

Advancements in the HYPROB-BREAD project: design and testing of a LOX/LCH₄ demonstrator

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ABSTRACT

The present paper reports recent results from development activities conducted at the Italian Aerospace Research Center (CIRA) in the framework of the Italian National Propulsion program "HYPROB", whose strategic objective is to consolidate the National background on rocket engine systems for future space applications, with specific reference to LOX/LCH₄ propellants. The Program is carried out under contract by the Italian Ministry of University and Research (MIUR), in coherence with the long-term vision of the Italian Space Agency on Space Propulsion

The mid-term objective is to design, manufacture and test a regeneratively cooled LOX/LCH₄ demonstrator, a pressure fed thrust chamber assembly (TCA), with the main scope of validating critical design and technology features and then to assess technology readiness level of potential solutions for future engines. The design approach has been defined in order to proceed step by step, by means of simpler technological breadboards, allowing to address and verify the main critical design issues.

So far some intermediate technological breadboards have already been developed, manufactured and tested, in particular the Methane Thermal Properties (MTP) breadboard, the GOx-GCH₄ igniter and the sub-scale single-injector combustion (SSBB) breadboard. At the moment, the demonstrator is in the manufacturing phase and some hardware have been produced and will be tested by the end 2016.

1. INTRODUCTION

Propulsion systems based on hydrocarbons, either liquid or hybrid, represent nowadays a major technology challenge for future launchers and space transportation systems. Methane is one of the most interesting solutions as propellant for liquid rocket engines, in combination with Oxygen, due to good performances achievable in terms of specific impulse combined with operation advantages, such as storability, low toxicity, availability and production cost, as compared to hydrogen

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. With the aim of supporting and promoting the consolidation and the evolution of competences in that core field by the National scientific and industrial community, an integrated mid/long-term R&D plan has been defined, in synergy with Ministry of Research and University initiatives and ASI programs, preparing

national players for the future technical challenges [1], [2].

A relevant implementation of the HYPROB Program (the system line), named HYPROB BREAD is aimed at designing, manufacturing and testing a LRE demonstrator, of 30 kN thrust class, based on a regenerative cooling system using liquid methane as coolant [3].

One of the mid-term objectives of the HYPROB-BREAD project is to design, manufacture and test, in a relevant facilities (CIRA HYPROB-PLUS and FAST2 AVIO-ASI), technology demonstrators of suitable class of thrust, with the main scope of validating critical design and technology features and then to assess technology readiness level of potential solutions for future expander engines [3].

In this framework, CIRA settled up an integrated project team where the best available competencies were involved at the maximum extent, from both industrial and scientific sides: AVIO, CRAS (University of Rome – La Sapienza), Purdue University and different Italian SME have been granted of contracts to support the activity relative to the liquid demonstrator. 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 analysis after the intermediate breadboard testing results.

2. PROJECT DESCRIPTION AND ADVANCEMENTS

As discussed above, the System project line devoted to the LOx/LCH₄ 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 (Figure 1), implemented in the present project, 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 has been defined in order 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.

Thus, breadboards are used for validation of the analytical models, reducing the risks associated with the use of those models in engine design. Establishing the credibility of design and simulation tools at subscale level where high fidelity measurements can be performed is a critical step in gaining acceptance for the use of these tools and realizing the benefits of reduced design cycle times and costs.

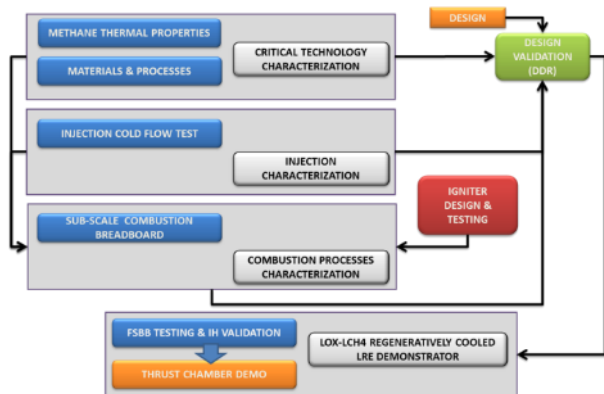


Figure 1 - Study Logic of the LOx/LCH4 technology demonstrator

With that approach in mind, several intermediate breadboards have been manufactured and tested, before realizing the final demonstrator.

