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Experimental Tests Results of Transpiration Cooling Subscale Injector Head in the frame of LYRA Program

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Abstract

In the frame of the LYRA Program, funded by the Italian Space Agency, the LM-10-MIRA engine has been successfully tested. The engine has a vacuum thrust of 10-tons and has been developed by a joint Avio-KBKhA propulsion team in the frame of a dedicated ASI-Roscosmos inter-agencies agreement.
After the experimental test campaign, further improvement for flight application have been identified, including the improvement of the efficiency and new technologies for of injector head manufacturing. The 'lesson learned' allowed ASI to promote further activities in collaboration with Avio. In particular, two main activities have been developed, the first one aimed to reduce the methane line pressure drop and the second one related to the optimization of the methane/oxygen interfaces. The results have been implemented on a subscale version of the injector head. The present work describes the improvements obtained and confirmed by the results of the subscale experimental test campaign.

1. Introduction

The Italian Space Agency (ASI) and Avio have been collaborating in the framework of the LYRA Program in order to acquire a technical background in design and development of cryogenic liquid rocket engines. In particular, a dedicated ASI-Roscosmos inter-agencies agreement lead to the development of the LOX/LNG expander cycle LRE LM-10 MIRA, carried out by a joint effort of Avio and KBKhA [1]. After a successful test campaign, some improvements, to be implemented, have been identified in the design of the Injector Head. Therefore, ASI promoted further development activities in collaboration with Avio.
In particular, two activities have been defined:

- To reduce Pressure Losses in the Methane feed line;
- To optimize the design to exclude any potential leak between Methane and Oxygen dome in a faster and more robust way.

The main objectives of the collaboration are the design, manufacturing and test of a subscale injector head that implements the improvements identified from the LM-10 MIRA campaign.

2. Pressure Loss Reduction in Methane Line

The injector head has the scope to inject the propellants within the combustion chamber in such a way they are properly atomized and mixed for the combustion reaction. The injector head developed by Avio for the LM-10 MIRA liquid rocket engines is constituted by 60 shear coaxial injectors, where the liquid oxygen is injected through the inner post and the gaseous methane from the outer sleeve. Before being injected, the methane flows through narrow passage, the cooling gap, to protect the head from the high temperatures of the combustion chamber. Both the injection and the cooling system are critical in term of pressure drop, therefore the activities carried out for the methane line pressure losses reduction focused on the modification of the sleeve geometry of the injector and the modification of the cooling system.

2.1 Injector Design

As the experimental data suggested that the methane injector was a critical component in the overall pressure loss in the methane line, efforts were made to improve the efficiency of the component. The optimization of the design exploited extensively Computational Fluid Dynamics (CFD) to study the flow field inside the methane injector. The numerical models had been selected matching experimental data with simulation results, and the typical value of

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Additive Layer Manufacturing (ALM) roughness has been set for the internal injector wall boundaries. A CFD simulation campaign has been carried out leading to the selection of an optimized injector configuration in terms of pressure drop minimization.
The injector features mainly affected by the review are:

- The position of the holes between the manifold and the sleeve, moved upwards to the sleeve upper wall;
- The sleeve geometry, changed from a constant cross-section with a narrowing at the end to a gradual cross-section reduction along the sleeve length.

The comparison between the two geometries are shown in figure 1, with the modifications highlighted.

