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The HYPROB Demonstrator Line: Status of the LOX/LCH4 Propulsion Activities

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Abstract
LOX/Methane regenerative cooled rocket engines are expected to bring many advantages for future propulsion systems, like reusability, long term storage and reduced toxicity. The present work illustrates the recent advancements, achieved by CIRA in LOX/LCH4 propulsion. The research activities on this topic have been divided into three main branches, dedicated to development of regenerative thrust chamber assembly, combustion small scale breadboards and additive technologies for future generation thrust chambers, respectively and for each line details on progresses are given. In particular, the development of each breadboard and demonstrators is presented as well as the connected research activities. Moreover, the paper will focus on the DEMO-0A thrust chamber assembly manufacturing by means of the electroplating methodology and its testing activities.

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. Other advantages are relative easy storability, low toxicity, availability and production cost, as compared to hydrogen or kerosene and mono-propellant systems [1]-[3]. In a long term perspective, such a propulsion technology may cover 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 [4], in Japan (with the impulse of JAXA and IHI [5]) USA (SpaceX's Raptor Project [6]) and ESA (Prometheus [7]), for example.
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 for future space propulsion systems, with specific regard to LOX/LCH_4 technology, as described by Salvatore et al. [8] . 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. One of the most relevant implementations of the HYPROB Program is named HYPROB "Dimostratori" (Technological 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 target of validating critical design and technology features. The line "Dimostratori" is divided essentially in four WPs:

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

The present paper describes the activities linked to the development of LRE LOX/LCH_4 engines (mainly to point 1, 2 and 3). The final goal is to assess the technology readiness level of potential solutions for future expander engines. In this framework, CIRA involved the best available competencies from both industrial and scientific sides in an integrated multidisciplinary project team logic. In fact, AVIO, CRAS (University of Rome – La Sapienza), Purdue University, CSM and different Italian SMEs (VLT srl, Marotta srl, CECOM srl) have been granted of contracts to support the activities. The paper is divided mainly in three section: the first one gives an outlook on the project and adopted approach. The other sections point out the main advancements and achievements in the specific research line.

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2. Project Description and Approach

The project main objective consists into develop LOX/LCH$_4$ technologies. This result will be achieved through the design, manufacturing and testing of different test articles including a Thrust Chamber Assembly (TCA) regenerative cooled ground Demonstrator (DEMO) of 30-kN-thrust in flight conditions.
The study logic, leading the HYPROB LOX/LCH$_4$ demonstrator development, is based on the following drivers to:

- design suitable intermediate breadboards to address the most critical design solutions, such as injection, combustion and cooling;
- 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, heat transfer material behaviour, 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 reliable 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. The results achieved, according to the study logic, from the beginning of the project have been summarized in Figure 1.