Table 1 - Outcomes of HYPROB BREAD projects

Intermediate breadboards:
Methane Thermal Properties Breadboard (MTP) Subscale single-injector breadboard (SSBB) Fullscale multi-injector breadboard (FSBB)
Final products:
30 kN LOx-LCH4 demonstrator (DEMO)

So far, both MTP breadboard and SSBB-HS have been manufactured and successfully tested, along as critical subsystems, such as injectors and igniter.

A more complex version, the SSBB-CC, based on a calorimetric configuration have been designed.

In the following paragraphs, objective and main results of the performed testing activities are reported and discussed. Next 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. 2015 has been devoted to BB testing review/rebuilding, preliminary manufacturing activities and technology consolidation.

Delivery and test readiness of the demonstrator is scheduled by 2Q-2016.

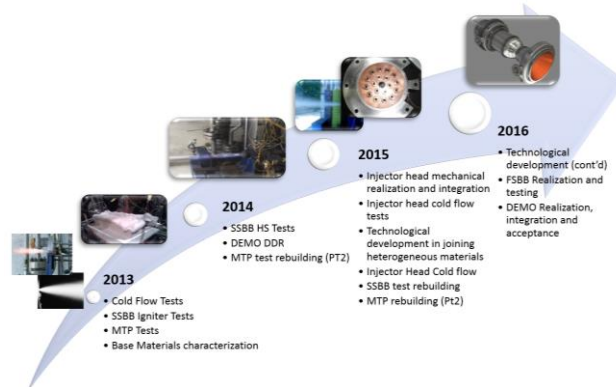


Figure 2 - Project Time-Line

Next figure wraps up the current status of the project.

3. BREADBOARD TESTING ACTIVITIES

MTP BB

The MTP Breadboard is a test article conceived for the study of the thermal characteristics of the methane as a coolant in conditions typical of expander liquid rocket engines, both for design validation and collect experimental data to share results with the scientific community. Its concept is based on an electrical heating of a conductive material that transfers heat fluxes, similar to those experienced by methane in the regenerative cooling chamber of a rocket, to a channel (dimensions comparable with the DEMO) in which methane flows at high pressure. The Breadboard has been correctly shaped in order to 'drive' heat to the channel wall (see Figure 3). The design issues of the MTP breadboard are reported in [4]. The MTP-BB has been tested at Zucrow Laboratories of the University of Purdue in West Lafayette (USA).

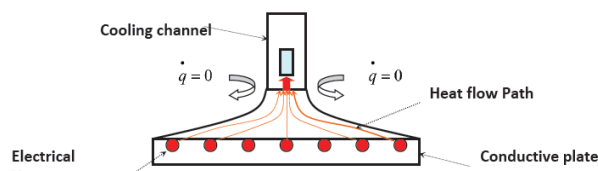


Figure 3 - Schematics of MTP



Figure 4 - MTP, ready to be tested

To operate the MTP experiment has been important to:

1. Control of temperature and mass flow rate of liquid methane at the inlet of the breadboard;
2. Control of the pressure inside the breadboard;
3. Control of the cartridge heaters supplying the thermal heat input to the breadboard.

Temperature, within each cartridge heater as well as within the breadboard, was constantly monitored during tests. Some aluminium-silicate blankets were placed to insulate the test article and obtain the conditions reported in Figure 3. MTP is also equipped with three embedded thermocouples group for four different stations; thermocouples numbering and position are depicted in Figure 5. The fluidic lines are equipped at inlet and outlet with temperature and pressure sensors (see Figure 6). In Figure 6, also cartridges control thermocouples map is shown. On body thermocouples are displayed in Figure 7.

