Testing and Preliminary Assessment of Experimental Data of a LOX/GCH4 Heat Sink Combustion Chamber

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Abstract

The work described in this paper has been conducted in the framework of the HYPROB Program that is carried out by the Italian Aerospace Research Centre (CIRA), under contract by the Italian Ministry of Research. The Program has the main objective to enable and improve National System and Technology capabilities on liquid rocket engines (LRE) for future space propulsion systems and applications, with specific regard to LOX/LCH4 technology. The first implementation of the Program, named HYPROB BREAD, is aimed at designing, manufacturing and testing an LRE demonstrator, of three tons thrust, based on a regenerative cooling system using liquid methane as coolant. In order to achieve such goal some breadboards have been designed in order to investigate major critical phenomena. Among these breadboards, the SSBB-HS, a heat sink single injector thrust chamber, has been designed with the aim of investigating combustion and heat release to the wall. This paper deals with brief design/manufacturing issues, components integration and testing for the SSBB breadboard. Test campaigns, performed in AVIO/FAST2 facility, have been preliminarily numerical rebuilt with the final goal of estimating the heat release to the wall in different conditions.

1. Introduction

With the aim of supporting and promoting the consolidation and the evolution of competences in the field of LREs by the national scientific and industrial community, an integrated national vision for mid-long term R&D activities has been defined, which takes the maximum benefit from both Ministry of Research and University initiatives and ASI on going and future programs, then preparing for the future technical challenges.

In this frame the HYPROB Program has the main objective to enable and improve National System and Technology capabilities on liquid rocket engines (LRE) LOX/LCH4. The Program is structured in three main development lines, each corresponding to a specific implementation project:

- “System”: design and development of technology LRE demonstrators, including intermediate breadboards;
- “Technology”: R&T development in the areas of CFD combustion modelling, thermo-mechanical modelling and materials, advanced optical diagnostics;
- “experimental”: testing capabilities for both basic physics and system-oriented (demonstrators) experimentation.

The first implementation of the Program (the system line), named HYPROB BREAD, is aimed at designing, manufacturing and testing a LRE demonstrator, of three tons thrust, based on a regenerative cooling system using liquid methane as coolant [1].

In the framework of this program, two single injector combustion chambers (Sub Scale Bread Board SSBB) have been designed and manufactured in order to investigate single injector behaviour, heat transfer to the wall and combustion stability. Sub-scale testing could be used for the 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 the acceptance for the use of these tools and realizing the benefits of reduced design cycle times and costs. Thus, according to this logic (Figure 1, Figure 2), subscale combustion chambers have been designed by following two approaches: a calorimetric (SSBB-CC) and a heat sink (SSBB-HS). They consist in a single coaxial injector (LOX/GCH4) mounted on an injector head that can be used with the two interchangeable combustion chambers.

The present paper briefly presents different aspects of the design and it is mainly focused on testing preparation, experimental activities execution (in AVIO/ASI Fast2 facility) and experimental data preliminary rebuilding.

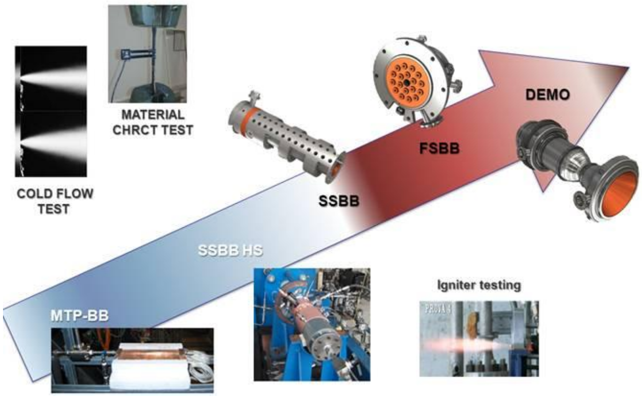

Figure 1 - Logical steps of LOX/CH4 Demonstrator development.

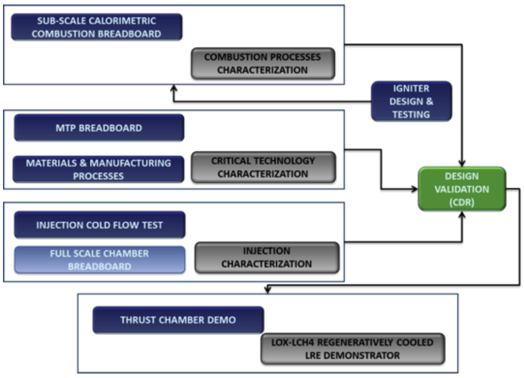

Figure 2 - HYPROB-BREAD Study Logic

2. THE SSBB-HS: HEAT SINK CHAMBER

A single injector thrust chamber version, named “heat sink” SSBB, has been designed, manufactured and tested in order to mitigate the risks in the HYPROB-DEMO development and testing. As anticipated in the previous section, the SSBB-HS combustor has been designed with the aim of investigating the combustion process, the single injector behaviour and the heat release to the wall [2]-[5].
The SSBB-HS objectives are the following:

- to investigate the behaviour of the injector
- to obtain a first estimate of the heat flux on the combustion chamber for model validation
- to implement a chamber "battleship" for a first verification of the combustion stability.

The SSBB-HS consists of three main parts, as depicted by Figure 3: the injection head, the combustion chamber module (made of a copper alloy) and the throat/nozzle module (made of molybdenum alloy, capable to withstand the high throat heat fluxes).

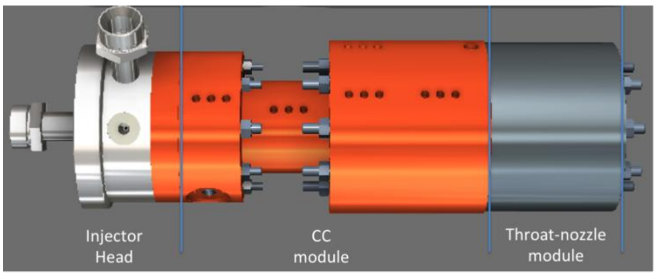

Figure 3 – SSBB-HS with visible thermocouples holes.

The combustion chamber is equipped with embedded thermocouples that allow for heat load evaluation and different pressure transducers for monitoring chamber pressure.

Heat fluxes rebuilding logic

The SSBB-HS is equipped with 14 embedded thermocouples (in the second campaign configuration), which will be able to operate to high heat flux levels up to 40 MW/m^2. They can be mounted in the copper wall without disturbing the temperature and heat fluxes, have a response time of 0.1 seconds and they are easy to install. For these purposes "K" thermocouples have been selected with a frequency response of 100Hz. The thermocouples have been installed in the positions shown in Figure 4.