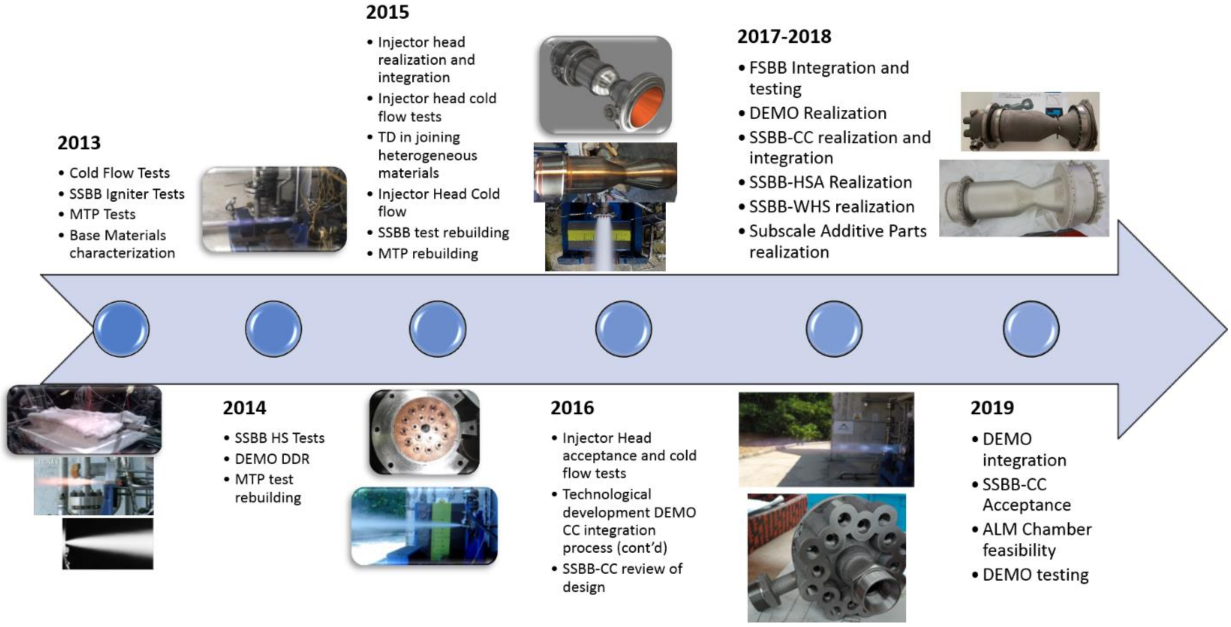

Figure 1: Updated timeline of the project

3. Subscale Breadboards (SSBB) research activities

The SSBB concept has been conceived mainly for research purposes in order to investigate the heat release to the chamber walls from the hot gas side, verify single injector behaviour and validate design and numerical methodologies used in DEMO design, and in general in LOX/LCH$_4$ propulsion. Different versions of this single injector breadboard has been produced taking into account the heat-sink approach (SSBB-HS), that is preferable, in a first stage, for research purposes because of its simplicity, low structural costs, ease to manufacture and high accessibility for thermocouple installation. A different approach has been followed by the calorimetric one (SSBB-CC), where multiple individually cooled short segments are used for a direct measurement of heat release to the wall.

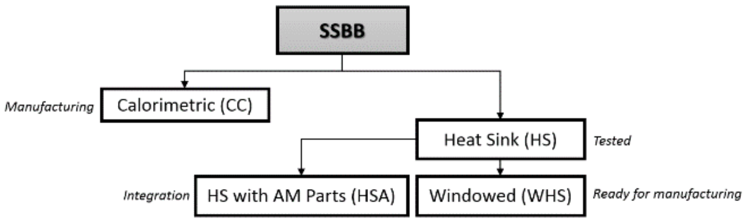

Figure 2: SSBB breadboards versions

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3.1 SSBB-HS (Heat Sink version) and SSBB-WHS (Windowed Heat Sink version)

SSBB-HS has been manufactured and tested in FAST2/ASI-AVIO facility. Its sketch is reported in Figure 3: for this BB a customized igniter has been developed and tested [9].

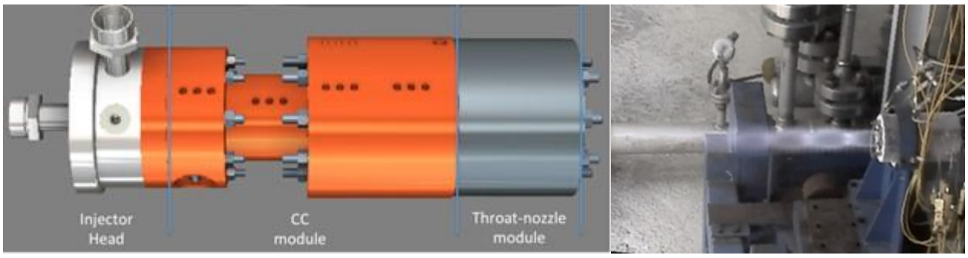

Figure 3: Test article detail and an image from test campaign

In the first test campaign, after the igniter testing and the ignition testing sequence, 10 firing tests were accomplished [10], [11] The results have been also used to improve the design of the windowed version of the breadboard.
The SSBB-WHS is an evolution of the sub-scale breadboard "heat sink" (SSBB-HS) and has been built, in order to enable the application of non-intrusive diagnostic systems (fast camera and OES). This BB is a preliminary step for the design and testing of the 3IWBB (3-Injectors Windowed BreadBoard), foreseen in this line, which consists into a more instrumented and accessible multiple injectors 4-windowed chamber.
The windowed breadboard consists in a first "heat sink" part, instrumented with 12 thermocouples, able to investigate heat release to the walls in the zone of reattachment, and presents a N_2 cooled quartz window in the cylindrical part of the chamber. The nozzle has the same design of the HS one. The breadboard has been assembled and preliminary leak checked and is ready to be tested. It has a certain number of interchangeable coaxial injectors with different gap and recess between the oxygen post and methane sleeve with the purpose of investigating the effect of these design parameters on the flame structure and reattachment zone.