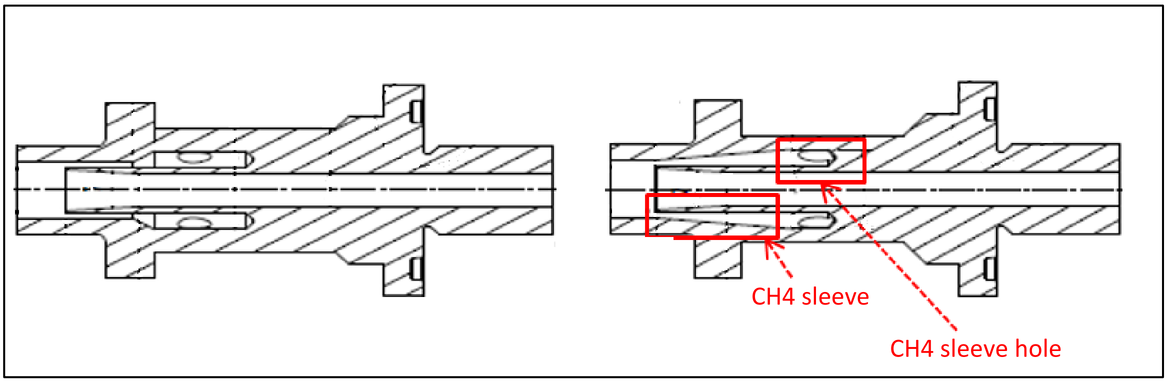

Figure 1: Cut of the injectors. Old configuration on the left, new configuration on the right.

While the outcome of the activity is the design of a new subscale injector head, the simulations have been performed for both sub scale (SS) and full scale (FS) operative conditions. The performance parameters predicted are listed in table 1. The new geometry successfully achieves a pressure drop reduction, decreasing of 16% in FS with respect to the old geometry.

	Full Scale	
	Old Geometry	New Geometry
Δp_{CH4}	-	**- 16 %**
A_{eff_CH4}	-	**+ 8 %**

Table 1: CFD simulation results for the methane injector

The selected injectors have been manufactured using Additive Layer Manufacturing (ALM) technology, which is being researched by Avio for the development of new injector heads [2].
A cold flow test campaign has been carried out to characterize the pressure drop in the new injector configuration, to compare it with the CFD results and with the older geometry. The finished component can be realized without the need of further machining, reducing production time and cost, taking into account a higher surface roughness in the injector recess. To study the effect of this technology on the performance, two version of the injector have been manufactured and tested, one with a machined recess and one with a non-machined recess, for a total of 20 injectors.
Methane has been simulated with nitrogen, and liquid oxygen with liquid water. A total of 60 tests have been performed, changing the mass flow rate in the injector, testing the old configuration against the new configuration, and the machined recess against the non-machined recess. The test matrix is given in table 2.
The campaign confirmed that the oxygen line pressure drop does not change between the two injector configuration, as well as for a machined and non-machined recess, since this part of the component did not change during the design review.
Methane pressure drop, on the other hand, showed the expected reduction with the new injector geometry (see Figure 2), compliant with the reduction predicted by CFD results. The surface finishing also influences the pressure drop, which is lower for the machined version.
After these consideration, proved by experimental data, the machined new injector configuration has been selected for the manufacturing of the new subscale injector head. Figure 3 is a picture of the injectors after ALM fusion.

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			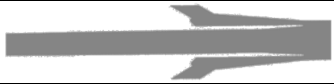	
#Test	Machined	Not Machined	Machined	Not Machined
N2	5	5	5	5
H20	5	5	5	5
N2/H2O	5	5	5	5

Table 2: Test matrix of the injectors cold flow test campaign

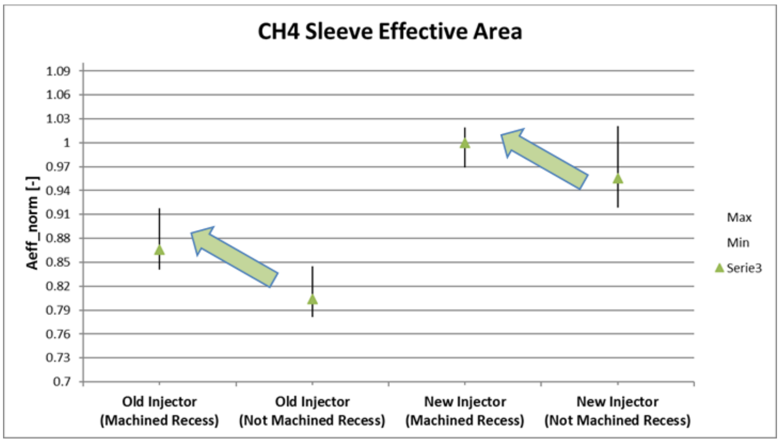

Figure 2: CH4 sleeve effective area detected for the new and old configuration

Figure 3: Manufacturing of the injectors after ALM process

2.2 Cooling System Design

The interface between the injector head and the combustion chamber is a copper-alloy thin plate called firing plate. The heat protection is achieved through forced convection: before being injected, the methane flows through a narrow passage called cooling gap, taking heat away from the firing plate. The process is effective if the velocity of the flow is high, which is achieved in exchange for a high pressure drop in the gap.