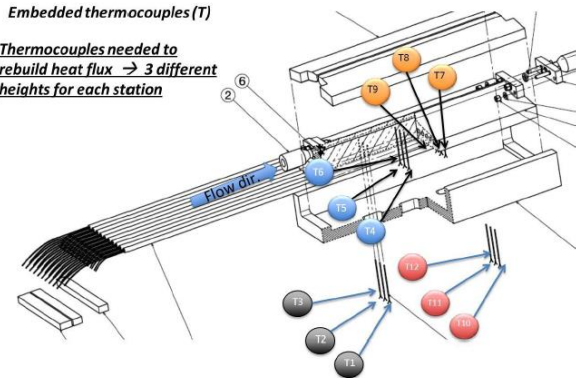


Figure 5 - MTP schematic of the embedded thermocouples map

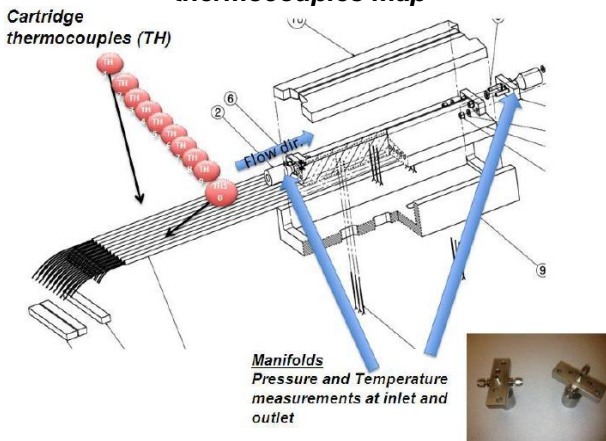


Figure 6 - MTP schematic of Cartridges thermocouples map

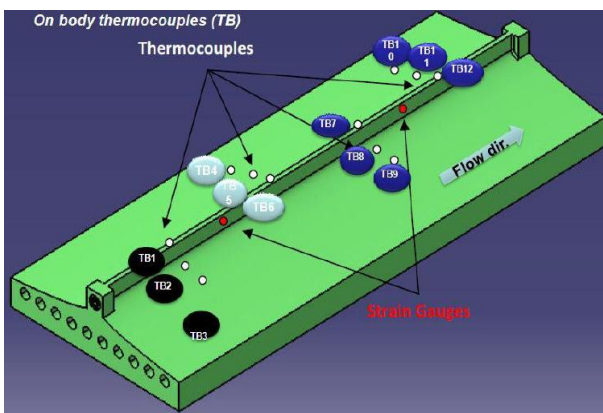


Figure 7 - MTP, on body thermocouples map

Figure 8 and Figure 9 shows the MTP mounted on the test stand, respectively with and without thermal insulation blanket.

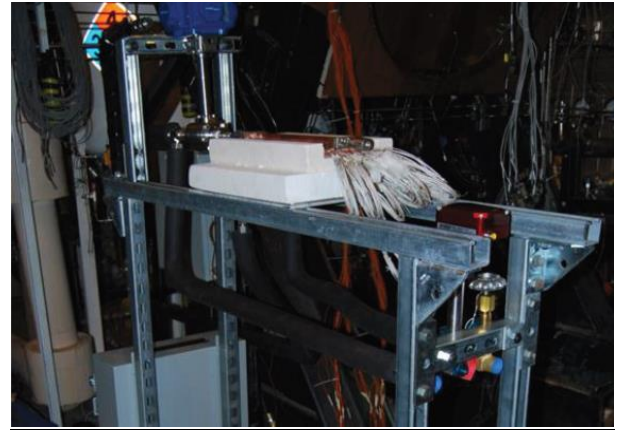


Figure 8 - MTP mounted on test stand



Figure 9 - Insulated MTP on test stand during testing

A schematic view of the main components of the test set-up in Purdue facility is reported in next Figure 10.

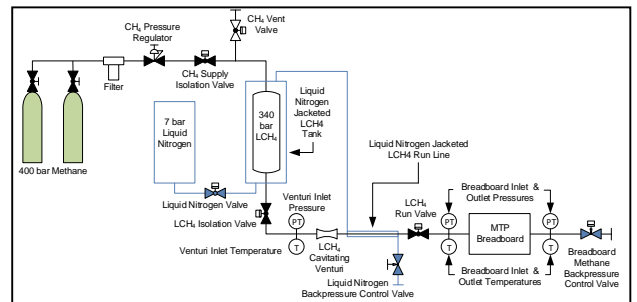


Figure 10 - Simplified Schematic for Methane Propellant and Test Conditions Control

Tests have been executed at different inlet pressure, ranging from 150 to 60 bar, and at different inlet mass flow rate, from 15 to 25 g/s. All tests rely on impressed power equal to 12 kW except one case ID.17 in which the power impressed is equal to 20 kW. Moreover, two tests (ID.14 and 15) have been performed without power source in order to hydraulically characterize the channel using two value of mass flow (i.e., 15 and 20) for an exit pressure of about 80 bar. Each test has been repeated twice for repeatability purposes.