Figure 4: SSBB-WHS integrated

3.2 SSBB-CC (SubScale Breadboard – Calorimetric Chamber)

The SubScale Calorimetric BreadBoard (SSBB-CC) has been designed to deepen the oxygen-methane combustion issues at high pressures, investigate the behaviour of different injectors and characterize the heat flux profile along the combustion chamber walls.
Moreover, due to the design choice it has been selected to develop and validate brazing between heterogeneous materials in relevant environment. The breadboard baseline concept is shown by Figure 5: a certain number of disks surrounds the chamber to allocate channels, fed up by water. Their role is dual: the cooling of the chamber and the measurement of the thermal load released from the combustion chamber to the walls by measuring the coolant flow rate and the temperature gain between the inlet and outlet sections. From Figure 5, it is also possible to note the injection head (on the left), where a single coaxial injector is allocated: it allows the injection of liquid oxygen and gaseous methane into the thrust chamber [12]. SSBB-CC has been designed to study combustion phenomena at the same chamber pressure of the final demonstrator (P_{cc} = 55 bar). At this moment the BB is in the manufacturing phase. The brazing process for the realization of the breadboard has been set up with some specimen tests and the mechanical parts are in production. It is foreseen that this BB will be assembled in the forthcoming months. It is important to underline that new efforts on the optimization and customization of brazing process have been provided to overcome some problems encountered in the development of the chamber in the early stage of the project.

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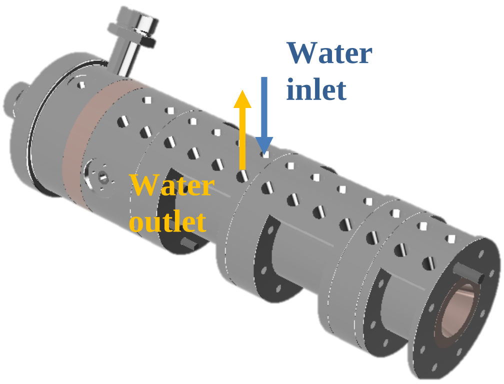

Figure 5: Sketch of SSBB-CC

Figure 6 depicts some modules in the SSBB-CC manufacturing phase. Close-out parts, made up by Inconel© and copper liner parts of module have been produced; then, they will be joined by means of brazing process and withstand leak and proof tests.

Figure 6: SSBB-CC modules in the manufacturing phase: a) injector plate; b) close-out of cylindrical part module 1; c) close-out of cylindrical part module 2; d) close-out of nozzle module; e) copper liner of throat module; f) assembly of throat module.

4. Regenerative cooled TCA Development Activities (DEMO)

The HYPROB demonstrator (DEMO) is a regenerative cooled pressure fed engine of 30 kN thrust, technologically representative of the cooling jacket of an expander engine. The main elements, reported in Figure 7, are the igniter (1), the injection head (2), the combustion chamber, including the cooling jacket (4), outlet (3) and inlet (5) manifolds.

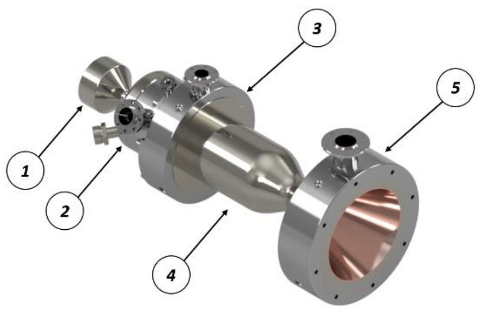

Figure 7: DEMO assembly and main components of architecture

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The injection head is provided with 18 coaxial injectors, designed according to the criteria described in [14], whose arrangement is reported in Figure 9a.

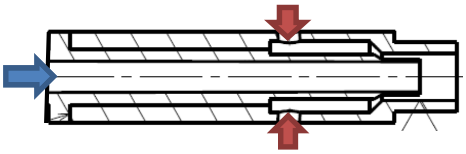


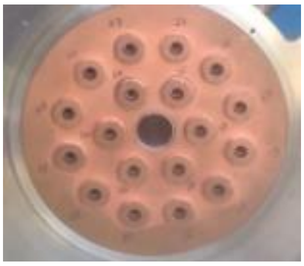
Figure 8: Sketch of the coaxial injector element (blue=oxygen, red=methane)

