DOI: 10.13009/EUCASS2017-360

The HYPROB LOX-LCH4 Demonstrator: status of the manufacturing and experimental activities

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Abstract

The activities, described in the present paper, have been conducted in the framework of the HYPROB Program, carried out by the Italian Aerospace Research Centre (CIRA) under contract by the Italian Ministry of Research (MIUR). The Program has the main objective to enable and improve National system and technology capabilities in the field of liquid rocket engines (LRE) for future Space Propulsion Systems and applications, with specific regard to LOX/LCH4 technology. Moreover, the Program is in coherence with the long-term vision, provided by the Italian Space Agency (ASI) on Space Propulsion.

According to the last implementation of the program, a system line, named "HYPROB-DIMOSTRATORI", has been included: it aims at designing, manufacturing and testing LRE demonstrators, LRE and HRE breadboards.

The main objective of this line is to design, manufacture and test a regeneratively cooled LOX/LCH4 demonstrator, a pressure-fed thrust chamber assembly (TCA), aiming at validating critical design and technology features and then assessing the technology readiness level of potential solutions for future engines.
The present paper illustrates the advancements in the development of the demonstrator. In particular, the cold and hot testing activities for the design validation of the injector head will be presented. Moreover, technological and manufacturing issues for the combustion chamber manufacturing will be exposed by giving details about the experimental activities recently performed.

1. Introduction

Space propulsion systems, based on liquid or hybrid hydrocarbons, represent very promising technologies to be adopted for future launchers and space transportation systems. In this view, methane is considered one of the most interesting solutions as propellant for liquid rocket engines (LRE), coupled with oxygen, because of its good performances in terms of high vacuum specific impulse and high thrust-to-weight ratio performances. These features combine with other advantages like relative easy storability, low toxicity, availability and production cost, as compared to hydrogen or kerosene and mono-propellant systems [1],[2].
In a long term perspective, such a propulsion technology may encompass a wide range of propulsion systems, from launcher main stages up to small thrusters. Given these motivations, some important programmes have been recently launched in Europe, like LYRA Project, led by ASI-AVIO and KbKha [3], in Japan (with the impulse of JAXA and IHI [4]) and USA (SpaceX's Raptor Project [5]), for example. Moreover, the Italian Ministry of Research (MIUR) launched the HYPROB Program, managed by the Italian Aerospace Research Centre, with the main objective to enable and improve the national system and technology capabilities on liquid rocket engines (LRE) for future space propulsion systems, with specific regard to LOX/LCH4 technology, as described by Salvatore et al. [6]. In this framework, an integrated mid/long-term R&D plan has been defined, in synergy with MIUR initiatives and ASI programs, preparing national players for the future technical challenges [1].
One of the most relevant implementations of the HYPROB Program is named HYPROB "Dimostratori" (Demonstrators): it aims at designing, manufacturing and testing a LRE demonstrator and a HRE one. These engines will be tested in relevant facilities (CIRA I2PS and AVIO-ASI FAST2), together with the intermediate test articles, with the main scope of validating critical design and technology features. The line "Dimostratori" is divided essentially in four WPs:

1. Technologies and DEMO development;
2. LOX/CH4 breadboards to support the DEMO development;
3. AM technologies applied to LOX/LCH4 propulsion;
4. Small-scale HRE studies.

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In the present paper, the activities linked to the development of the HYPROB LO_x/LCH_4 demonstrator (mainly to point 1 and 2) are described. The final goal is to assess technology readiness level of potential solutions for future expander engines.
In this framework, CIRA settled an integrated project team where the best available competencies were involved at the maximum extents, from both industrial and scientific sides. In fact, AVIO, CRAS (University of Rome – La Sapienza), Purdue University, CSM and different Italian SMEs (VLT srt, Marotta srl, CECOM srl) have been granted of contracts to support the activities related to the liquid demonstrator development. In conclusion, the final configuration of the demonstrator (DEMO) has successfully passed the DDR (Detailed Design Review) milestone and currently is in the manufacturing phase, where technological issues are going to be solved, together with the verification analyses after the intermediate breadboard testing results.

2. Project description and advancements

As indicated in the introduction section, the project line, devoted to the development of LO_x/LCH_4 technology, aims at designing, manufacturing and testing a TCA regenerative cooled ground demonstrator, representative of a 30 kN of thrust in flight conditions.
The study logic, leading the HYPROB LO_x/LCH_4 demonstrator development, is presented by Figure 1 and is based on the following drivers:

- to design suitable intermediate breadboards to address the most critical design solutions, such as injection and cooling;
- to make use of existing know-how and design solutions for critical items.

That approach is based on an incremental strategy and foresees to proceed step by step, from the understanding of the basic physical processes, i.e. combustion and heat transfer, and then to validate design and analysis methodologies, designing and manufacturing simpler breadboards. In this view, the design and tests of breadboards represent important tools for validation of the analytical models, reducing the risks associated with the use of those models in engine design. In fact, establishing the credibility of design and simulation tools at subscale level, where highly realiable measurements can be performed, represents a critical step in gaining acceptance for the use of these tools and realizing the benefits of reduced design cycle times and costs.