Table 2 - MTP Test Matrix

Test ID	Pex (bar)	mdot (g/s)	POWER IMPRESSED (kW)
1	150	20	12
2	150	25	12
3	150	15	12
4	120	15	12
5	120	20	12
6	120	25	12
7	100	15	12
8	100	20	12
9	100	25	12
10	80	20	12
11	80	15	12
12	80	25	12
13	80	10	12
14	80	15	0
15	80	25	0
16	60	20	12
17	80	20	20

Next Figure shows the ID.10 case experimental results. The inlet temperature (green curve in Figure 11) recorded during the test is about 140 K, while the inlet pressure is about 90 bar (green curve in Figure 12), therefore, the methane is in liquid supercritical conditions.

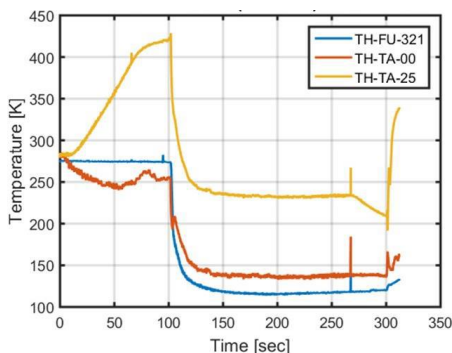


Figure 11 - MTP test #10 inlet and outlet temperature

The outlet temperature is about 240 K (red curve in Figure 11), while outlet pressure is 80 bar (red curve in Figure 12). From the inlet outlet pressure still remains supercritical, while the temperature passes from under-critical to supercritical value, therefore the supercritical transition of the methane has been achieved.

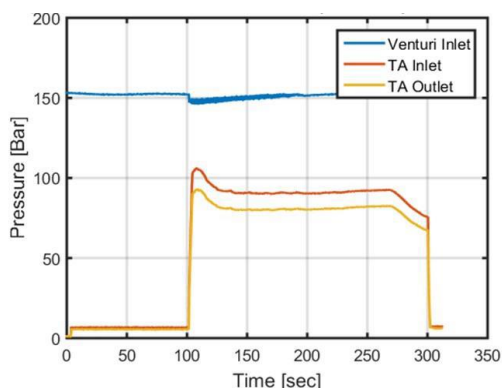


Figure 12 - MTP test #10 inlet and outlet pressure

Also the embedded thermocouples (referring to Figure 13) have reached steady conditions allowing a correct evaluation of the heat flux and thermal field inside the solid part of the breadboard. Measurements performed in the solid part reach the steady conditions

in about 150 seconds (see Figure 13) while, as expected, the fluidic part (Figure 11 and Figure 12) in about 50 seconds.

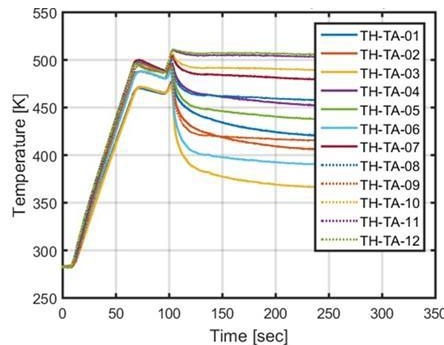


Figure 13 - MTP test #10 embedded thermocouples

The next Figure 14 shows, in a concise way, that for all the test selected the supercritical transition occurs.

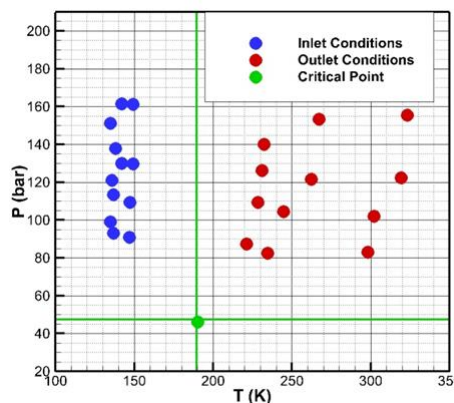


Figure 14 - MTP Outlet Pressure/temperature diagram

Of course, as the mass flow raises temperature decreases and pressure drops increases. Temperature increase of methane, for each mass flow, is higher as the pressure level rises, while pressure drops at each mass flow decrease: this is due to the C_p behaviour of the methane with pressure.