DEMO injector head (IH) after passing the design review, has been manufactured in 2015. It is characterized by a copper alloy firing plate and is actively cooled [15]. The acceptance plan, before DEMO integration, foresees a dedicated test campaign with a dummy combustion chamber. So the IH has been coupled with the PROTO-D combustion chamber (creating the thrust chamber assembly has been named FSBB – Full Scale Bread Board) in order to validate design, robustness, and also to evaluate the overall power exchanged with the cooling system, to have a preliminary validation of the heat fluxes distribution. The test campaign was carried out at ASI/AVIO FAST2 facility in Colleferro (RM-Italy). This campaign consisted of several runs, using an incremental approach for what concerns the targets in terms of chamber pressure and firing duration. Thus, starting from a low combustion chamber pressure of about 31 bar (corresponding to about 12 kN of thrust), it was reached more than 48 bar (nearly 21 kN) in the last one for a maximum firing duration of 10 s; the relevant test (excluding low duration tests) experimental pressures and heat exchanged with the cooling jacket recorder during the test campaign are reported in Table 1.

Table 1: Main experimental test points from FSBB test campaign

Test Label	***Experimental data***		
	Chamber Pressure	***Steady State Duration***	***Power exchanged with cooling system***
Test 1	34.70 bar	9.10 s	1.38 MW
Test 2	37.37 bar	9.05 s	1.50 MW
Test 3	39.92 bar	10.10 s	1.57 MW
Test 4	48.51 bar	10 s	1.80 MW

In Figure 9a and b, the DEMO-IH firing plate is shown before and after FSBB firing test-campaign, it can be noticed the good status of the hardware confirming the reliability of the analysis and the cooling system design. In Figure 9c, an image of the plume during the nominal mode test is depicted. Details on the test campaign could be found in [16].
The status of the hardware as well as the performances, acquired during testing activity, are in line with design requirements, and give green light for IH integration with DEMO.



a)

b)

c)

Figure 9: DEMO Injector head – Before (a) and after (b) test campaign. FSBB TCA a during firing test (c)

After accomplishing FSBB firing tests, an extended rebuilding activity has been planned in order to:

- assess experimental data;
- consolidate modelling issues on chemistry and gas state (see Figure 10a);
- verify heat fluxes distribution (see Figure 10b).

Some details on this activities are reported in [17]. These activities are currently on going.

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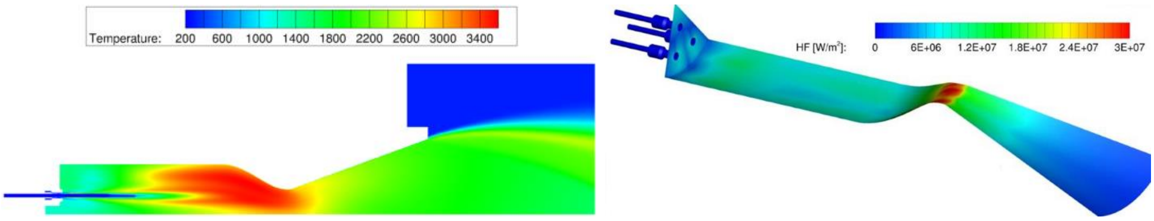

Figure 10: Temperature contour of FSBB combustion chamber and heat fluxes form 3D CFD dual step simulation

For what concerns DEMO combustion chamber cooling system, a counter-flow architecture has been considered: the coolant (LCH_4) is injected liquid into the fuel manifold and enters the cooling jacket counter-flow with respect to the combustion gases (Figure 11). Due to heat release to chamber walls, the propellant temperature increases and finally fluid is injected directly in the fuel dome as supercritical vapour and then, by means of the injectors, in the chamber where atomizes, mixes and burns with liquid oxygen.

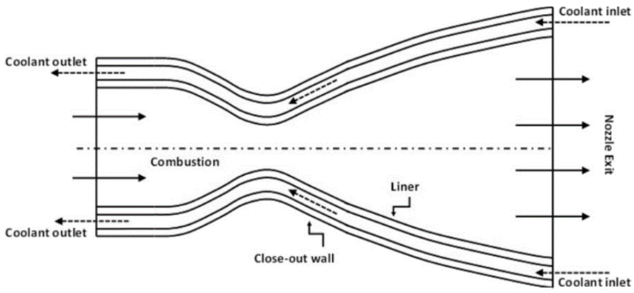

Figure 11: Counter-flow architecture of the cooling jacket

The combustion chamber has a cylindrical shape whose radius is 0.06 m while throat radius of nozzle is 0.03 m and the expansion ratio is 9. The cooling jacket includes 96 channels and the final arrangement has been selected, choosing a constant value for the channel rib width while a variable value of the rib height has been adopted in order to optimize the cooling performances in the nozzle, throat and chamber zone. The baseline concept included channels, defined by a liner, made up by a copper alloy in the bottom part, joined with a close-out, made up by Inconel, in its upper part by means of brazing process.