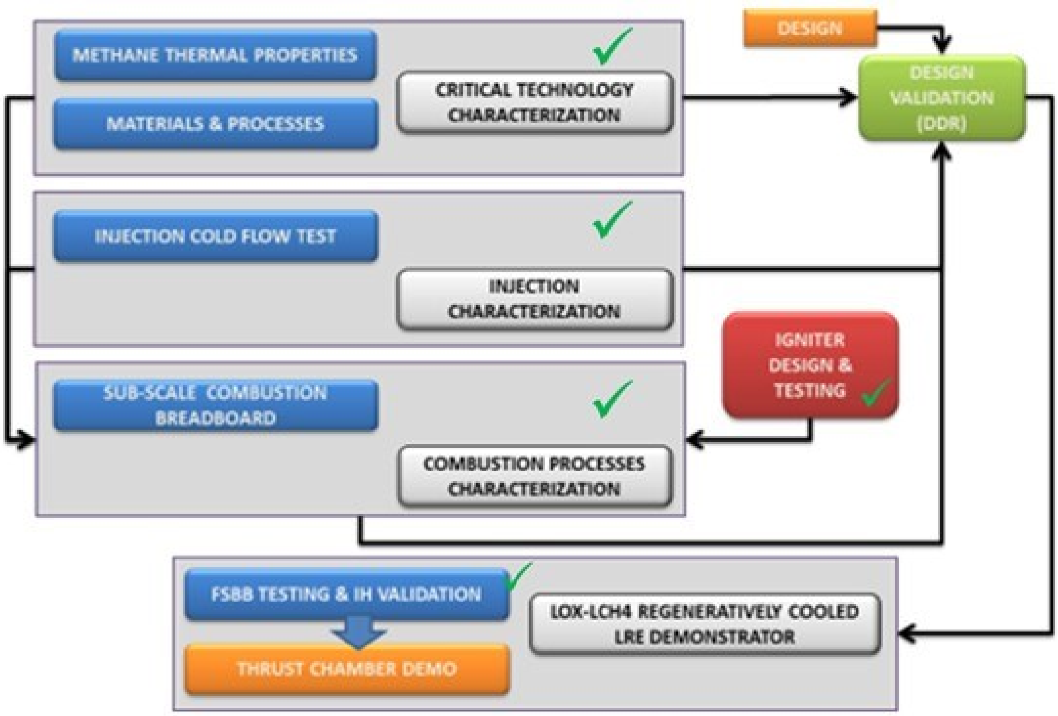

Figure 1 - Study Llogic of the LOx/LCH4 technology demonstrator

Thus, several intermediate breadboards have been manufactured and tested, before realizing the final demonstrator.

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Table 1 - Outcomes of "Demontrators" project line included in the development activities for LO_X/LCH_4 DEMO

Intermediate breadboards:	
	Methane Thermal Properties Breadboard (MTP) *Subscale single-injector breadboards (SSBB)* *Full-scale multi-injector breadboard for DEMO injection head validation (FSBB)*
Final product:	
	30 kN LOx-LCH4 demonstrator (DEMO)

So far, both MTP breadboard (Methane Thermal Properties Breadboard) and SSBB-HS (Subscale Breadboard - Heat Sink Version) have been already manufactured and successfully tested, along as critical subsystems, such as injectors and igniter. The former bread-board enabled the in-depth study about the thermal and fluid-dynamic behaviour of methane in supercritical conditions in LRE channel-like environment and resulted important to set-up the numerical approach to be adopted also for the final DEMO. The latter breadboard, mounting the injector to be adopted for the final test article, allowed analyses of combustion processes for chamber pressure values greater than 30 bar and tested the stability of the injector.
A more complex version, named SSBB-CC, based on a calorimetric configuration, has been already designed in order to improve the knowledge on heat release from combustion gases to chamber walls, by using a cooling/measurement system, composed by several cooled discs. Further details on these breadboards are available in [7][8].
In the following paragraphs, the objectives and main results of the performed testing activities are reported and discussed.
Figure 2 shows the current time-line and the development plan of the project. The Detailed Design Review (DDR) has been undertaken last July 2014. Year 2015 has been devoted to BBs testing review/rebuilding, preliminary manufacturing activities and technology consolidation. Delivery and test readiness of the demonstrator is scheduled by 2Q-2018. Next figure wraps up the current status of the project.