Further details on MTP testing activities at Zucrow Laboratory (Purdue University) are reported in [4].

Test results have been used for the numerical rebuilding and set up of the tools applied in DEMO design. In particular ECOSIMPRO EPSS models validation has been presented in previous papers [4], currently also rebuilding CFD activities is concluded using FLUENT software; thanks to the data acquired it has been possible to have a validated set up for cooling channel modelling with supercritical methane, some of the results of this activities are reported in the following figures (Figure 15-Figure 17) for one of the test of the test campaign (@ $P_{in}=12.9$ MPa, $T_{in}=140$ K, $m_{dot}=0.02$ kg/s) and show a good agreement between experimental data and numerical results), further details are reported in [6].

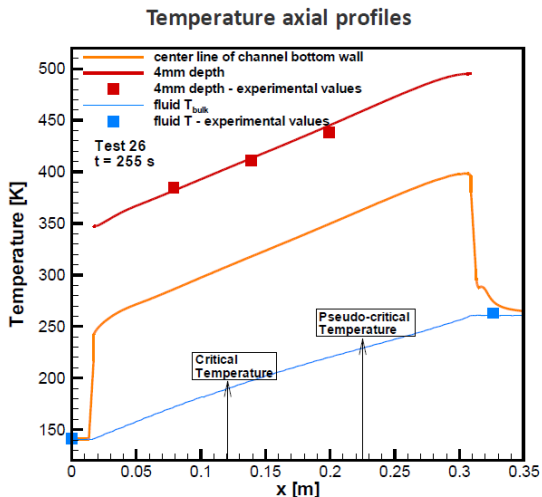


Figure 15 - Numerical vs experimental temperatures

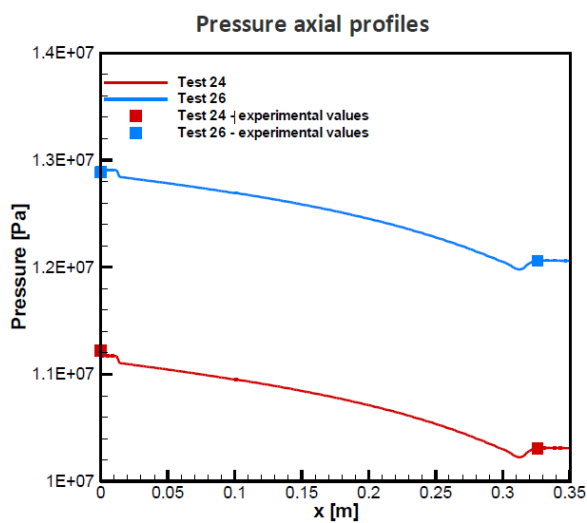


Figure 16 - Numerical vs experimental Pressures

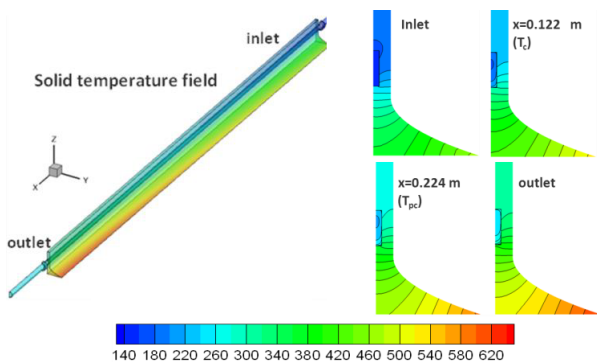


Figure 17 – Temperature distributions

SSBB

In order to characterize the heat release to the wall in the hot gas side and validate design and numerical methodologies used in DEMO design a SSBB has been designed. Two different version exist for this single injector (based on DEMO one) breadboard, one heat-sink and one calorimetric. The latter is going to be manufactured, the first one has been manufactured and tested in FAST2/ASI-AVIO facility. The SSBB-HS

geometry is reported in Figure 18, for this BB a customized igniter has been developed and tested [8].