Verifications after the FSBB, SSBB and MTP (Methane Thermal Properties Breadboard) testing have been repeated on DEMO DDR configuration [18], [19], taking into account for the results obtained in the experimental campaigns. In the following Figure 12 cooling jacket performance results in terms of bulk temperature and wall temperature from 3D CFD combustion simulation Figure 10 coupled with solid are reported: no criticalities are envisaged.

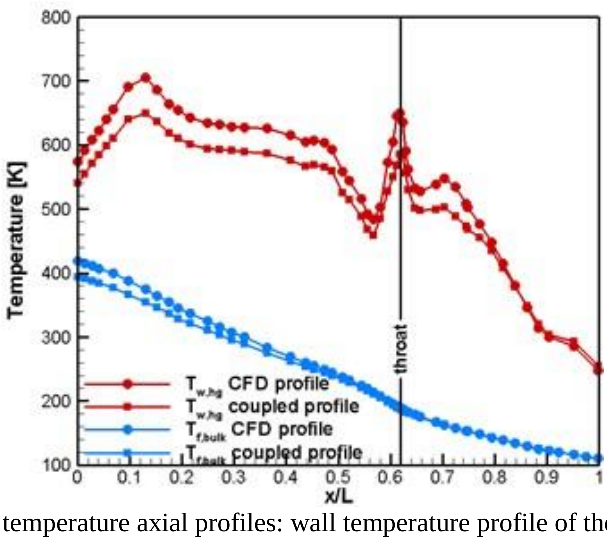

Figure 12: Cooling Jacket temperature axial profiles: wall temperature profile of the liner (red) and fluid bulk temperature (blue)

In June 2016 CIRA, after some difficulties, encountered in the repeatability of the brazing process for chambers with hundreds of cooling channels, started a cooperation with CECOM in order to apply the electroplating process to the DEMO chamber manufacturing. The idea consisted into maintain the base mechanical process since grooves in the liner part are obtained by means of milling and overlay them with copper and nickel [16], as depicted by Figure 13b.

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In fact, channels are generated by a combination of two special galvanic depositions of pure copper and nickel. The advantages of this technique are listed below:

- Brazing and welding free - copper and its alloys could be applied even in the annealed condition (no thermal stress affects the component during its manufacturing cycle) and the elimination of the brazing cycle sensibly reduces costs allowing to exactly know the material mechanical properties.
- Reliability: the manufacturing process repeatability can be controlled improving mechanical resistance, thermal and electrical conductivity of the deposited copper.

Figure 13: Sketch of the Cooling system junction by means of typical brazing process (a) and electroplating one (b)

Thus, the use of that advanced manufacturing process has been motivated by the possibility to avoid any deterioration of base materials, being a cold process, and by a high level of repeatability and reliability. Results were very encouraging and 1:1 mock-up, truncated at $A_e/A_t = 4$ (expansion area to throat area ratio), was realized and the cooling jacket passed proof tests up to 200 bar (see Figure 14). Thus, CIRA selected as baseline process electroplating process to realize the final HYPROB DEMO and this choice led to plan an optimization activity on the cooling system arrangement to adapt the “brazed” configuration to “electroplated” one. In particular, an optimization of the channel profile and the manifolds have been accomplished.

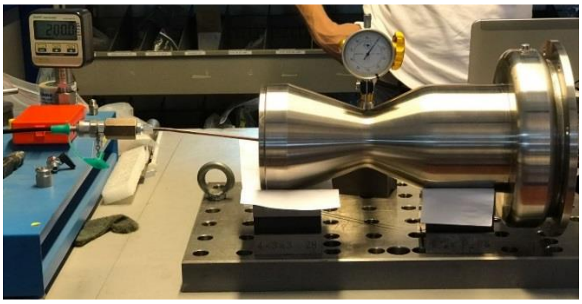

Figure 14: DEMO 1:1 mock up under proof test (up to 200bar)

Figure 15 depicts the CFD results in terms of axial profiles for hot gas wall, channel bottom wall and fluid bulk temperature. The considered fluid is water since the water cooled version of DEMO will be the first one to be tested in a firing campaign in order to fully validate electroplating process. At a fixed mass flow rate a generalized slight reduction in terms of thermal stresses is observed, comparing DEMO “electroplated” version and “brazed” one (first and last lines) and a significant decrease in the throat region. This confirming that the selected architecture for the cooling jacket has been further optimized. In fact, the thermos-structural analyses confirms that the cycle life of the cooling system has been improved by a factor of 1.5.