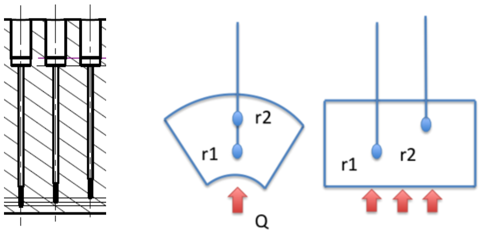

Figure 4 - Thermocouple triplets and scheme for measurements

A methodology similar to the one proposed in [7] has been applied in order to rebuild data, due to its simplicity and at the same time accuracy, using a polar coordinate system adopting a 4th order polynomial development of the temperature function and using the following 1D equation.

$$\rho c \frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \frac{1}{r}\frac{\partial}{\partial \mathrm{r}} \ \mathrm{kr}\frac{\partial \mathrm{T}}{\partial \mathrm{r}}$$

With this kind of approach two thermocouples are needed, the third one is used as a backup and to account for axial effects.

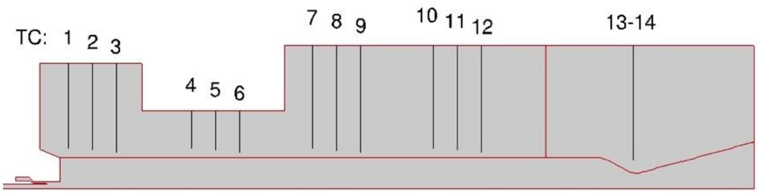

Figure 5 - Thermocouple positioning

3.IGNITER

A customized igniter, sketched in Figure 6, has been developed and tested for the SSBB combustion chambers [8]. This is a spark torch ignition system that uses two propellants (GOX and GCH4) that are mixed in the igniter combustion chamber and ignited by a commercial spark plug. The igniter is made up of two main parts (Figure 7), the igniter head (1) and the torch outlet (2) with flanged interfaces sealed by metal O-rings. The fuel and oxidizer are injected via orifices. The inlet paths of CH_4 and O_2 are equipped with PT sensors; additionally a pressure sensor is installed in the main chamber in order to monitor chamber pressure [9]. The nominal performances are reported in Table 1 and a CFD numerical contour obtained during the numerical rebuilding phase is reported in Figure 8.

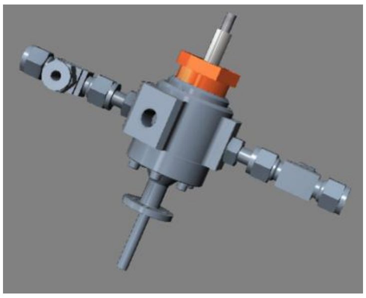

Figure 6 - Igniter sketch.

Table 1 - Nominal performances of the igniter

Performance	**Value**
Total Power (kW)	64
Nominal firing time (s)	1.5
Maximum firing time (s)	2.0
Demonstrated shelf life cycles	≥ 20
Chamber Pressure (bar)	14

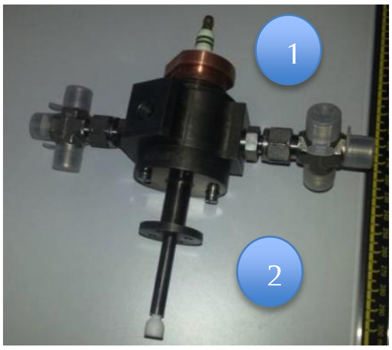

Figure 7 - Igniter assembled

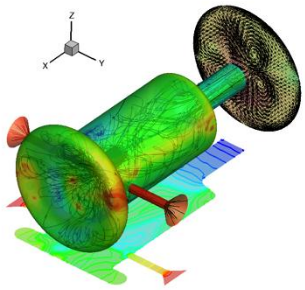

Figure 8 – Igniter CFD simulation

4. SYSTEM ANALYSES

The aim of the system analyses, performed by means of ECOSIMPRO tool [10], is to have a preliminary evaluation of chamber behaviour during the transient phases and a verification of its performances. The model mainly consists of a combustion chamber and a nozzle interfaced with different parts of walls: 1 to 4 for the copper alloy chamber and 5 to 6 for the molybdenum-based alloy part (see schematics in Figure 9).
Looking at Figure 10 and Figure 10, the expected behaviour of thermocouples is shown. The derivative of the temperature in time is proportional to the heat fluxes incident on the chamber.

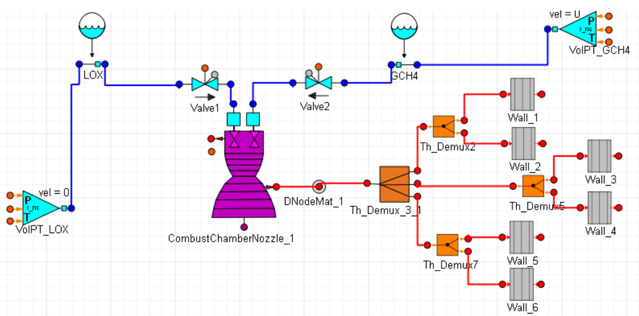

Figure 9 - Schematics of the HEAT SINK SSBB

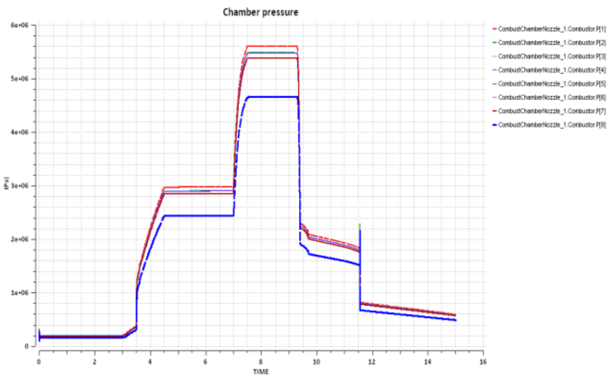

Figure 10- Chamber Pressure in time

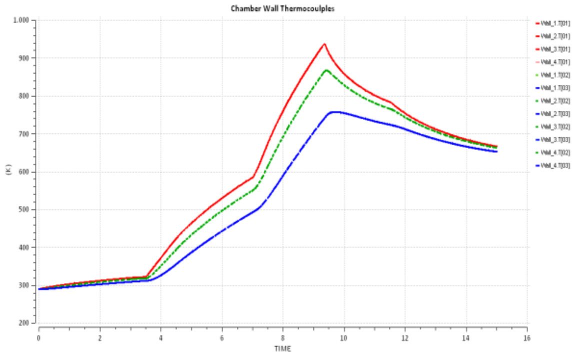

Figure 11 - Wall Nodes temperature in time.

Regarding the system stability study, the ROCCID© code has been used for all the extremes of the operative envelope [11]. No criticalities are foreseen. In any case the SSBB-HS has been designed in order to withstand more than 3 times the nominal pressure level, and a second unit will be equipped with a high frequency pressure transducer. The results of the stability analysis, both in low and high frequency range, are reported in Figure 12 and Figure 13.