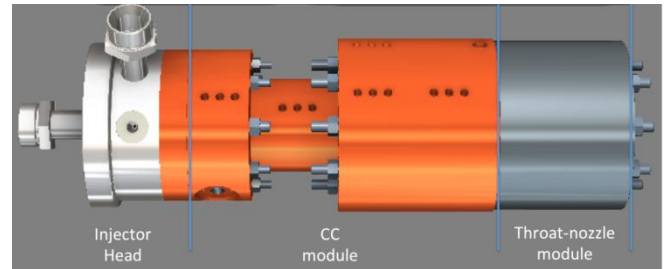


Figure 18 – Test article detail

In the first test campaign, after the igniter testing and the ignition testing sequence, three firing tests have been accomplished. It has to be remarked that both methane pressure and oxygen temperature delivered by the facility were not perfectly in line with the design values. This caused the injector to work not in nominal condition, but in any case the injector demonstrated wider than expected operative flexibility. Two experimental test campaigns have been planned in AVIO-FAST2 facility.

In the first test campaign, 4 tests have been successfully completed:

- 3 tests at high pressure (nominal P_c about 50 bar) for a steady state duration of about 3s.
- 1 test at high pressure (nominal P_c about 50 bar) for a steady state duration of 5 s.

In this test campaign 12 thermocouples have been installed on the cylindrical part of the chamber.

In the second test campaign, two thermocouples have been added also in throat region, and the following tests have been performed:

- 3 tests at high pressure (nominal P_c about 50 bar) for a steady state duration of about 3s (first test campaign repeatability)
- 1 test at low pressure (nominal P_c about 30 bar) for a steady state duration of 9 s.
- 2 tests at low pressure (nominal P_c about 30 bar) for a steady state duration of 11 s.

The test duration has been increased at the end of each test in order to acquire further data for a more accurate rebuilding of the tests, and to investigate design limit of the hardware.

In the following figures, data acquired in two reference high and low pressure tests are presented.

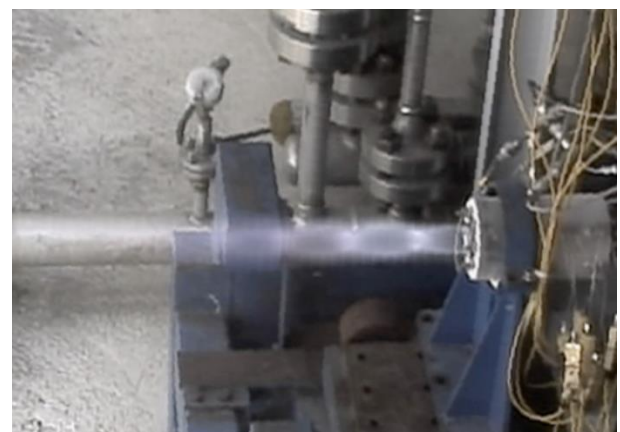


Figure 19 - Test article during firing

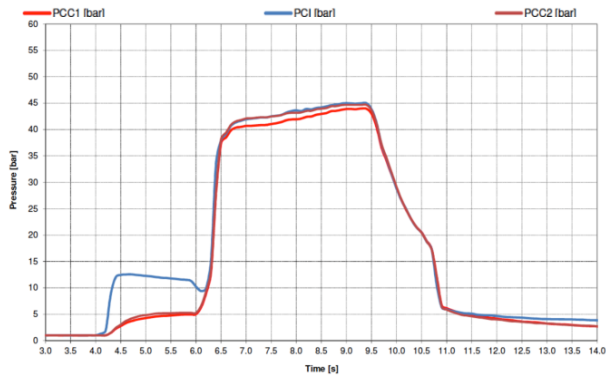


Figure 20 - Test #7 (High pressure test): Pressure vs time (in barg)

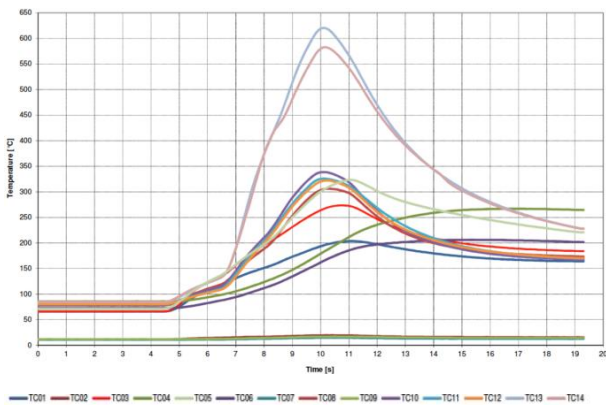


Figure 21 - Test #7 (High pressure test): thermocouple temperatures vs time

It is important to underline that the test article has shown a stable behaviour in all the testing conditions; however, some thermocouples have not been acquired and some other moved from their position during tests; in total 5 thermocouples data were unusable. Moreover the data acquisition of the mass flow rate could not be used due to major delay problems in the acquisition. For this reason, some difficulties have been found in the rebuilding activity of the test campaigns, but has been solved by using numerical procedures based on the experimental data available also by cold flow testing. CFD rebuilding activities are currently on going. Data assessment of the experimental campaign and main outcomes are presented in the companion paper [9].