To reduce the pressure losses in the methane line, an alternative solution has been identified through implementation of transpiration cooling. With this cooling technique, a small quantity of methane flows directly into the combustion chamber through a series of holes drilled on the firing plate. The effect is not only efficient from the heat reduction point of view, but allows for a slower methane flow in the cooling gap, which in turns translates to a smaller pressure drop. The present design does not include the cooling gap anymore, except for a very small portion located in correspondence of the very external part of the firing plate.

Again, CFD simulations have been exploited to investigate the influence of the number, diameter and distribution of the holes on the plate, as well as the mass flow rate percentage drawn from the cooling gap, on the pressure drop in the cooling gap and the effect on the firing plate temperature. The temperature distribution over the firing plate obtained from CFD simulations is given in Figure 4, as well as the properties of the transpiration cooling holes. A drawing and a picture of the manufactured perforated copper alloy firing plate are shown in figure 5.

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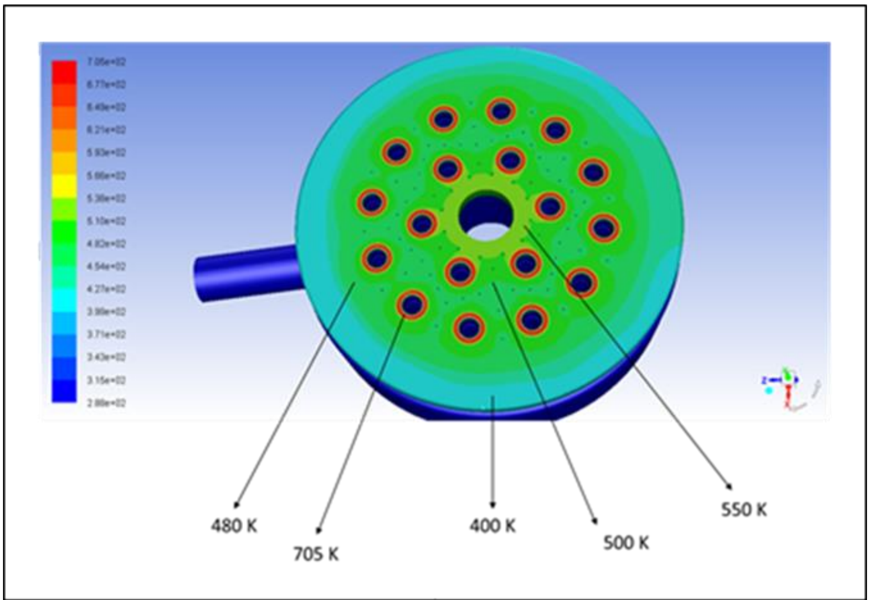

Drawn Mass Flow Rate wrt the Total	10 %

Figure 4: Main features of the firing plate.