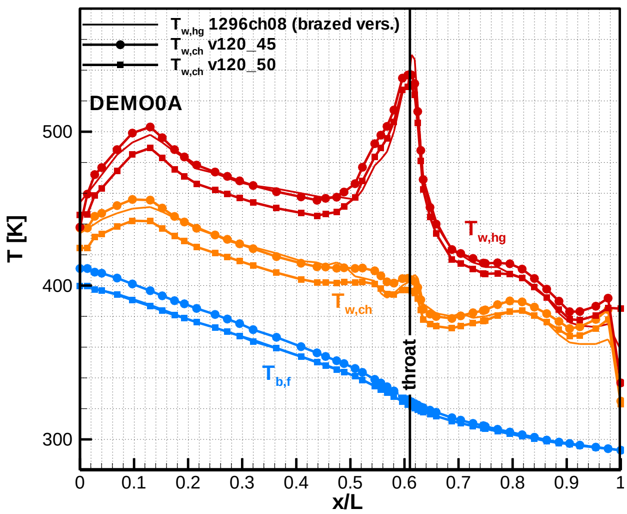

Figure 15: HYPROB DEMO cooling jacket: axial profiles for hot gas wall, channel bottom wall and fluid bulk temperature – “brazed” and “electroplated” versions

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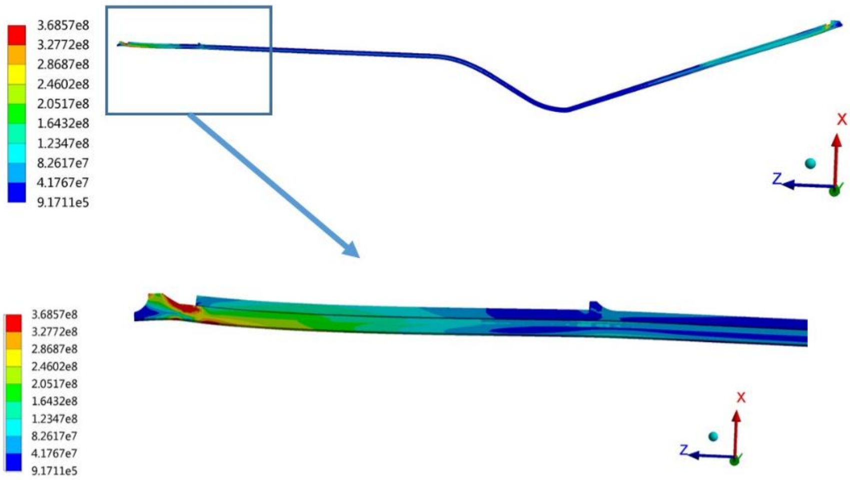

Figure 16: Von Mises Stresses (Pa) on the copper liner

HYPROB-DEMO manufacturing is on the way to be completed. The phases of internal milling of the manifold and the copper layer deposition and nickel layer deposition have been completed. Figure 17 gives some details on channels after milling while Figure 18 depicts the turning of the thrust chamber before the final assembly with inlet and outlet manifolds. DEMO will be tested by the end of 2019.

