM

4.1 The importance of the control system

The control system of a liquid rocket engine (LRE) is a vital component determining its stability, efficiency, and operational safety. The primary function of the control system is to maintain specified thrust, propellant ratios, and system loads within acceptable limits [12]. Deviations in these parameters can lead to reduced efficiency, unstable combustion, or even engine failure.

In modern LREs, the control system is integrated with automation and sensors, forming a closed-loop control system [15]. This allows for real-time adjustments to component delivery and maintains the engine in optimal operating mode at all stages of operation.

4.2 SLME control system

The SLME control system must meet the following requirements:

- Achieving 67% thrust within 44 seconds without sudden surges, according to the throttling profile (Fig.6)
- The rate of thrust change should not exceed 310 kN/s, based on requirements from [15]
- Maintaining the MR (mixture ratio) value equal to 6, with a permissible deviation of 1%, based on requirements from [15]
- Maintaining the hot wall temperature below the limit value (1173 K), according to the temperature limitations considered in paragraph 3.3
- Maintaining the turbomachine speed within acceptable limits, based on turbopump maps

Fig.11 shows the components of the control system that control the engine while throttling. Fig.12 represents the throttle control system scheme modeled by the AxSTREAM System Simulation tool.

The circuit was based on the control system of the RS-25 engine [14].

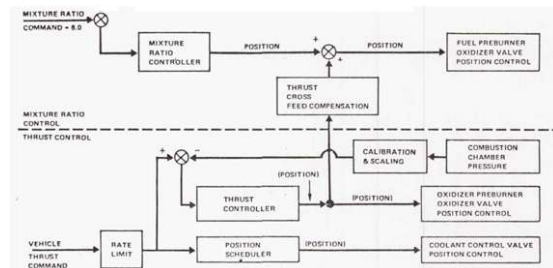


Figure 11 – Control system scheme, extracted from [15]

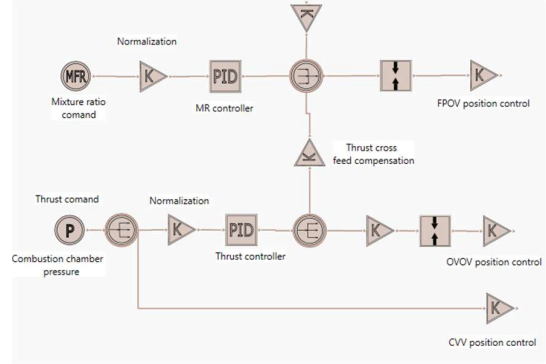


Figure 12 – Control system created with AxSTREAM System Simulation tool

The input parameters for the control system are current values of the chamber pressure and engine mixture ratio (MR). The system compares the received signals with the required thrust and MR values, and then adjusts OPOV and FPVP positions using PID controllers, the calculation model (14), using proportional, integral and derivative dependencies:

(14)

- OPOV – maintains thrust level;
- FPOV – maintains the mixture ratio at a specified level (MR = 6);

The process is repeated until the desired mode is achieved. Before the signals are processed by the PID controllers, they are normalized, since the pressure values in the chamber and the MR differ significantly.

The CCV position is controlled by a schedule of its valve constant to maintain the nozzle wall temperature and turbomachine rotation speed within acceptable limits.

4.2.1 Valve transient models

The valves used in the circuit offer simplified 0D models, a spatially lumped representation of flow control, ideal for simulating transient behavior in fluid systems. To control the valve lift, the model uses a valve constant (15) that depends on the mass flow rate, fluid density, and the pressure drop across the valve:

$$C_v = \frac{MF}{\rho_1 \sqrt{dp}} \quad (15),$$

where $\rho_1 = f(p_1, h_1)$ - inlet density of the flow,

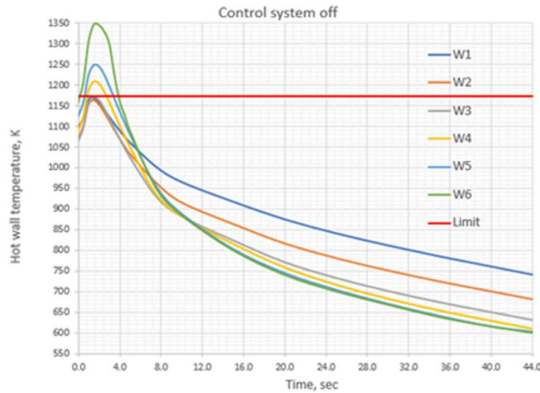
$dp = p_1 - p_2$, if $p_1 \geq prc$,

$dp = p_1 - p_2$, if $p_1 < prc$

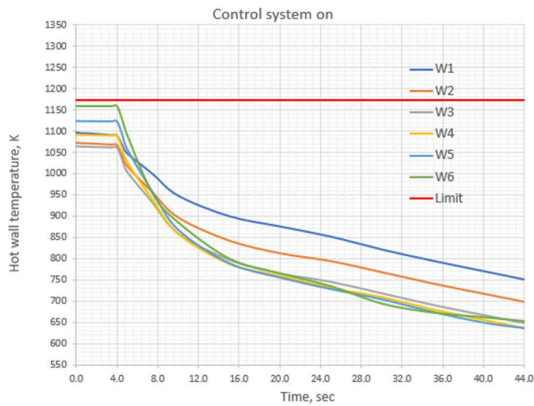
To summarize, in this model, the control system controls the valve positions by changing the valve constant values obtained at a given moment in time.