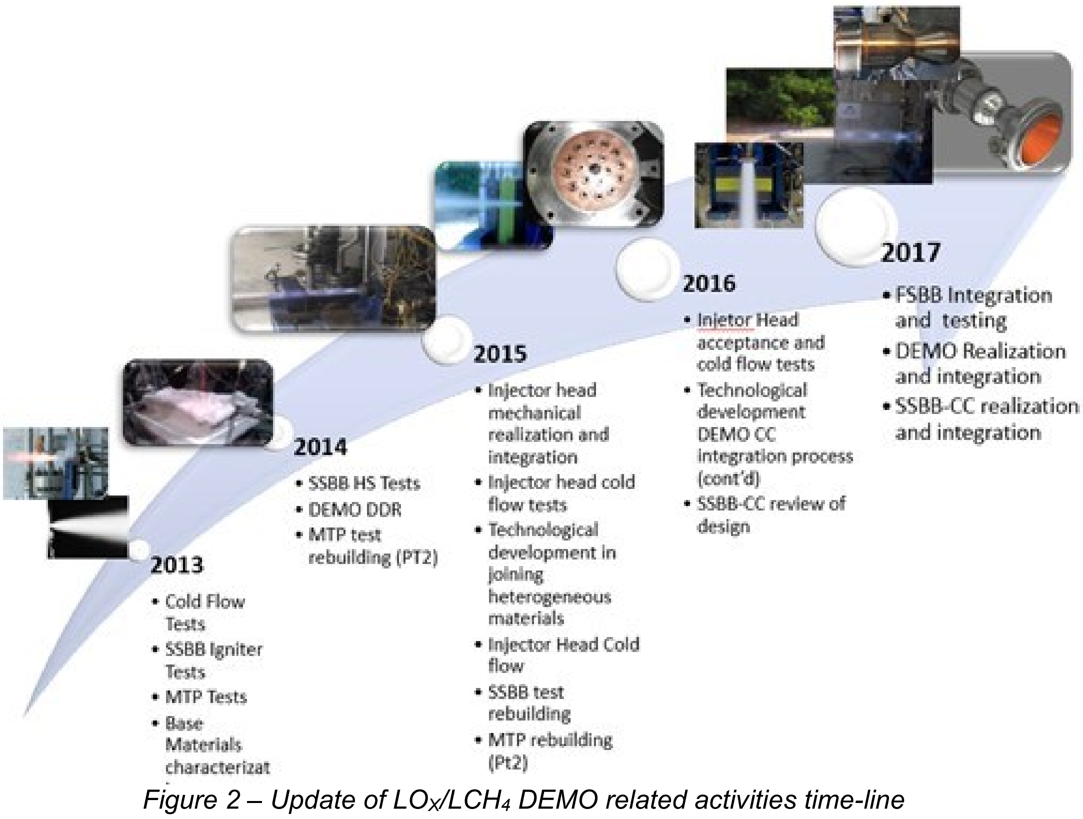

Figure 2 – Update of LO_X/LCH_4 DEMO related activities time-line

The demonstrator (DEMO) is a regeneratively cooled pressure-fed engine of 30 kN thrust, technologically representative of the cooling jacket of an expander engine. The main elements, reported in Figure 3, are the igniter (on the top), the injector head and the combustion chamber with its manifolds.

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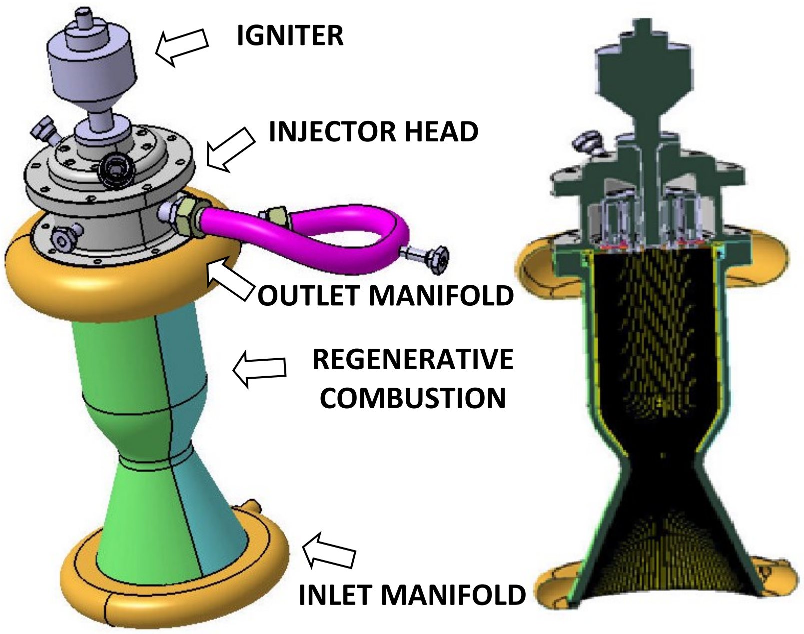

Figure 3 - Assembly view of the demonstrator with the main components

A counter-flow architecture has been considered for the chamber cooling system, where the coolant (LCH_4) is injected liquid into the fuel inlet manifold and enters the cooling jacket counter flow with respect to the combustion gases (Figure 4). The thermal load, coming from the combustion gases, warms up the propellant and, after being heated, methane is injected directly in the fuel dome as a supercritical gas and then in the chamber by the injectors where mixes, atomizes and burns with liquid oxygen.