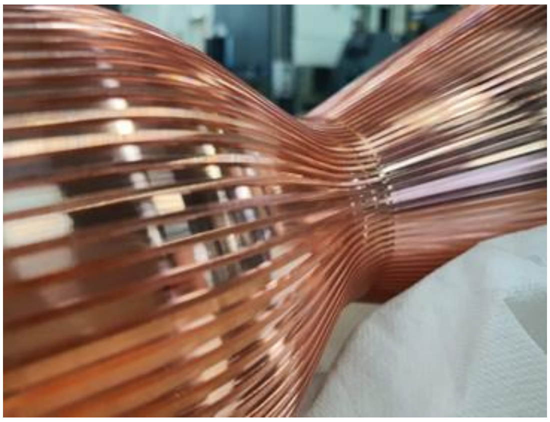

Figure 17: Details of the cooling channel after milling in the throat zone

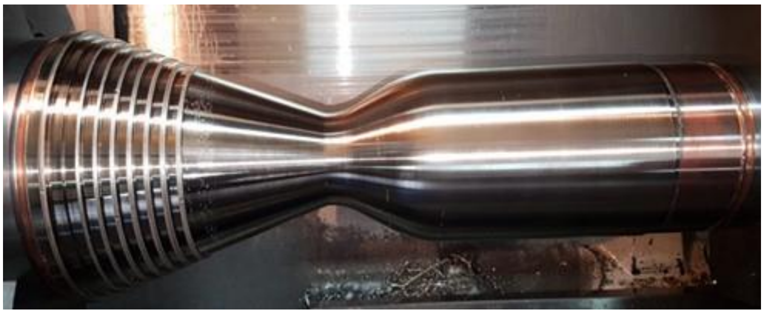

Figure 18: DEMO: Turning after nickel layer deposition

5. Additive Manufacturing Activities

Additive manufacturing (AM) can combine integrated functionality, lightweight construction, a simpler design, and shorter lead times in a single component, these features are appealing for LRE component that are characterized by complex geometries. Given these motivations, the third line of HYPROB "Demonstrators" line is devoted to the AM

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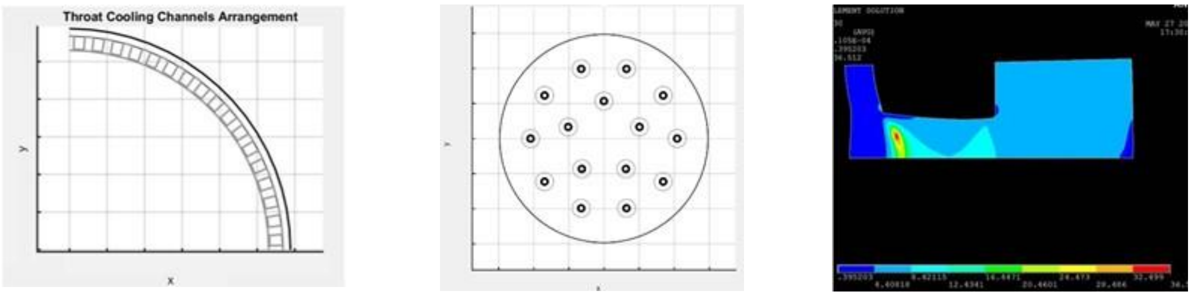
technology, applied to the manufacturing of LRE parts. The final objective is to verify the applicability of this technique to liquid rocket engine parts. This feasibility will be verified by means of the fabrication and test of a light weight thrust chamber assembly pressure fed (a combustion chamber and an injection head) composed by a limited number of parts to be integrated. This small TCA will be entirely manufactured by the AM Machine (ARCAM A2X) based on the Electron Beam Melting (EBM) technology with the Ti6AlV4 alloy. The selected material is characterized by good mechanical properties and low density (1:2) compared with copper and Inconel. The drawback is a low thermal conductivity that complicates the cooling system design. Preliminary activities, carried out to characterize material and fabricate simpler rocket parts, are described in [16] and [20].
The design activity of the chamber has been integrated with some mock-up printing in order to consolidate the feasibility of the design. Preliminary design has been accomplished with CIRA design tool; the performances and the channel arrangement with preliminary structural analysis results are reported respectively in Table 2 and Figure 19.

Table 2: Ground performance parameters of the ALM TCA

Parameter	***Value***
P_{cc} (Pa)	$2.5e^6$
I_{sp} (s)	289
Thrust [N]	5000
N_channels	60
N_injectors	15



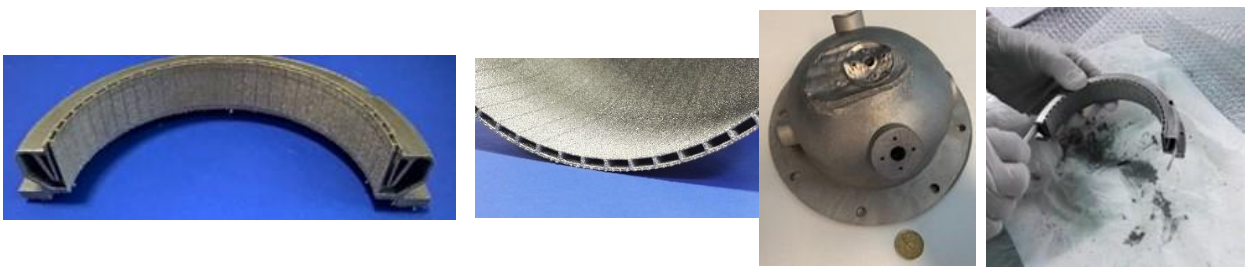
a) b) c)

Figure 19: Throat channels arrangement, injectors' arrangement and Margin of Safety (MOS) in throat section

After the preliminary design, according to the logic reported in Figure 20, some printing experiments have been carried out in order to verify:

- the internal roughness of the surfaces;
- the stock material to be added;
- the level of the occlusion of the sintered parts;
- the orientation of the piece during the printing process;
- the design of the supports for heat exchange;
- the minimum number of parts in which to divide the component.