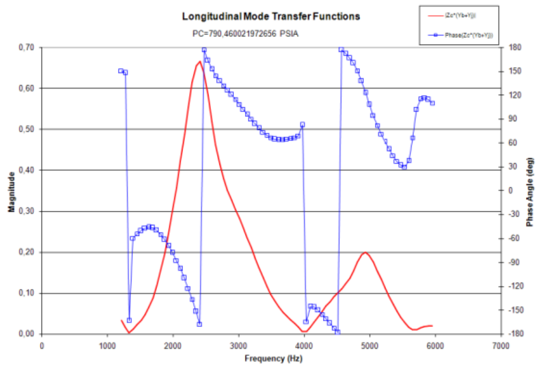

Figure 12 - 1L High Frequency Transfer Functions at nominal operating condition

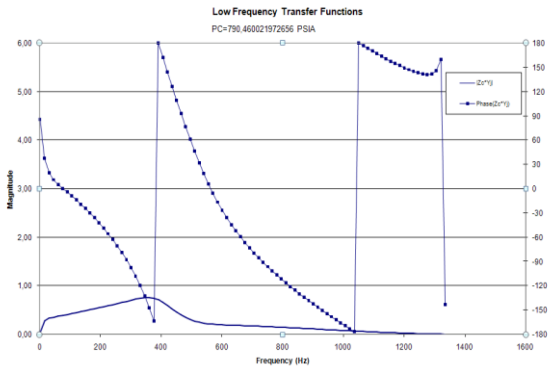

Figure 13 - Low frequency transfer function at nominal condition

CFD analysis

The main aim of the preliminary CFD analysis is to verify the pressure levels (Figure 14) and heat loads on the combustion chamber [12],[13].

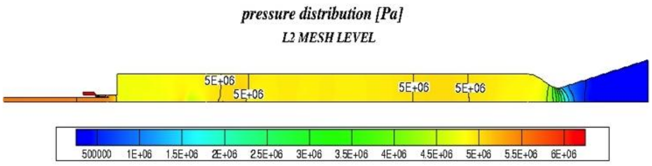

Figure 14 - Pressure distribution in the computational domain, flood and 50 bar iso-lines

The chamber/nozzle and wall heat flux profile is shown in Figure 15. It is worth noting that, because of the fluctuations of the RANS field, the distribution in Figure 15 is only a snapshot of a solution which is continuously evolving, so that it is possible to identify only the average values.

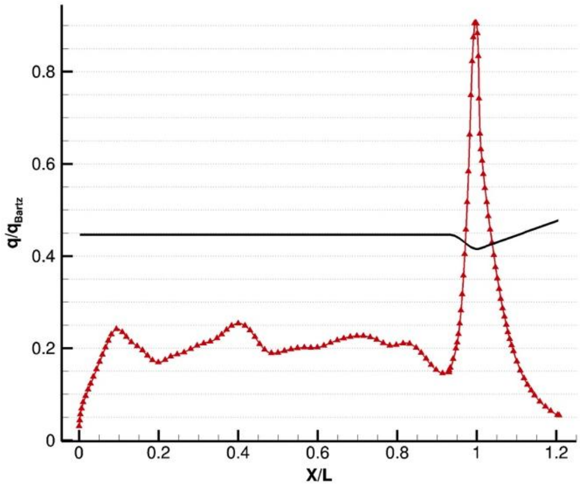

Figure 15 - Heat flux distribution along the chamber and nozzle walls

FEM results

For the verification of the chamber, a thermo-structural analysis has been carried out in order to evaluate if the maximum firing time is compatible with the structure and by applying a load cycle to evaluate the life cycle of the chamber [12].

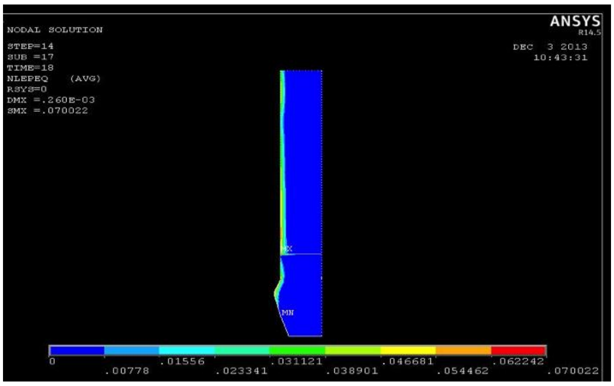

Figure 16 - Equivalent plastic strain after 2 cycles

2. Experimental test campaign

Two experimental test campaigns have been performed in AVIO FAST2 facility.

In the first test campaign, after the igniter testing and the definition of the ignition testing sequence, 4 tests have been successfully accomplished:

- 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 only on the cylindrical part of the chamber.
In the second test campaign, two thermocouples have been added 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 Pc about 28 bar) for a steady state duration of 9 s.
- 2 tests at low pressure (nominal Pc about 28 bar) for a steady state duration of 11 s.

The test duration has been increased at the end of each test campaign in order to acquire further data for a more accurate rebuilding of the tests.

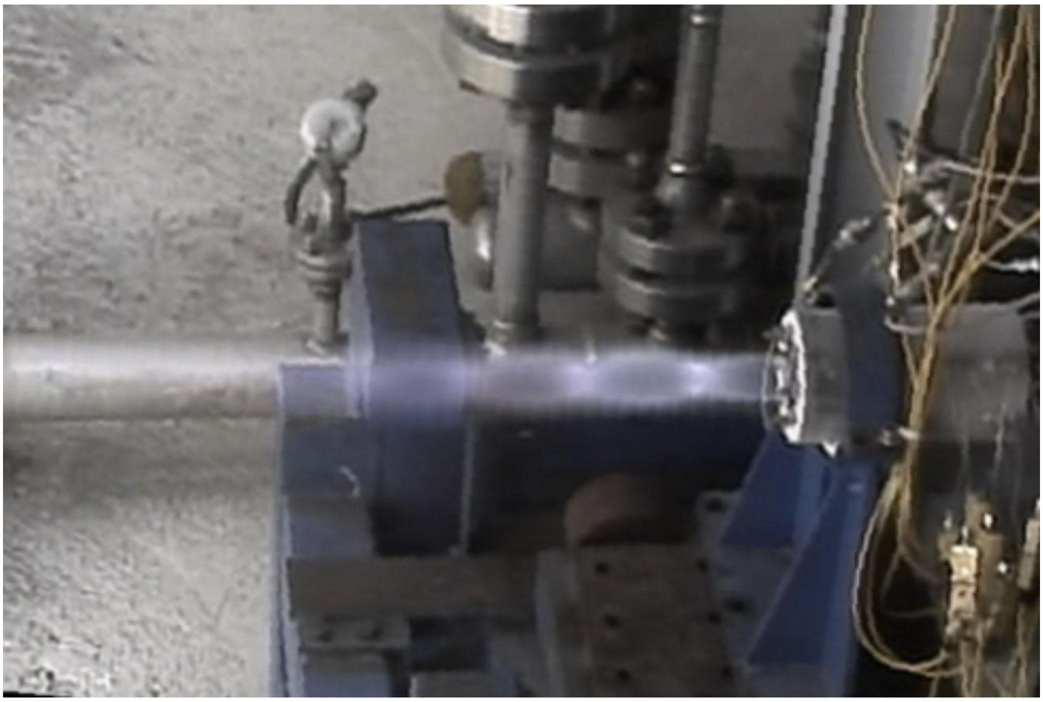

Figure 17 - Test article during firing

It has to be remarked that both methane pressure and oxygen temperature 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.

