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Space Propulsion

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Acronyms

LOX Liquid Oxygen. 4

NASA The National Aeronautics and Space Administration. 5

RP-1 Rocket Propellant 1. 4

RPA Rocket Propulsion Analysis. 4

TBC Thermal Barrier Coating. 4

Abstract

This report aims to analyze, through the use of the RPA software, whether Inconel 718 can be an appropriate choice for the study case assigned, a bi-propellant liquid engine. The report will analyze, both from a thermodynamic and a stress perspective, the result given by the software in order to establish if the material could be used and discuss, furthermore, how the propulsion system could be improved in the event of failure.

1 Case Study Presentation

1.1 Initial Data

The engine analyzed is a bi-propellant liquid engine powered by RP-1, stored at 300 K and 7.5 MPa, and LOX, stored at 90 K and 7.5 MPa. The engine is characterized by the use of 3 chambers and a Rao nozzle at 80% of length with respect to a conical nozzle with 15° as exit angle.
The initial data of the case study, which is used as an input by the RPA software, is collected in Table 1:

Data	**Value**	**Unit**
P_c	7.5	MPa
$T\,(1\,atm)$	100	kN
L^*	1.143	m
O/F	2.3	-
Ac/At	10	-
Ae/At	14	-

Table 1: Initial data for the case study

Furthermore, the cooling of the engine is performed through the entire length of the combustion chamber and the nozzle by implementing three distinct methods:

- **Regenerative Cooling**, carried out with RP-1 at 300 K and 8.5 MPa and a relative mass flow rate of 0.3 with respect to the total mass flow rate of the chamber. The regenerative cooling is composed of 50 channels with a width of 1 mm each and a rib height of 5 mm each.
- **Film Cooling**, performed with RP-1 at 300 K and 7.5 MPa and a relative mass flow rate of 0.05 with respect to the total mass flow rate of the chamber.
- **Thermal Barrier Coating (TBC)**, with a thickness of the shield of 0.1 mm and a thermal conductivity of 1.5 W/(m k).

1.2 Inconel 718

Inconel 718 is a nickel-chromium based alloy containing iron and niobium as well. It was developed for use at medium-high temperatures due to its low thermal conductivity, high yield, and high tensile strength.

The thermal and mechanical properties used for this report were found in the "Materials Data Handbook: Inconel Alloy 718" [2], in which all the samples were tested at different temperatures to provide a better approximation of their values.
Table 2 contains all of the thermal and mechanical properties of Inconel 718 at a temperature of 650 °C (923.15 K).

Data	**Value**	**Unit**
Maximum Operating Temperature	$977,55$	K
Thermal Conductivity	21.447	$W/(m\,K)$
0.2% Tensile Yield Strength	848	MPa
Ultimate Tensile Strength	1017.7	MPa
Coefficient of Thermal Expansion	$1.55 \cdot 10^{-5}$	$1/K$
Modulus of Elasticity E	160	GPa
Poisson Ratio ν	0.283	-

Table 2: Inconel 718 mechanical and thermal properties [2]

2 Results

The results obtained from the thermal analysis of the engine are presented in Figure 1.

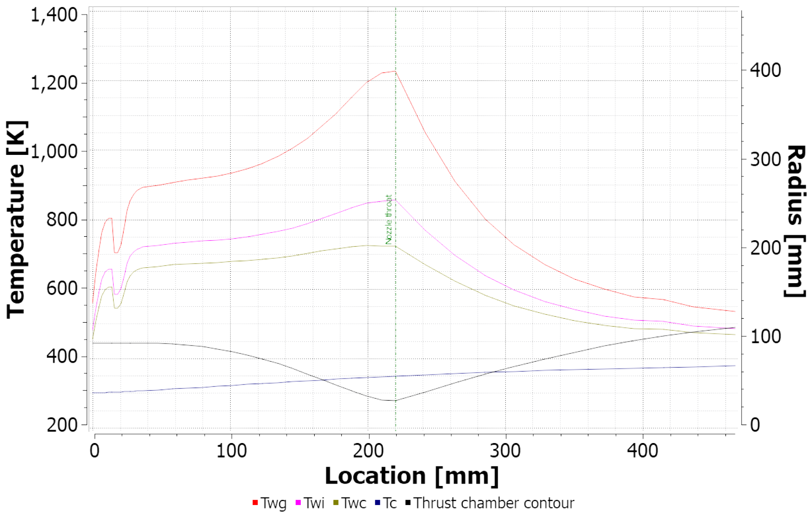

Fig. 1: Temperature distribution at chamber throttle level R = 1

It can be seen that the maximum temperature reached by the inner chamber wall is 855.34 K, at the throat of the nozzle.
This temperature does not exceed the maximum operating temperature of 977.55 K for Inconel 718, but could still cause an engine failure due to thermal stresses present in the material.