Figure 20: Design process for AM parts



a) b) c) d)

Figure 21: Printing experiments: manifold, combustion chamber, injector plate (erroneous supports design) ultrasonic cleaning)

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At the end of the process the design has been consolidated and the optimized result is depicted in Figure 22.

Figure 22: Consolidated AM TCA design

This design has been fabricated into a mock-up that has been finished and assembled. The final mock up is not a fully functional mock-up and needs a consolidation activity for an extra internal surface finishing and manifold close-out welding. The fully functional chamber will be completed by the end of 2019.

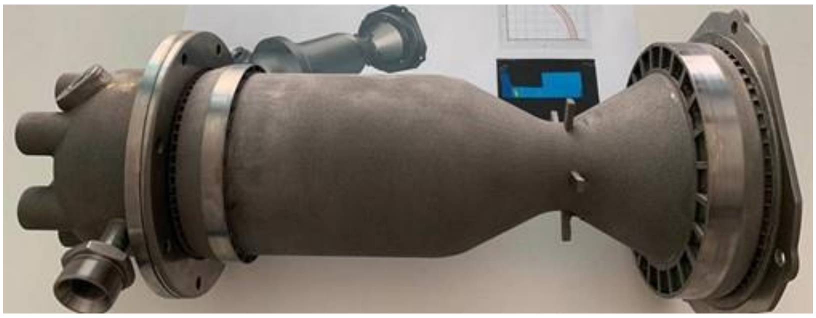

Figure 23: AM thrust chamber mock up printed and finished

6. Conclusions

The activities, related to the Demonstrators line of HYPROB Program, and their recent advancements have been described. At this moment, no particular problems are foreseen for the program both from the technological and development side. On the final DEMO realization side, after successfully performing the Injector Head firing campaign (FSBB test campaign) and completing the realization by means of electro-plating technology and proof testing of a 1:1 scale DEMO chamber mock-up, the manufacturing phase is on going. A design optimization, starting from the "brazed" version of the engine, was needed but, at present time, DEMO realization is on the way to be completed. After withstanding leak and proof tests, the thrust chamber will be integrated with IH in the framework of the dedicated firing campaign to be held by the end of 2019.
On the breadboards side, the final design of SSBB-WHS has been completed. This breadboard was derived by the successfully tested SSBB-HS version while the calorimetric configuration (SSBB-CC) is under manufacturing phase. Regarding the AM sub-line, preliminary activities on material assessment have been accomplished and several components have been realized in the view of perform functional tests and the manufacturing of HSA chambers. The back-plate of SSBB-HSA has completed the machine finishing phase. Several mock-ups (like manifolds, cooling jacket and a preliminary version of injector head) to a 5-kN cooled combustion chamber have been realized. A first complete AM cooled thrust chamber has been manufactured but is not fully functional since it needs some consolidation on internal surface finishing and manifold close-out welding before final version, available by the end of 2019.

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Acronyms

3IWBB 3-Injectors Windowed BreadBoard
AM Additive Manufacturing
ASI Agenzia Spaziale Italiana (Italian Space Agency)
BB BreadBoard
CC Calorimetric Chamber
CFD Computational Fluid Dynamics
CH4 Methane
DDR Detail Design Review
EBM Electron Beam Melting
DEMO Demonstrator
FSBB Full Scale BreadBoard
HRE Hybrid Rocket Engine
HS Heat Sink
HSA Heat Sink AM version
IH Injection Head
I_{SP} Specific Impulse
LOx Liquid Oxigen
LRE Liquid Rocket Engine
MIUR Ministero dell'Istruzione, Università e Ricerca (Italian Ministry of Education, University and Research)
MTP Methane Thermal Properties
OES Optical Emission Spectroscopy
PCC Combustion Chamber Pressure
SS Steady State condition
SSBB SubScale BreadBoard
TCA Thrust Chamber Assembly
TCC Adiabatic Temperature in the Combustion Chamber
UTS Ultimate Tensile Stress
WHS Windowed Heat Sink
WP Work Package