4.3 Comparison of changes in engine parameters with the control system on and off

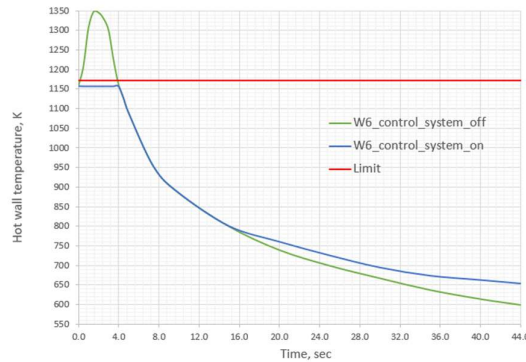
The changes in system parameters during throttling, as used in the previous section (without regulation), and during control system operation are shown in Fig.13 – Fig.15:



a)



b)



c)

Figure 13 – Comparison of changes in the W1-W6 hot wall temperature during the throttling process with:

a) Control system off

b) Control system on

c) Comparison of W6 hot wall temperature with the control system off and on

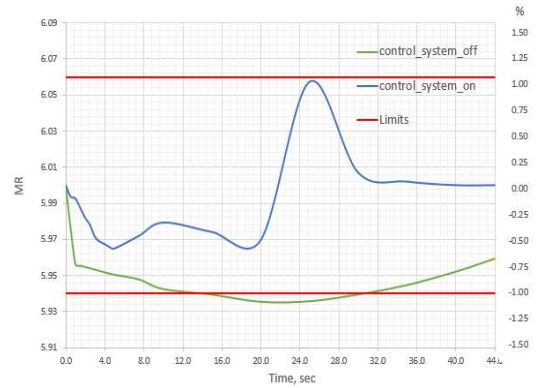


Figure 14 – Comparison of changes in the MR during the throttling process with the control system on and off

When throttling without a control system (described in paragraph 2.3), the flow rate through HPFTP turbine decreases more rapidly than the power required to spin up the HPFTP compressor.

Therefore, the turbine speed increases and at a certain point exceeds the maximum rotational speed (based on HPFTP models restrictions developed for [4]).

The control system helps solve this problem by changing the CCV position.

Fig.15 shows the change in HPFTP rotational speed (normalized to the value at the nominal mode) during the throttling process.

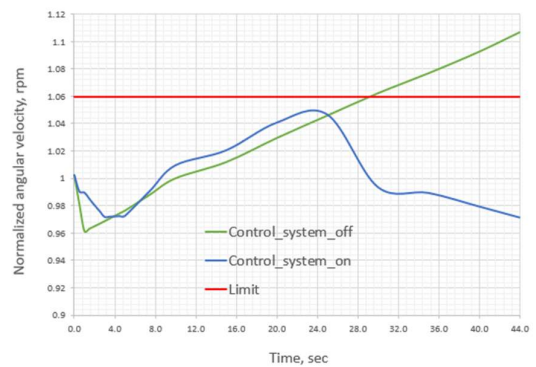


Figure 15 – Comparison of changes in the HPFTP rotational speed during the throttling process with the control system on and off

The control system ensures a smooth and monotonic reduction in thrust to the specified level without abrupt fluctuations (Fig.16):

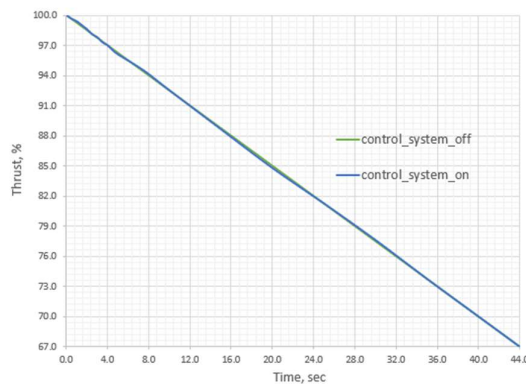


Figure 16 – Comparison of changes in the thrust value during the throttling process with the control system on and off

5. CONCLUSIONS

5.1 Analysis of the results

This paper presents a study of the behavior of a liquid rocket engine (LRE) operating on a full-flow staged combustion cycle during the throttling process, which is used to limit acceleration loads during the final stages of ascent in vacuum conditions.

A comparison of nozzle wall temperature values obtained using steady-state and transient models has been carried out. The results demonstrate that employing a transient model as the primary calculation approach is essential for identifying issues that appear during transient processes, since system inertia plays a significant role in the variation of system parameters.

Transient throttling analysis shows that, at the initial stages of throttling, the nozzle wall temperature in the lower section exceeds allowable limits, which may lead to a significant reduction in engine service life. Additionally, when throttling below 80%, an increase in the rotational speed of the high-pressure fuel turbopump (HPFTP) is observed, which can be explained by the need to generate sufficient power under conditions of rapidly decreasing mass flow through the turbine.

To ensure efficient and reliable engine operation under throttling conditions, a control system has been designed to achieve the required thrust level within a specified time, while maintaining the mixture ratio (MR) at approximately 6 and keeping nozzle wall temperatures and turbomachinery rotational speeds within allowable limits.

Such a model, developed and analyzed using the AxSTREAM System Simulation tool, makes it possible to identify and resolve issues at the design stage, thereby reducing the resources required for engine manufacturing and testing.

5.2 Improvement plan

The SoftInWay [16] team is currently working on developing a higher-level combustion chamber

model that would take into account combustion kinematics and all inertial effects that arise during system operation, in order to bring the combustion model's behavior as close to the real process as possible.

A 1D model of the valve is also being developed that would take into account the valve geometry and could account for inertial effects arising from flow delays.

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