Design and Testing of a GOX/GCH4 Igniter for Small Scale Rocket Engine Thrust Chambers.

Francesco Battista, Michele Ferraiuolo*, Adolfo Martucci*, Ainslie French*, Pietro Roncioni*, Manrico Fragiacomo*, Vito Salvatore*,*

**CIRA (Italian Aerospace Research Centre)*

Via Maiorise, 81043 Capua (CE), Italy

*Leonardo De Rose***

***AVIO,*

Via Ariana, 00034 Colleferro (RM), Italy

Abstract

The work described in this paper is conducted in the framework of the HYPROB Program that is carried out by the Italian Aerospace Research Centre (CIRA) with 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. This paper discusses the design and fire-testing results of the gaseous oxygen-gaseous methane torch igniter designed for a subscale experimental "breadboard" (SSBB) LOX/Methane rocket engine. The igniter presented in this work is reliable and easy to interface with different small-scale combustion chambers.

1. Introduction

The HYPROB program is carried out by CIRA under contract by the Italian Ministry of Research with the main objective to enable and improve National system and technology capabilities on liquid rocket engines (LRE) using propulsion systems for future space applications, with specific regard to LOX/LCH$_4$ technology. As far as the System line devoted to the LOX/LCH$_4$ technology is concerned, a first implementation project has been launched, called HYPROB BREAD, aimed at designing, manufacturing and testing a LRE demonstrator of 3 ton thrust class, based on a regenerative cooling system using liquid methane as refrigerant. Moreover, within the HYPROB-BREAD project the design of various breadboards aimed at the investigation of critical design aspects in the development of the complete system is planned. These breadboards and their position in the work-logic of the project are widely described in [1]. Among these the Sub Scale Breadboard (SSBB, Figure 1) is a scaled down version of the 3 ton thrust LRE Demonstrator with only one injector and represents an important intermediate step of the project to validate the design and the performance of the injector. For this breadboard the igniter, the subject of this paper, has been designed.

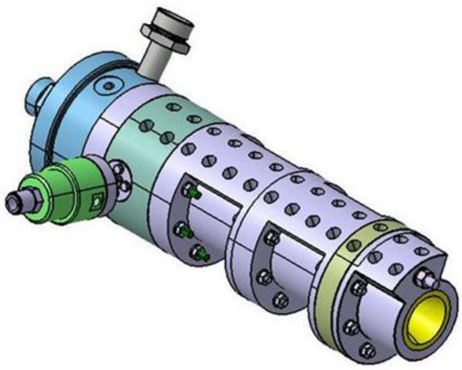


Figure 1 – Sub Scale Bread Board 3D view

In order to fulfil the SSBB system requirements the igniter has to be at the same time reliable, simple and cheap, customized on the SSBB thrust chamber but easy to adapt for the installation on other small-scale chambers. Keeping these requirements in mind and also following the indications reported in [2] the choice of developing a spark-torch igniter has been made. Moreover, it should be noted that most modern restartable rocket engines use either a spark-torch igniter or a pyrophoric (hypergolic) igniter. Spark-torch igniters burn a bipropellant mixture, which is obtained from the main propellant tanks (e.g. RL10) or from a separate feed system (Vinci). Pyrophoric igniters have been used to ignite restartable LOX/Kerosene engines (e.g. RD-180) and LOX/LH2 engines (EADS cryogenic 300N engine), and operate by injecting a third chemical into the combustion chamber, which reacts spontaneously with oxygen. The chemical used is usually a mixture of the substances triethylborane and triethylaluminium. These chemicals are highly toxic and ignite spontaneously on contact with air, making them difficult to produce, store and handle. In light of these considerations, it is important to remark that the design of a "green" solution with oxygen and methane that could be installed on modern rocket engines, providing a multiple restart capability, surely represents an important technological opportunity.