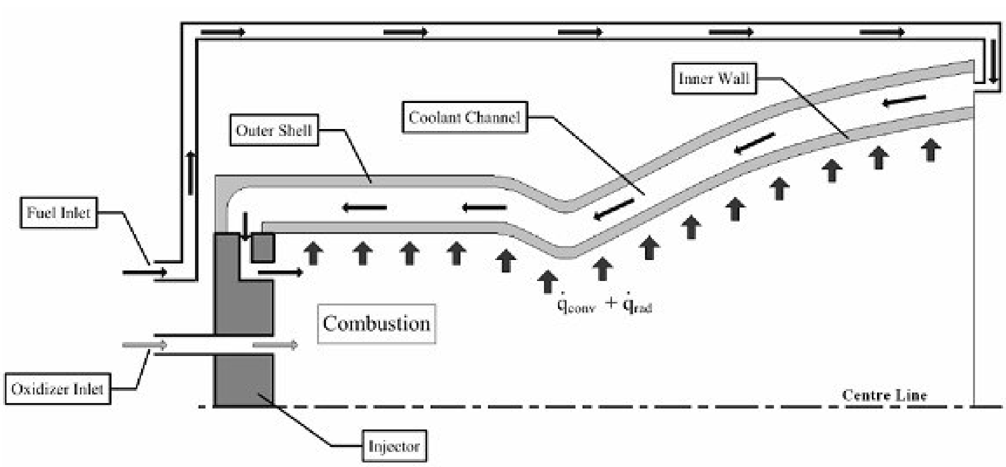

Figure 4 - Counter-flow architecture of the cooling jacket

The main engine parameters are shown in Table 2.

Table 2 - HYPROB Demonstrator main parameters

O/F	3.4	Reaction eff.	0.98
T_{CC}	3543 K	n. injectors	18
P_{CC}	5.5 MPa	n. channels	96
Isp	286 s		

The baseline solution foresees that the channels are defined by a liner, made of a copper alloy, in the bottom part, and by a close-out, made up by Inconel, in the upper part. The combustion chamber has a cylindrical shape whose radius is 0.06 m. The nozzle throat radius is 0.03 m and the expansion ratio is 9.

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The cooling jacket arrangement has been designed by means of an in-house 1-D code with 2-D corrections, considering a constant number of channels (optimized to 96) and a constant value for the channel rib width, *w*. Moreover, a variable value of the rib height, *h*, has been adopted in order to optimize the cooling performances, according to the sections, highlighted by *Figure 5*, such as in the nozzle (section NZ), throat (section CT) and cylindrical zone (section CC). A starting configuration has been selected and verified by means of by three-dimensional CFD analyses, considering a single channel with rough walls. However, taking into account the maximum allowable temperature from a thermo-structural point of view (< 750 K), the pressure conditions required by the sub-systems placed downstream (P_{out} of about 10.0 MPa) and the manufacturing technological limits, other solutions were investigated in order to accomplish a trade-off analysis.

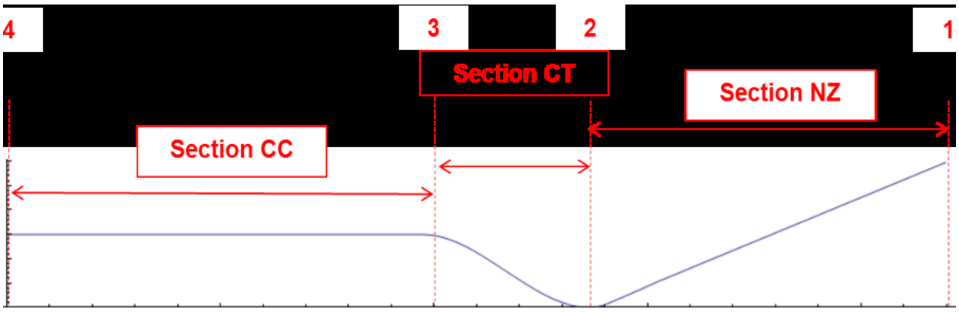

Figure 5 - Sketch of the model including the chamber, convergent-throat and throat-nozzle sections