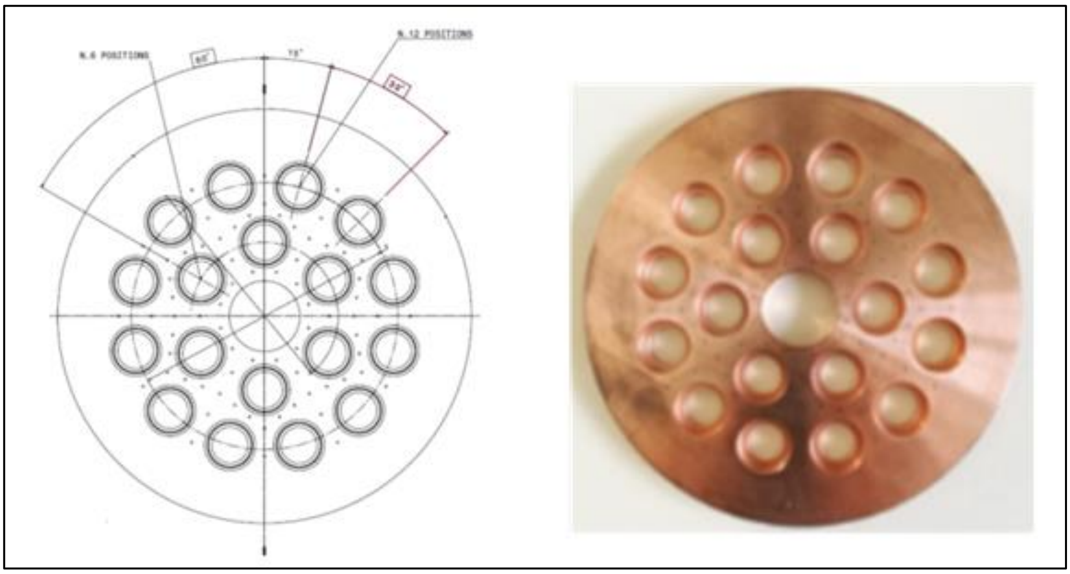

Figure 5: Drawing and manufactured Firing plate configuration

3. An Innovative Injector Head Configuration

The injector head developed for LM-10 MIRA was characterized by a large number of parts, jointed each other through welding and brazing. These processes require a dedicated validation campaign to achieve the strength and quality required for space applications. The special acceptance and verification activities required for the brazing joint between the fuel and the oxidizer interfaces are time expensive, therefore an optimized injector head should take into account this critical part of the development process, to achieve a design which is robust and faster to manufacture.
Additive Layer Manufacturing has been exploited to achieve a robust design able to eliminate the brazing joint between the methane and oxygen lines, requiring a less time expensive validation and acceptance campaign. Thanks to this innovative manufacturing technology, the fuel and oxidizer lines can be physically separated (two bodies manufactured through two jobs), and the welded joints can be placed in non-critical points of the head assembly. The technique has

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been already successfully used by the company to realize injector heads [2], and the material chosen for manufacturing is Inconel 718.
The other main component of the assembly is the firing plate, which is attached to one of the two ALM bodies through nuts screwed on the injector sleeves.

3.1 Design Assessment

The design of the new injector head configuration has been supported by Finite Element Method (FEM) analysis, to assess the structural and thermal resistance of the component, and CFD, to verify the pressure drop in the domes and manifolds.
All the values predicted by FEM lie within the safety margins required from the design. The values obtained are listed in table 3.

Maximum Von Mises Stress	663 [MPa]
Equivalent Von Mises Strain	2.16%
Low Cycle Fatigue Estimation	23 cycles

Table 3: FEM results for the new injector head.

The effect of the new methane line design on the pressure losses has been investigated with CFD. Non reacting steady simulation of the propellant distribution along the methane line in its relative dome have been carried out. The aim of the analysis was the verification of propellant distribution uniformity and its relative pressure drop. The results suggest that the new geometry developed is more efficient in terms of pressure drop, which decreasing when compared with the older subscale configuration. A qualitative map of the pressure distribution in the volumes is given in figure 6. The main pressure drops are measured between the manifold and the dome, when the methane flows inside the cooling gap, and inside the injector.
Moreover, coupled methane – oxygen non-reacting simulations have been performed. The aim was the verification of the distribution uniformity of the mass flow rate flowing through the injectors, and the computation of the pressure drops detected in each line. A mass flow rate contour map at the injection discharge section is given in figure 7. The red colored contour represents the liquid oxygen post, while the blue part is the methane sleeve. The mixture ratio of the propellants is about 3.4, confirming the goodness of flow distributions among the injectors.

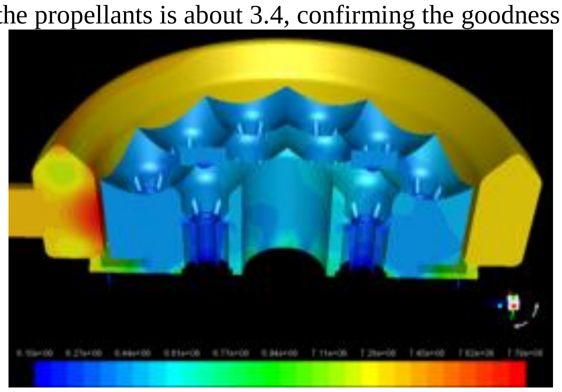

Figure 6: Pressure contours of methane line.