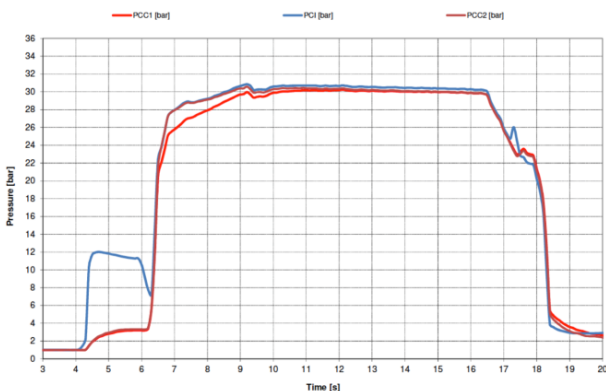


Figure 22 - Test #10 (low pressure test): Pressure vs time (in barg)

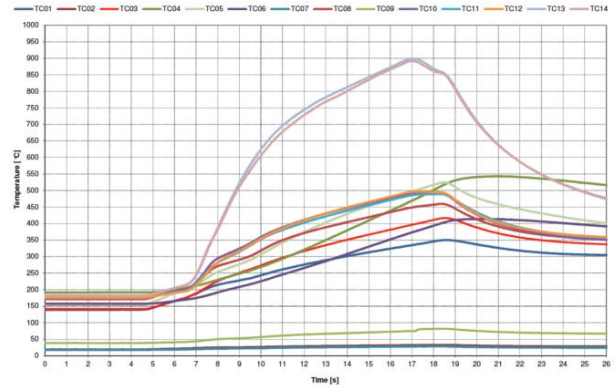


Figure 23 - Test #10 (low-pressure test): thermocouple temperatures vs time

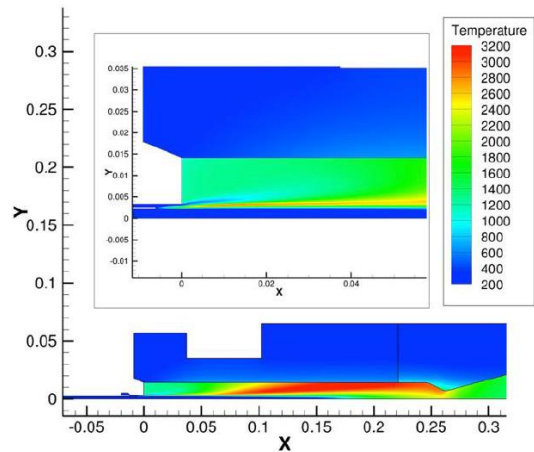


Figure 24 - Preliminary results of CFD rebuilding run on test #10

4. DEMONSTRATOR (DEMO)

The 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 26, are the igniter, the injector head and the combustion chamber. A counter-flow architecture will be considered for the chamber cooling system, where the coolant (LCH4) is injected liquid into the fuel manifold and enters the cooling jacket counter flow with respect to the combustion gases (Figure 25). After heating it is injected directly in the fuel dome and then from the injector in the chamber where atomizes, mixes and burns with liquid oxygen.

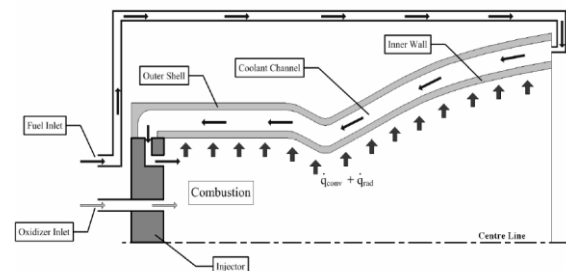


Figure 25 - Counter-flow architecture of the cooling jacket

The combustion chamber has a cylindrical shape whose radius is 0.06 m. The nozzle's throat radius is 0.03 m and the expansion ratio is 9.