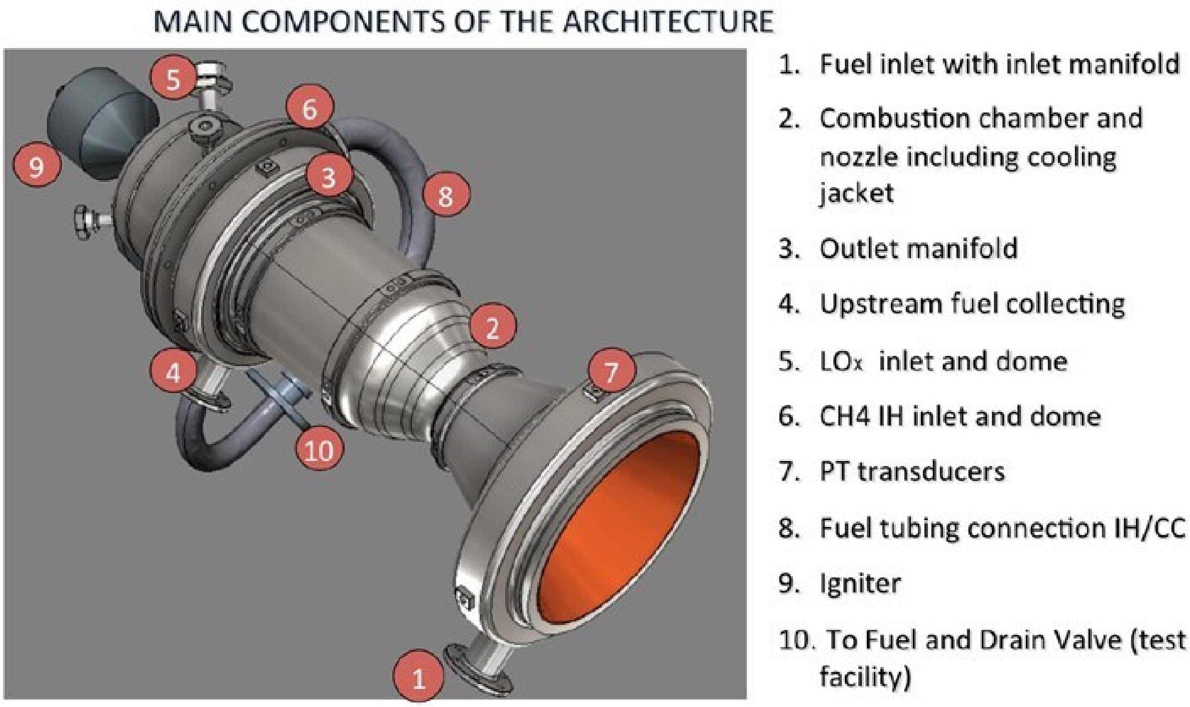

Figure 6 – HYPROB LO_X/LCH_4Demonstrator assembly

Verifications, after the SSBB and MTP testing and model validation phase, have been repeated on DEMO DDR configuration. In Figure 7 cooling jacket performance results in terms of bulk temperature and wall temperature from 3D CFD coupled with solid are reported. No criticalities are envisaged and such configuration is currently under manufacturing phase.

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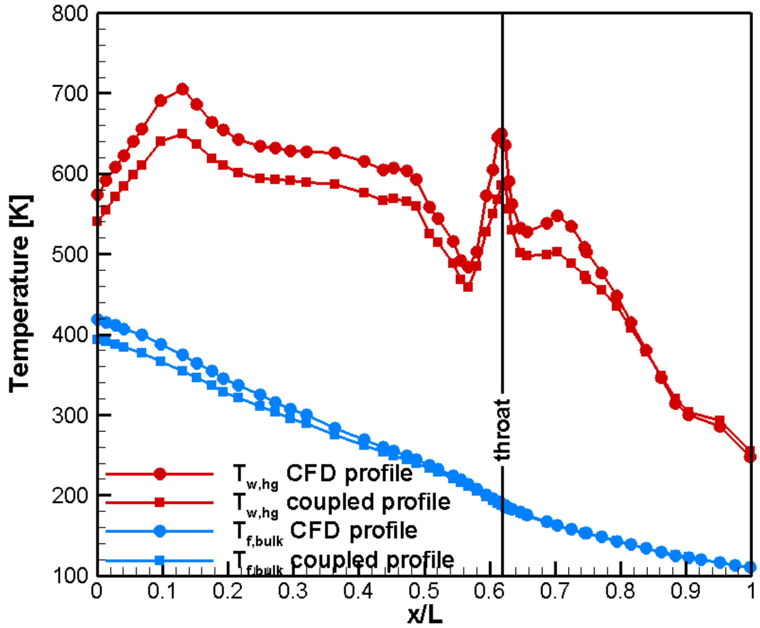

Figure 7 - Cooling Jacket temperature axial profiles: wall temperature profile of the liner (red) and fluid bulk temperature (blue)

3. Injector Head Manufacturing and testing

The injection head has been manufactured in all of its parts and each injector has been verified by means of cold flow tests in order to select the best ones to be assembled from a lot of parts. The component passed the integration phase acceptance, including the liquid penetrant inspection of welding, the final assembly testing and the final proof test on assembly at about 90 bar.
After this phase a cold flow test activities have been performed in AVIO FAST2 facility, located in Colleferro. The objective of the activities was to understand hydraulic characteristics of the injector head from both oxygen and methane side and the behaviour of the jets using water and N_2 as simulants.
Different tests have been performed varying inlet pressure conditions. Results are in line with the design parameters.