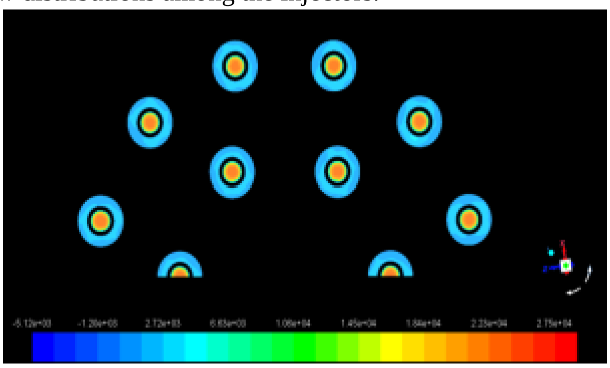

Figure 7: Mass flow rate contours at injector discharge.

3.2 Manufacturing

The two parts ALM injector head manufacturing have been carried out following the steps described in the flowchart of figure 9. This manufacturing process has been refined with the experience gained over the years by Avio, to achieve the quality required for a firing test campaign.
The first step is the ALM manufacturing of the raw components, followed by the Hot Isostatic Pressing process, which reduces the porosity of the parts. The components are then machined and jointed together with welding.
The injector head then undergoes two heat treatments, namely annealing and ageing, to increase the material strength. The properties of Inconel 718 measured with tensile tests after each manufacturing step and heat treatment are given in table 4.
After a final machining process, the injector head quality is verified in order to accept it for testing. The details and advantages of the manufacturing process are described in detail in [2].

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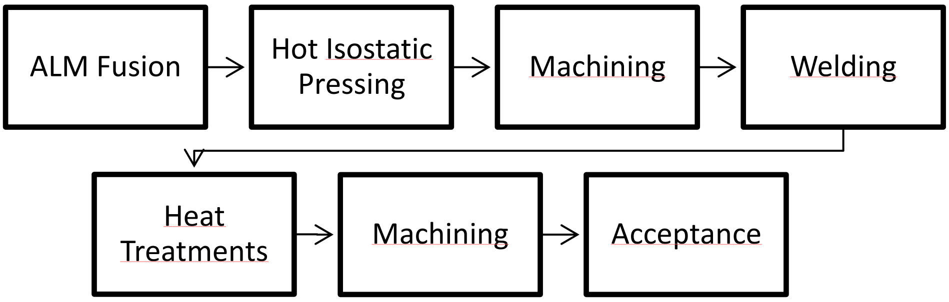

Figure 9: Manufacturing process flowchart.

	AMST Standard [3]	PBF			Comparison
	+ Annealing + Ageing	Raw After ALM	+ Annealing	+ Annealing + Ageing	+ Annealing + Ageing
σ_y [MPa]	≥ 1123	619.7	862.7	1082.7 ± 34.8	-4.6%
σ_u [MPa]	≥ 1348	970.3	1151.0	1338.7 ± 11.4	-5.0%
ε [%]	≥ 8.0	29.5	20.8	12.5 ± 0.0	+25.0%

Table 4: Tensile test results of manufactured components

The semi-finished additive layer manufactured components are shown in figure 10 after the first machining process. Two pictures of the injector head after the welding process and heat treatments are shown in figure 11. After the final machining and acceptance test, the firing plate is attached to the head with the nuts, and the assembly is test-ready.

Figure 10: Manufacturing of the injector head components.

Figure 11: Welded injector head.

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4. Experimental Test Campaign

After undergoing a series of leak and proof tests for acceptance, cold flow tests using liquid water and nitrogen have been exploited to characterize the pressure drop in the LOX and CH4 lines prior to the firing tests.
Figure 12 shows the injector head mounted on the test bench of Avio FAST2 test facility, integrated with the modules used to characterize the pressure drop in the methane line with nitrogen.