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

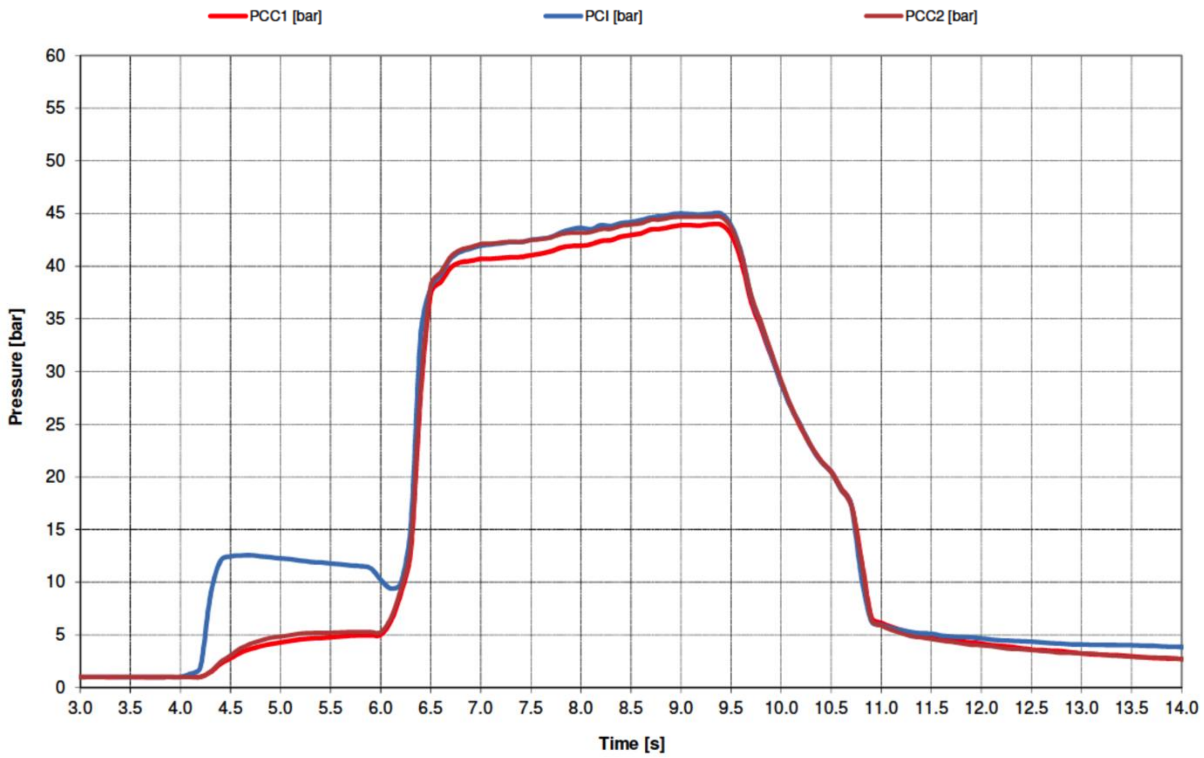

Figure 18 - Test #7 (High pressure test): Pressure vs time (in barg)