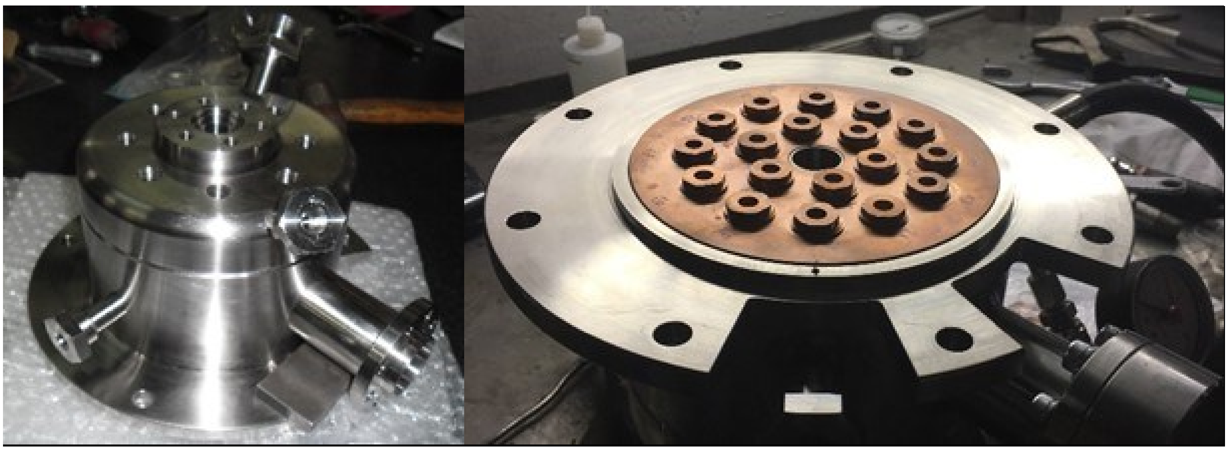

Figure 8 - DEMO Injector head after assembly phase and during firing plate leak tests

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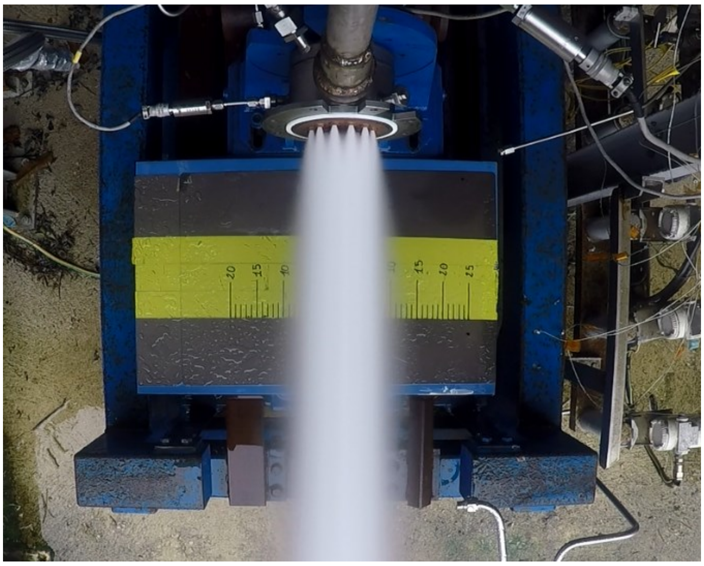

Figure 9 - Cold flow test performed in FAST2 AVIO facility

4. Combustion chamber manufacturing

4.1 Activities on brazing process development

A central point for the successful result of the program is the development of the technological line. One of the major concerns for combustion chamber manufacturing is linked to the joining of the internal liner with the external close-out. Significant efforts have been made by CIRA and partners (AVIO, CSM) in order to validate brazing technique. An activity, related to planar samples, have been developed in cooperation with CSM (*Centro Sviluppo Materiali*). The main results are reported in the next table and are compatible with DEMO design requirements.

Figure 10 - CSM Brazed samples

Table 3 - Results on CSM samples

WIDTH [mm]	AREA [mm^2]	BREAKING FORCE [N]	UTS [MPa]
13.89	67.23	11300.467	169.4
13.85	81.72	13235.981	162.0

On the other side, AVIO developed a “dummy chamber” to test the brazing procedure on a real combustion chamber geometry. This chamber represents the first attempt into manufacturing a brazed one in Italy. However, some samples have been produced and tested: proof test results on the cylindrical zone of the chamber showed a quite good behaviour of the joint. Finally, the preliminary tests on the chamber cooling system showed a good behaviour up to 76 bar of pressure. The combustion chamber, designed to be cooled by water, after passing the proof and cold flow performance tests has been assembled with DEMO Injection head in order to perform IH design validation firing test (FSBB TCA).