To verify engine safety it is sufficient to compare the thermal stresses, with a sufficient safety factor applied, with the most demanding damaging load, in this case the yield load. The steps to compute the thermal stresses and compare them with the damaging loads are shown in the following formulas:

$$s = \frac{2\lambda \cdot E \cdot \Delta T}{1-\nu} \qquad (1) \qquad\qquad s \cdot f_s < min(F_u\, , \, F_y) \qquad (2)$$

Where s is thermal stress of the material, λ is the coefficient of thermal expansion, E is the modulus of elasticity, ΔT is the maximum temperature difference between the hot side of the wall and the cold one, ν is the Poisson ratio, f_s is the safety factor, F_u is the ultimate tensile strength and F_y is the tensile yield strength.
The maximum ΔT is 131.7 K and occurs at the throat of the nozzle, coinciding with the highest temperature location.

As documented in NASA's "White Paper on Factors of Safety" [1], a suitable safety factor relative to the propulsion system's stress loads could range from 1.25 to 1.5. For this study case a safety factor of $f_s = 1.4$ was implemented, as it represents the mode of historical design safety factors for NASA's space vehicles.

By solving these computations and applying the correct safety margin the stress due to thermal expansion is obtained, $S = 1275.5\ MPa$, , which is considerably higher compared to the minimum damaging load of $F_y = 848\ MPa$.

This shows that, even though the maximum temperature reached was inferior than the maximum operating temperature, the engine would still fail due to thermal stresses.

In conclusion, these conditions are not suitable for the use of Inconel 718 as the chamber wall material.
In the next section, alternative design possibilities are briefly explored to showcase how the system might be improved.

3 Design Improvements

As discussed in the previous section, Inconel 718 does not satisfy the safety requirements of the engine, due to the high thermal stress it would undergo during firing. The design of the rocket engine could be improved in various ways in order to overcome this main issue. The following approaches provide a balanced trade-off between performance and thermal-stress management, ensuring that the engine operates as efficiently as possible without exceeding the constraints of its components:

- The thickness of the inner wall could be increased.
  This would reduce the thermal flux and consequently the temperature gradient across the wall. A lower temperature gradient would grant a lower mechanical stress which is critical since, as seen in the results, the stress on the walls is too high. Considering that the maximum temperature on the walls is below the maximum operating temperature, a problem optimization could be done in order to find a wall thickness which is a satisfactory compromise between mechanical stress and temperature of the wall. A downside of this possibility is the increase in system mass, due to the use of more material. In some cases this could be an even more demanding requirement, making this solution not possible.

- The film cooling performance could be improved, either by increasing the relative mass flow rate dedicated to it or by adding a number of inlets assigned for film cooling near the most demanding region of the nozzle, in this case the throat, where the temperature is critical. This would provide additional cooling where the engine needs it the most. A downside of this possibility is the waste of propellant, as the propellant used for film cooling goes to waste. This could result in an increase of propellant mass brought on-board and an increase of propellant mass-flow rate in the lines, both of which might not be possible due to other requirements

- The O/F ratio of the rocket engine could be reduced to achieve a slight decrease in performance, which would, in turn, result in lower temperatures within the combustion chamber. By adjusting the fuel-to-oxidizer ratio to a less aggressive mixture, the combustion process would produce less heat. This reduction in thermal intensity would help in maintaining the temperature within safer limits for the materials used in the combustion chamber. The downside of this possibility is a decrease in performances and efficiencies of the engine as the mixture burning would be either fuel-rich or oxidizer-rich.

- Since only a section around the throat is subject to high stress due to the high temperature gradient, this part could be produced or coated with a different material, with a lower conductivity, which could grant higher thermal performances and a greater maximum operating temperature in the critical section. The downside of this possibility is an increase in costs of production for the engine and an increase in the time dedicated feasibility studies and simulations to verify that the material added is suitable for use with Inconel 718

In conclusion, there are several methods to improve the engine's thermal performances, allowing Inconel 718 to be used as a chamber material.
The choice of which to implement depends on the specific mission at hand and its requirements, as not all options may be used in the same mission.

References

[1] R. Piascik I. Raju, J. Kramer-White. White Paper on Factors of Safety. October 2012. https://ntrs.nasa.gov/api/citations/20090028512/downloads/20090028512.pdf.

[2] J.S. Whittick R.F. Muraca. *Materials Data Handbook: Inconel Alloy 718*. Western Applied Reaserch and Development, Inc., April 1972. https://ntrs.nasa.gov/api/citations/19720022810/downloads/19720022810.pdf.