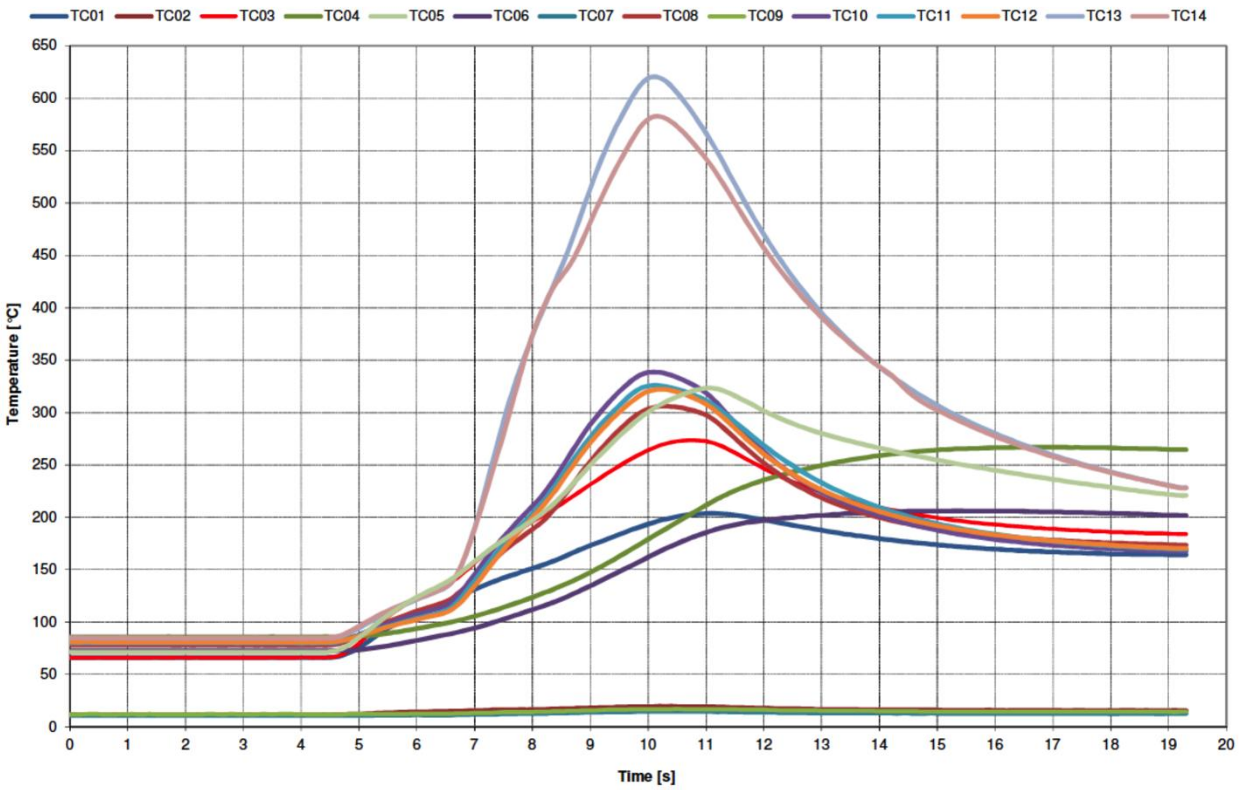

Figure 19 - Test #7 (High pressure test): thermocouple temperatures vs time

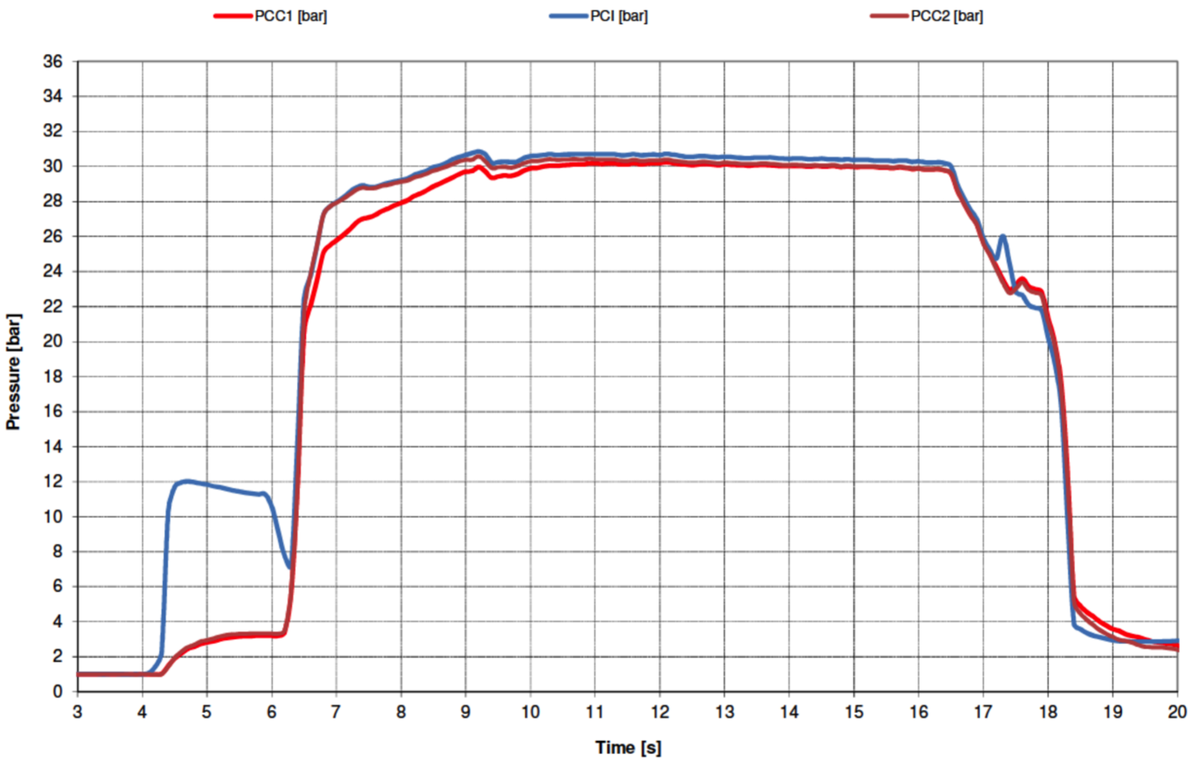

Figure 20 - Test #10 (low pressure test): Pressure vs time (in barg)

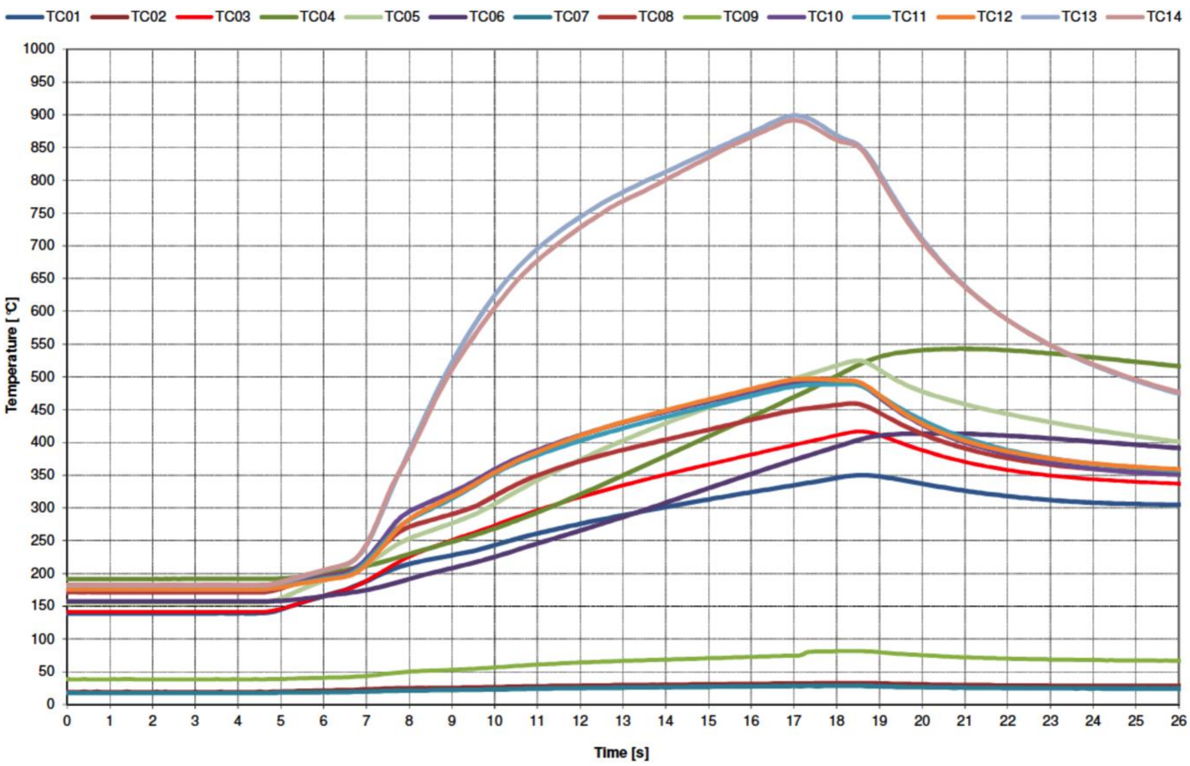

Figure 21 - Test #10 (low-pressure test): thermocouple temperatures vs time

It is important to underline that the test article has shown a stable behavior 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.

2.2 Data assessment and preliminary rebuilding

Due to the lack of data for what concerns flow rate, a numerical procedure has been set up in order to properly define firing condition in terms of MR and flow rate by means of ECOSIMPRO [10]. The procedure is based on the pressure data in domes and combustion chamber acquired during firing test campaign and on the data collected in the cold flow test campaign.