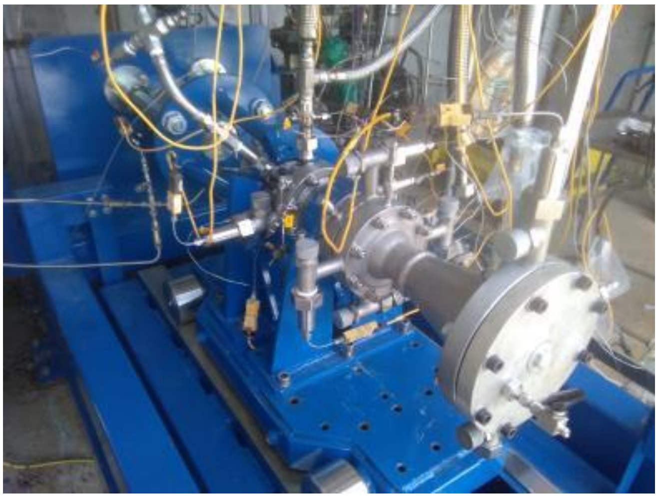

Figure 12: Injector head configured for nitrogen cold flow tests.

Figure 13 shows the setup used to measure each injector mixture ratio and pressure drop to verify if the distribution is homogeneous for all the injectors on the plate. The test confirmed the mixture ratio uniformity between the injectors, as predicted by the CFD results and validating the quality of the manufactured components.

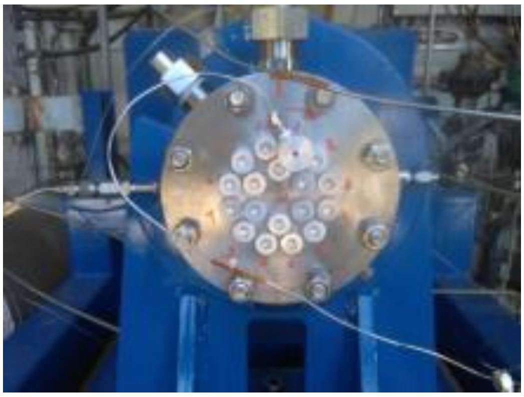

Figure 13: Injector head configured for mixture ratio distribution evaluation.

The firing test campaign consisted of five tests, all successful, comprising two ignition tests and three tests of about 17 seconds length. The test matrix with an average of the experimental measurements for each test is given in table 5.

Test #	Mean Time Range	Pcc	MR	Steady State Duration
	[s]	[barg]	[-]	[s]
01	8 ÷ 9	3.4	NA	N.A.
02	8 ÷ 9	3.1	NA	N.A.
03	15 ÷ 17	49.3	3.81	10
04	17 ÷ 18.5	56.4	3.63	10
05	15 ÷ 17	56.5	3.45	10

Table 5: Test results of the new injector head campaign.

The pressure values measured for the long duration tests three, four and five are given in figures 15, 16 and 17, respectively. The combustion has been smooth and stable for the entire burn time. The new design of the injectors guaranteed a pressure drop of more than 10% from the methane dome to the combustion chamber, which is a requirement found in literature to avoid chugging instabilities in the combustion process.
Figure 19 is a picture of a firing test of the thrust chamber assembly at Avio FAST2 facility.
Since the first scope of the research activity was the reduction of the pressure losses in the methane line, the experimental results confirmed that the requirement has been satisfied. When compared with the older sub scale, the new subscale injector head demonstrated an effective area increase of the methane line of 20%, leading to a decrease in the overall pressure drop of 30%. This important result confirms the positive impact of the implementation of such configuration on an engine fullscale concept, allowing higher system performance.

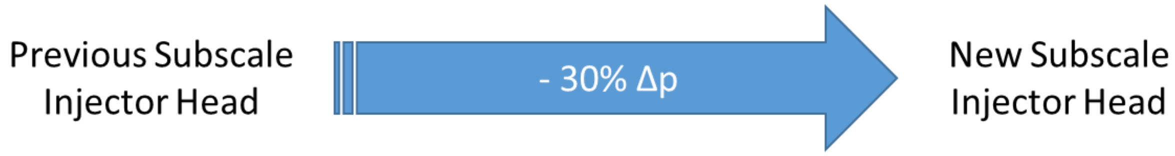

Figure 14: Methane line pressure losses reduction.