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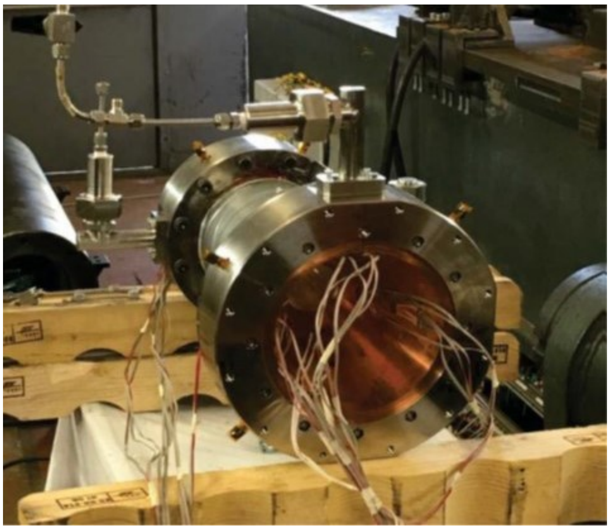

Figure 11 - Assembly of the proto-D (AVIO) chamber under proof test

A figure of the hardware during firing tests has been reported hereinafter Figure 12, the preliminary campaign showed a good behaviour of the assembly FSBB and combustion was stable and in line with the expected results.

Figure 12 – An Image from the FSBB test campaign.

4.2 Electroplating activities

Due to the problems, encountered in the development of the brazing process, another technique has been chosen and set up for DEMO combustion chamber manufacturing with the support of CECOM srl, an Italian SME, that mainly works in the field of nuclear fusion technologies and applications. The advantages of this process consist into:

- greater easiness of process repeatability than brazing one;
- the absence of thermal degradation of the base materials, composing the jacket, because electro plating is a cold process;
- lower weight of the hardware.

The basic idea behind this process is to manufacture the internal liner by milling the channels and then to overlay them with pure Copper and then pure Nickel (*Figure 13)*. The set-up of the process has requested a long time before the manufacturing of the final mock-up.

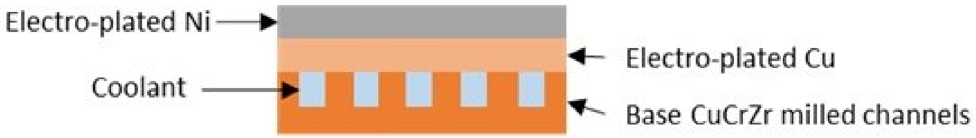

Figure 13 – Sketch of the Cooling system junction by means of electroplating

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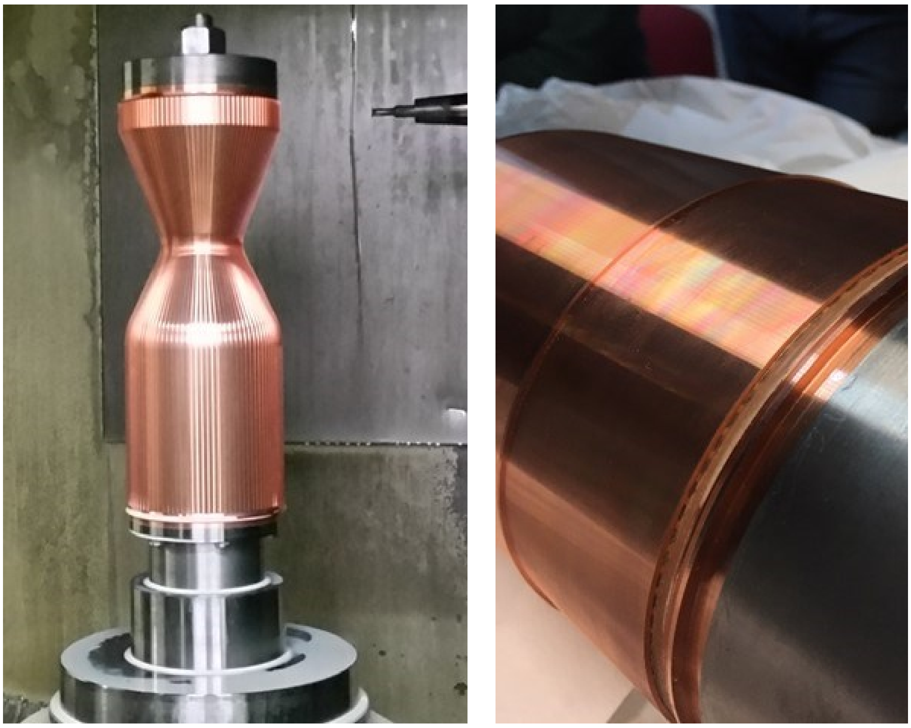
The final mock up is a combustion chamber in scale 1:1 with the DEMO one but truncated at $A_e/A_t = 4$. Some details of the manufacturing process are provided by *Figure 14* and *Figure 15*. The objective of this mock-up is to perform a proof test @150±5 bar and evaluate the behaviour of the hardware it terms of deformations and stresses. Once these tests will be completed with success, DEMO chamber will be manufactured.



(a) (b)

Figure 14 - Different phases of electroplating process: (a) milling; (b) mock-up after electroplated copper.

(a) (b)

Figure 15 - Different phases of the process: (a) after electroplating nickel; (b) final turning of the manifold.

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Recently, the 1:1 sample have successfully sustained the proof test by adopting water and the pressure target was enlarged up to 200 bar, as shown by the next figure, and no significant deformations have been observed.