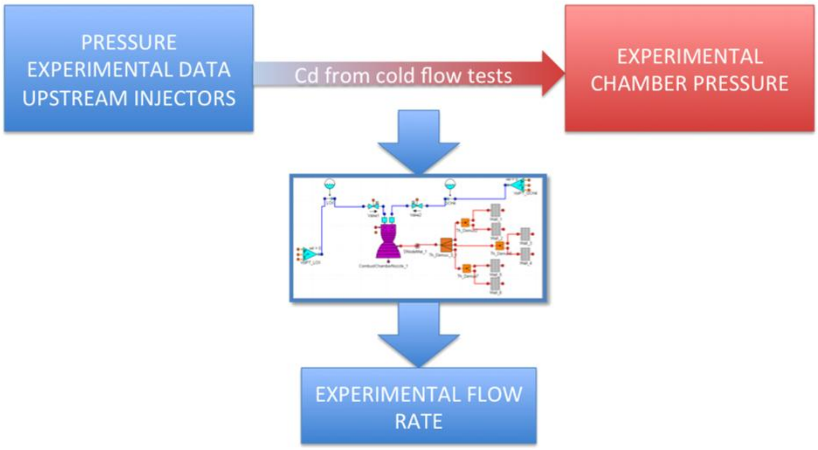

Figure 22 - Procedure to extrapolate experimental flow rate in the experiment

At this point of the procedure is possible to start Bartz equation model [14] tuning in the EPSS library. The steps of the procedure are reported in the following figures.

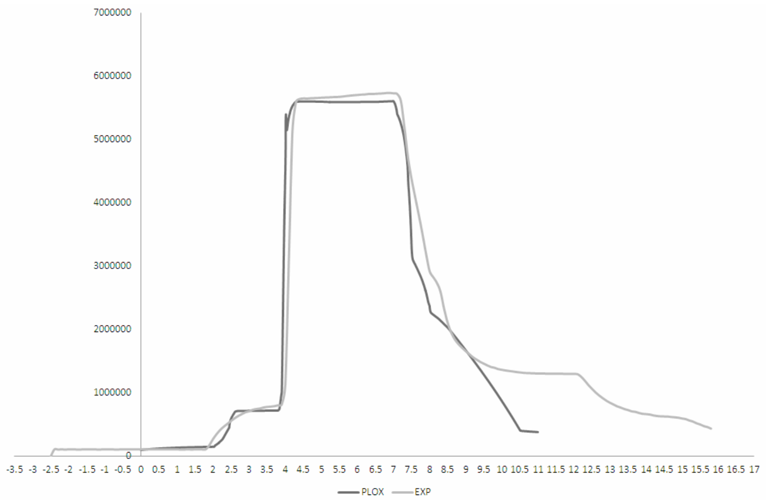

Figure 23 - Experimental upstream injector oxygen pressure versus predicted values with the Ecosimpro model

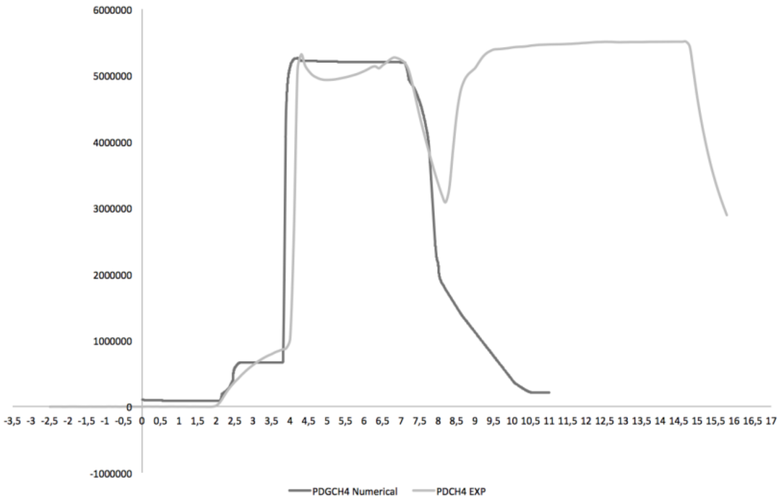

Figure 24 - Experimental upstream injector methane pressure versus predicted values with the Ecosimpro model

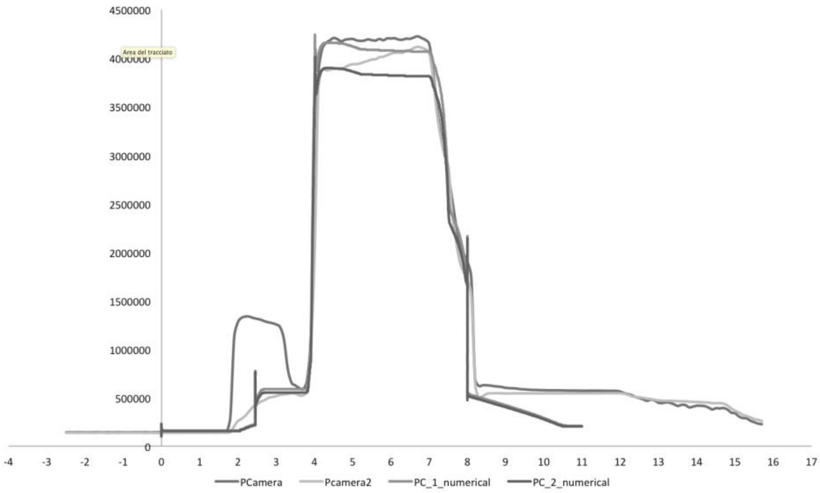

Figure 25 - Experimental chamber pressure versus predicted values with the Ecosimpro model

Once matching the experimental data in terms of pressure, the Bartz [14] equation in the ECOSIMPRO model has been tuned from thermocouples data.