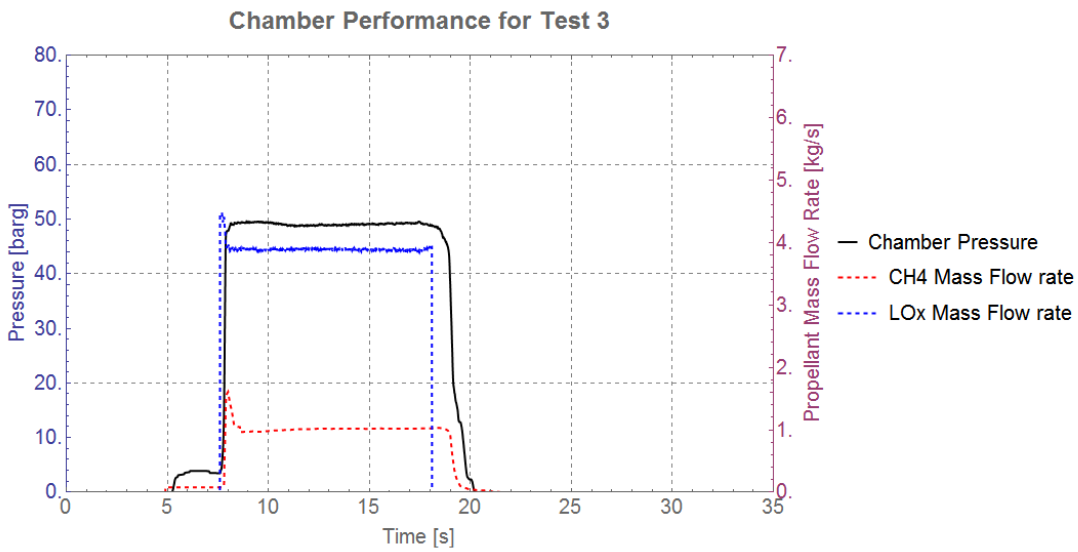

Figure 15: Test 3 Pressure in methane dome and combustion chamber.

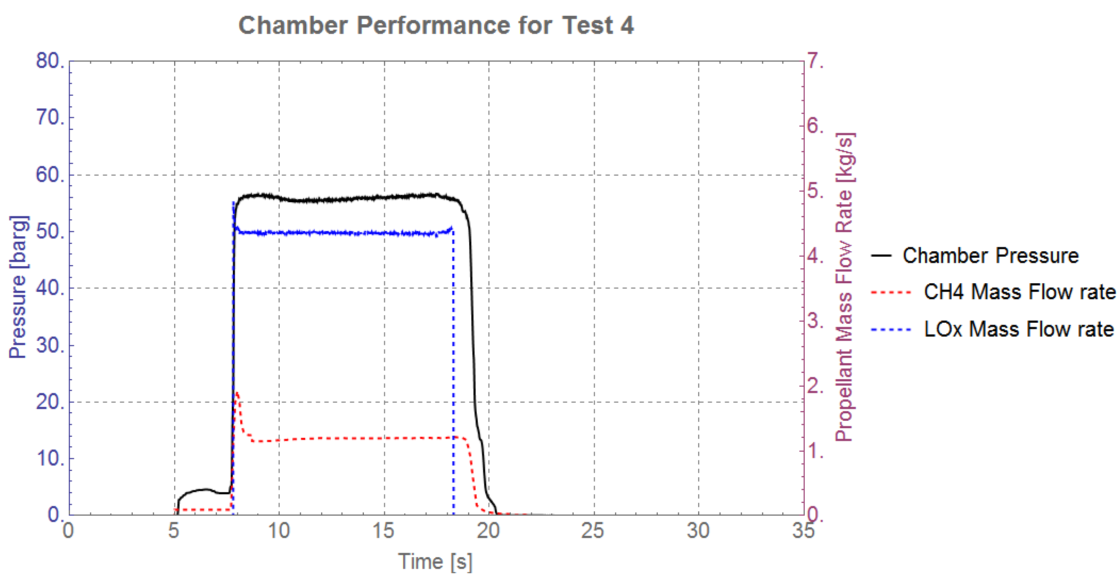

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Figure 16: Test 4 Pressure in methane dome and combustion chamber.