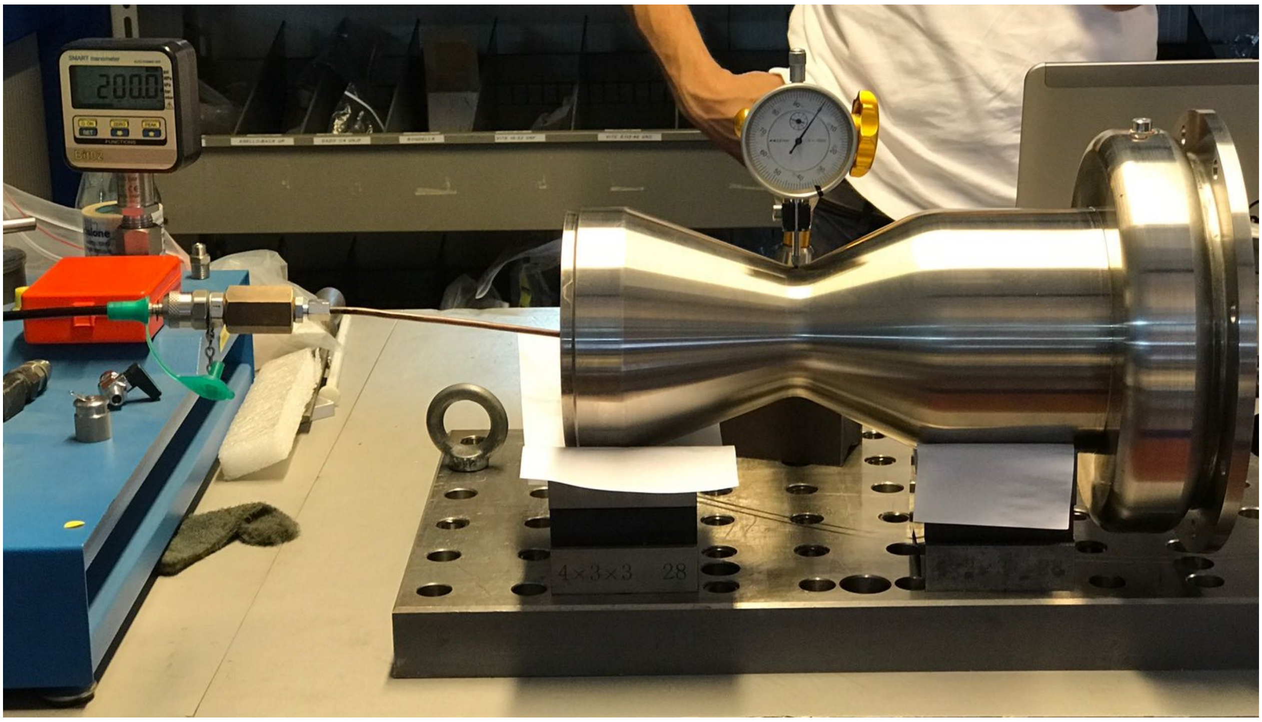

Figure 16 – Electroplated 1:1 final sample during the proof test

5. Conclusions

The activities, related to the development of the HYPROB LO_X/LCH_4 Demonstrator have been described and the current status discussed. At this moment, no particular problems are foreseen for the program both from the technological and development side. The project deadline of 2018 end will be fulfilled by achieving the manufacturing and testing of the Demonstrator. In 2017, relevant advancements have been performed on the Injector Head manufacturing and testing. The subsystem has passed the acceptance tests and functional tests, including cold flow tests. Recently, HYPROB IH has been mounted on a dummy chamber, developed by AVIO, in order to perform firing tests on FSBB TCA. At this moment, four successful tests have been accomplished. On the path of consolidating the technological aspects for the final demonstrator manufacturing, after setting-up some preparatory activities a 1:1 scale mock-up has been completed by means of electro-plating technology and, by the end of June 2017, it will be ready to withstand the leak and proof tests.

Acknowledgments

This project is financed by the Italian Ministry of University of Research, whose support is much appreciated. The authors would like to express their gratitude to all CIRA colleagues involved in the HYPROB program, AVIO HYPROB team (in particular, Francesco Ceccarelli, Daniele Liuzzi, and Davide Scarpino) CECOM personnel (in particular, Andrea Ceracchi and Luca Manni) for their precious support.

DOI: 10.13009/EUCASS2017-360

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Acronyms

AM	Additive Manufacturing
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
BB	Breadboard
CH_4	Methane
DEMO	Demonstrator
FSBB	Full Scale BreadBoard
HRE	Hybrid Rocket Engine
IH	Injection Head
I_{SP}	Specific Impulse
LO_x	Liquid Oxigen
LRE	Liquid Rocket Engine
MIUR	Ministero dell'Istruzione, Università e Ricerca (Italian Ministry of Education, University and Research)
P_{CC}	Combustion Chamber Pressure
TCA	Thrust Chamber Assembly
T_{CC}	Adiabatic Temperature in the Combustion Chamber
UTS	Ultimate Tensile Stress
WP	Work Package