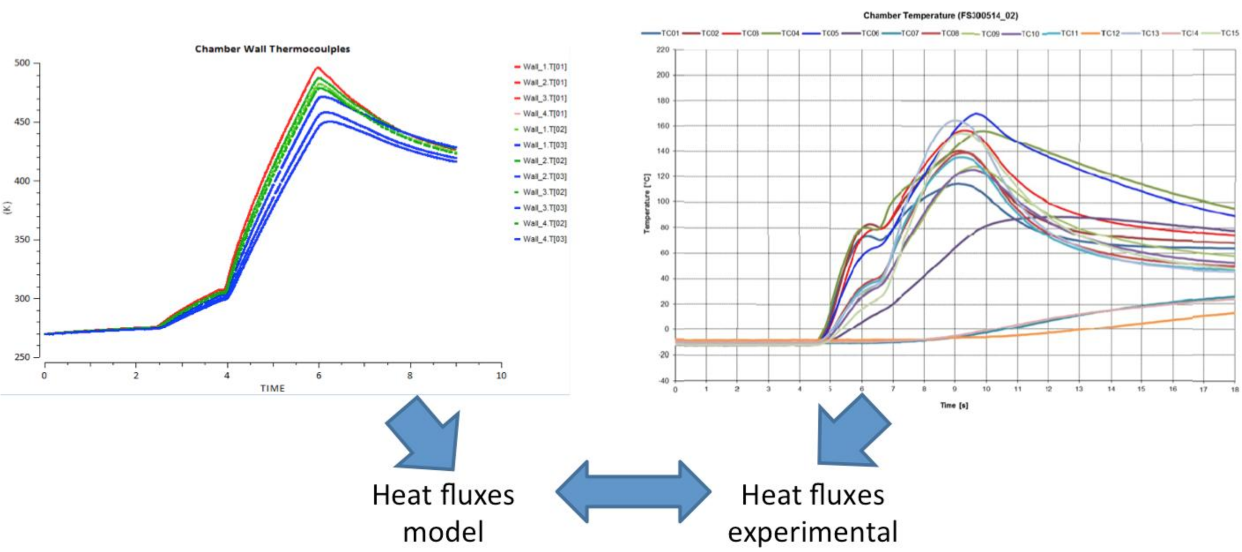

Figure 26 - Procedure to tune Bartz equation

2.3 CFD preliminary rebuilding

Numerical re-building of the experimental tests has been carried out in order to validate CFD methodologies. Unsteady simulations have been requested to reproduce as better as possible the firing test sequence. The coupling between combustion chamber and solid part has been simulated to estimate temperature values in the thermocouples' position. ANSYS Fluent Code (ver. 15.0) has been used [12].
The computational domain is depicted in Figure 27 with the imposed boundary conditions. It includes both the fluid part (in red), where the combustion occurs, and the two solid parts of different materials, CuCrZr and TZM (green and blue respectively) [15].

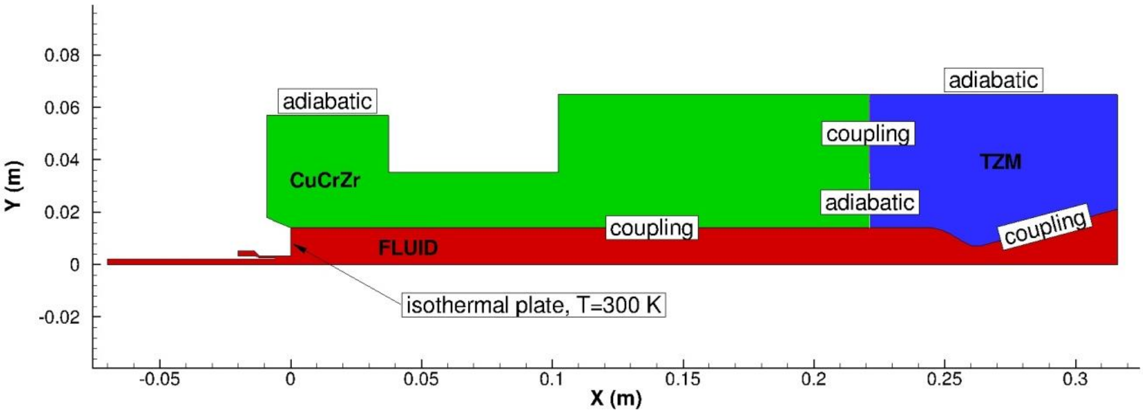

Figure 27: Computational domain and imposed boundary conditions

The thermal coupling has been considered between the solid/fluid interface and the solid/solid upper connection, while the adiabatic condition has been imposed for the solid/solid lower part connection and the external solid domain. The injection plate has been considered isothermal, with imposed temperature of 300 K. Mass-flow inlet condition has been used to inject oxygen and methane in the fluid domain, pressure outlet at the exit, according with the values reported in the following test for the test firing under analysis in the full mode condition. Mass-flow rate values, used in the preliminary mode, are 10% of the full mode values.

Table 2: Boundary conditions

	Temperature [K]	***Pressure [Pa]***
Oxygen inlet	*133*	*3000000*
Methane inlet	*297*	*3000000*
Outlet	*/*	*101325*

The structured computational mesh has been generated using ANSYS ICEMCFD and it was opportunely tuned to guarantee the validity of the wall function model (Standard Wall Function) and the accuracy of near wall flow field simulation. The mesh main characteristics are reported in Table 3.

Table 3: Mesh characteristics

Number of blocks	***Number of cells***	***Quality***
47	*24932*	*0.75*

The ideal gas equation of state has been implemented in order to make the computation as simple and quick as possible; the use of the real gas model in conditions below the critical point (equilibrium chamber pressure of the simulated firing test is about 27 bar) could have required a lot of effort because a specific computational strategy needs to be provided in order to avoid divergence.
Turbulence has been modelled by means of standard k-ε, with the standard wall functions for the near wall treatment.
The Eddy-Dissipation-Model has been selected for taking into account turbulence – chemistry interaction, together

with a mono-step kinetic reaction scheme which uses four species and an artifice on the formation enthalpy of the methane to decrease the adiabatic flame temperature (1) or nine species (2), allowing without artifice for a more realistic flame temperature.

$$CH4 + 2O2 \leftrightarrow CO2 + 2H2O \qquad (1)$$

$$298CH4 + 426O2 \leftrightarrow 365H2O + 235CO + 160H2 + 76OH + 66H + 63CO2 + 18O + 16O2 \qquad (2)$$

Preliminary and full mode have been simulated as in the experimental firing test, by means of transient simulations, trying to reproduce as better as possible the firing test sequence. A pressure-based scheme has been adopted using SIMPLE scheme. The time step size has been set to $1e^{-6}$ s to reach the solution convergence for the reacting flow in the fluid domain (some 10 ms) and then it has been increased to $1e^{-5}$ s to allow for a faster solution evolution in the solid domain.

A qualitative temperature contour plot in the computational domains, both solid and fluid parts, is depicted in Figure 28. The numerical solution is referred to a simulated time of 1.5 seconds in preliminary mode and 3 seconds of full mode, for a total time of 4.5 seconds. Values in the fluid domain reach 3200 K where the flame is completely developed; in the first part of the chamber, as displayed in the secondary frame of Figure 28, temperature values are around 2500 K where the reaction occurs.