A configuration with 96 channels 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 channel is defined by a liner, made up by a copper alloy, in the bottom part, and by a close-out, made up by Inconel, in its upper part.

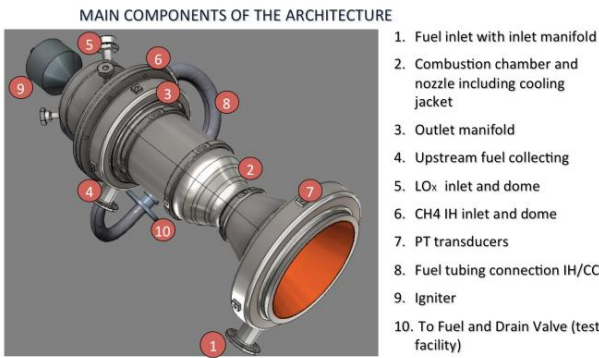


Figure 26 - Demonstrator assembly

Verifications after the SSBB and MTP testing and model validation phase, have been repeated on DEMO DDR configuration, in the following Figure 27 cooling jacket performance results in terms of bulk temperature and wall temperature from 3D CFD coupled with solid are reported, no criticalities are envisaged. Such configuration is currently under manufacturing phase.

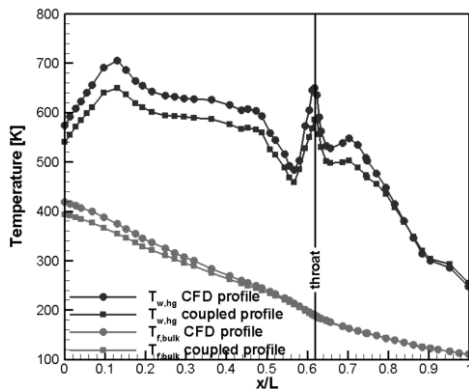


Figure 27 - Cooling Jacket temperature axial profiles: wall temperature profile of the liner (red) and fluid bulk temperature (blue)

Injector Head Manufacturing

The injection head has been manufactured and all the produced injector has been verified by cold flow testing. With a procedure, the best injectors to be assembled, have been selected.

The injector head assembly is currently on the integration phase acceptance.

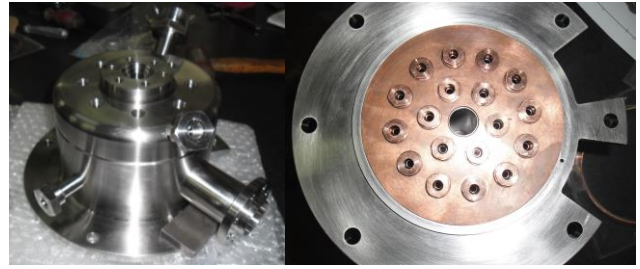


Figure 28 - DEMO Injector head.

Combustion chamber manufacturing

For combustion chamber manufacturing the major concerns is linked to the joining the internal liner with the external close out. Different efforts have been made by CIRA and its partner (AVIO, CSM) in order to validate brazing technique.

With CSM (*Centro Sviluppo Materiali*) an activities related to planar samples have been developed, results reported in table and are compatible with DEMO design.



Figure 29 - CSM Brazing 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

Figure 30 - Results on CSM samples

On the other side AVIO developed a “dummy chamber” to test the brazing procedure on a real combustion chamber geometry. Proof test results on the cylindrical zone of the chamber shows a quite good behaviour of the joint but some problems have been experienced at high pressure in throat-nozzle zone.



Figure 31 - Brazed 'dummy' chamber, cylindrical part section.

CIRA is currently working with its partners to solve the last process optimization problems and manufacture the first version of the DEMO for preliminary hot testing with water cooling (FSBB) foreseen by the end of 2016.

5. CONCLUSIONS

In this paper the advancements and main results of the experimental activities, conducted in the framework of the HYPROB-BREAD project, have been presented.

Main results have been briefly discussed, along as overview of numerical rebuilding activity.

Test rebuilding activity confirms a good agreement with the expected results. The numerical models and tools used for the system design loop are reliable enough and the developed configuration has been considered for manufacturing. Furthermore, Demo manufacturing activities advancements has been presented, according to the present situation, preliminary firing tests of the configuration (cooled with water) will be performed by the end of 2016.

6. ACKNOWLEDGMENTS

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