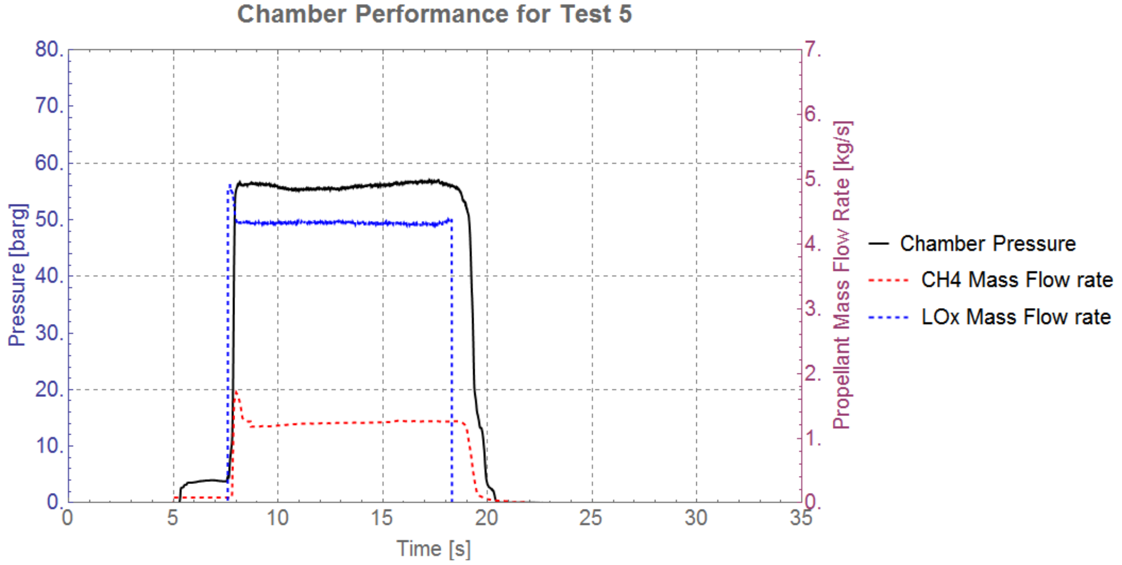

Figure 17: Test 5 Pressure in methane dome and combustion chamber.

Figure 18: Firing test of the new injector head

5. Conclusions

From the experience acquired during the LM-10 MIRA design and development, two improvements in the design of the injector head of the engine have been identified, namely the high pressure drop in the methane line and the existence of brazing joints at the interface between oxygen and methane lines that needs a long verification process to make it robust and validated.
The Italian Space Agency, in collaboration with Avio, promoted the realization of a new subscale injector head taking into account the outcomes of the previous test campaign. The scope of the proposed design activity was the creation of an innovative injector head that could incorporate the improvements detected from the previous test campaign, to achieve a design more efficient and robust.
To reduce the pressure drop in the methane line, the injectors have been re-designed, and a new cooling system has been implemented.
Exploiting the capability of Additive Layer Manufacturing, the joints that required a special acceptance and validation campaign have been eliminated, allowing for an innovative design which is more efficient in terms of manufacturing time, maintaining the high mechanical robustness required for space applications.
Finally, the experimental campaign confirmed that the new injector head succeeded in reducing the pressure losses in the methane line (30% less than previous configuration), achieving efficient and stable combustion.

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References

[1] A.A.Gurtovoi, V.P. Kosmacheva, V.S. Rachuk, D. Scarpino, S. Carapellese, M. Biagioni, A. De Lillis, E. D'Aversa, "Development of Thrust Chamber Assembly for LOX-LNG Expander Cycle Liquid Propellant Rocket Engine", in *5th European Conference of Aeronautics and Space Science, EUCASS 2013*, Munich, Germany, 1-5 July 2013.

[2] Terracciano, S. Carapellese, G. Bianchi, D. Liuzzi, M. Rudnykh, D. Drigo, F. Del Brusco, "Additive Layer Manufacturing Technology in Avio Injector Head Design", *7th European Conference of Aeronautics and Space Science, EUCASS 2017*, Milan, Italy, 3-6 July 2017.

[3] AMS 5596 – Nickel Alloy. Aerospace material specification for Inconel718.