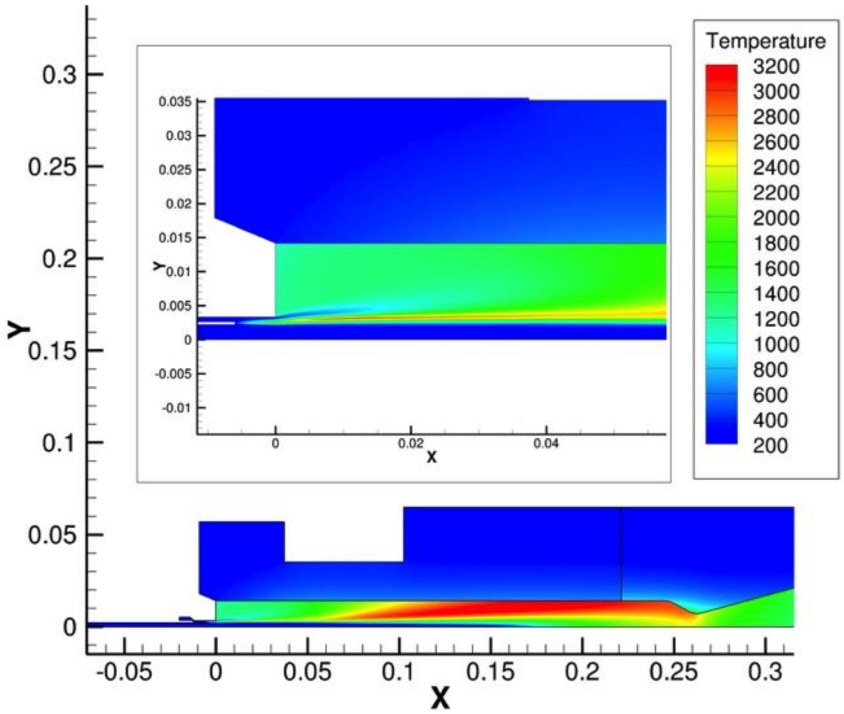

Figure 28 - Qualitative temperature contour plot, t = 3 s

The numerical simulations predicted a chamber pressure value of about 27 bar, as reported by Table 4, against the measured value of 30 bar. In the oxygen and methane lines numerical predicted values are, respectively, 34.3 and 42.9 bar, in good agreement with the experimental results.

Table 4: Comparison between pressure values

	Experimental*	***Numerical****
Oxygen line	*35*	*34.3*
Methane line	*42*	*42.9*
Combustion Chamber	*29*	*26.7*

** Values in [bar]*

For the test under analysis, temperature values experimentally measured during the first 7 seconds from the firing are reported in Figure 29, while temperature values estimated by CFD for the same thermo-couples in the same time interval are depicted in Figure 30. Thermo-couples TC4, 5, 6, 7, and 9 are not plotted since experimental values have not been acquired as aforementioned.

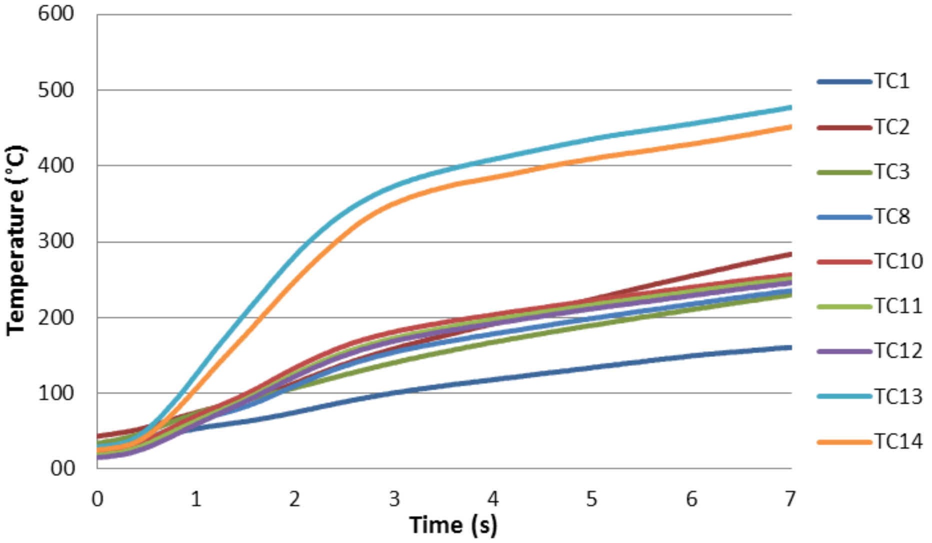

Figure 29 - Temperature values experimentally measured

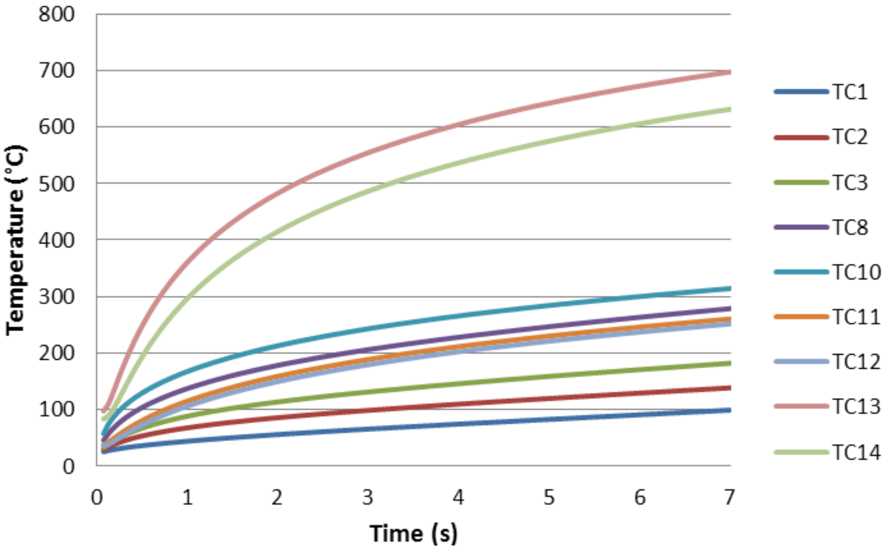

Figure 30 - Temperature values numerically predicted

The preliminary comparison shows a good agreement on the second part of the chamber wall while some discrepancies in the first part of the chamber and in the nozzle are observed. It is very important to underline that, comparing experimental and numerical results, the transient in the first seconds are quite different and, therefore, the initial transient modelling should be strongly improved. In particular, the under-estimation of temperature can be observed near the firing plate, for all the three thermo-couples; this is especially evident for TC2 where about 280 °C are measured after 7 seconds against 140 °C numerically predicted. The reason of this disagreement could be related to an erroneous description of the recirculating zone, probably linked to the ideal gas assumption: the implementation of a real gas equation [16] is expected to bring to a reduction of the recirculation, with a consequent up-stream movement of the re-attachment point and, therefore, of the heat flux peak; moreover the constant value of the temperature as boundary condition for the injection plate could have an influence on the numerical results predicted in this zone.
Taking into account all the previous considerations, it is evident that these preliminary analyses are not exhaustive and further studies are needed before making any final conclusions. However, the work seems to be quite promising.

Conclusions

All the activities related to the design, manufacturing and testing of the SSBB-HS single injector thrust chamber have been described in this work. Test campaigns have been carried out successfully, allowing for the collection of data for a interesting range of pressure for what concerns the LOX/GCH4 propellants. Data are still on processing due to some problems in the acquisition by the test facility. Rebuilding is on the preliminary phase and a strong work is still needed in order to complete this important and concluding phase of the work.

Acknowledgements

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