Ignition technology	Applicable in			Specific characteristics	
	LRE single ignition	LRE multiple	SRM	Pro	Con
Pyrogen	++	+*	++	TRL 9 Price per ignition relatively low (in comparison to spark torch and catalytic) Predefined performance Compact (no feed system)	Class 1 device Predefined performance Single ignition per device
Spark torch	+	++	-	TRL 6 Re-ignitable Clean combustion products Easily re-usable for tests	High voltage electronic parts Requires feed system for oxidiser, fuel and possibly purge gas
Catalytic	++	++	-	Re-ignitable No high voltage parts Re-usable after refurbishment Fuel flexible	TRL ~4 Catalytic bed needs refurbishment Requires feed system (for oxidiser, fuel and possibly purge gas)
Laser	++	++	-**	Compact and light Multi-point ignition, in desired spatial region Re-ignitable, re-usable	TRL ~2 Theoretical advantages, unknown disadvantages

++ Very suitable
+ Suitable
- Not suitable

* Multiple devices are required for multiple ignition
** On large SRM scale solid propellant ignition by laser is not (yet) deemed feasible

Figure 2 – Comparison of different igniter technologies [2]

2. Igniter Description

The spark torch ignition systems use two propellants (oxygen and a fuel) that are mixed in the igniter combustion chamber and ignited by a spark plug. In this way the igniter produces a torch flame that in turn is used to ignite the main combustion chamber of a rocket engine. A large benefit of spark torch igniters is their ability to provide restartability to a space engine. A spark torch system consists of three main parts:

- The igniter feed system in which the fuel and oxygen are stored under high pressure;
- The igniter, a small combustion chamber in which the igniter gasses are ignited by a spark plug;
- The exciter that delivers the energy to the igniter spark plug.

The architecture of the GOX/GCH_4 torch igniter presented here, takes into account different literature efforts regarding igniter design, in particular the one reported in [3] focused on H_2/O_2 pair of propellants. The architecture of the igniter is shown in the Figure 3. The igniter is mainly made up of two main parts, 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 spark torch (3) is provided by AVIO and has 5μs of duration and 25mJ per pulse. The igniter is not actively cooled and is made of TZM alloy. In this way high temperatures may be managed by radiation cooling for the necessary firing time, the stem part may be coupled with materials such as steel, Inconel or copper alloys. The inlets of CH4 and Oxygen are equipped with PT sensors; additionally a pressure sensor is installed in the main chamber in order to monitor chamber pressure. A summary of the nominal performances of the igniter is reported in the following Table 1.

Table 1 Nominal performances of the igniter

Performance	**Value**
Total Power (kW)	64
Total mass flow rate (g/s)	16
Nominal firing time (s)	1.5
Maximum firing time (s)	2.5
Shelf life cycles	≥ 20
Expected throat heat fluxes (MW/m^2) [4]	14

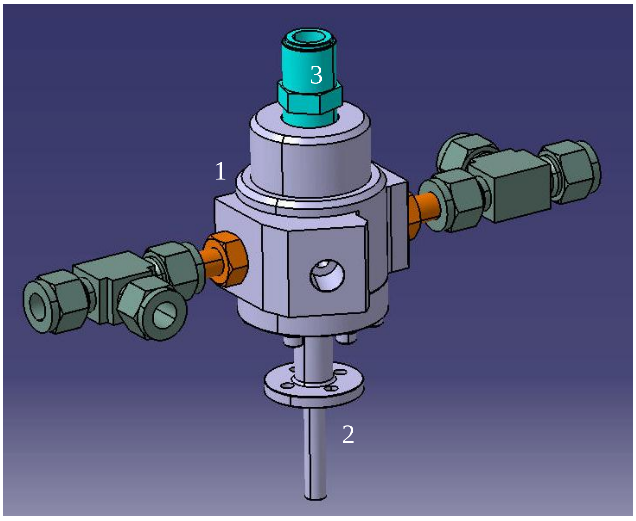


Figure 3 – Igniter Architecture

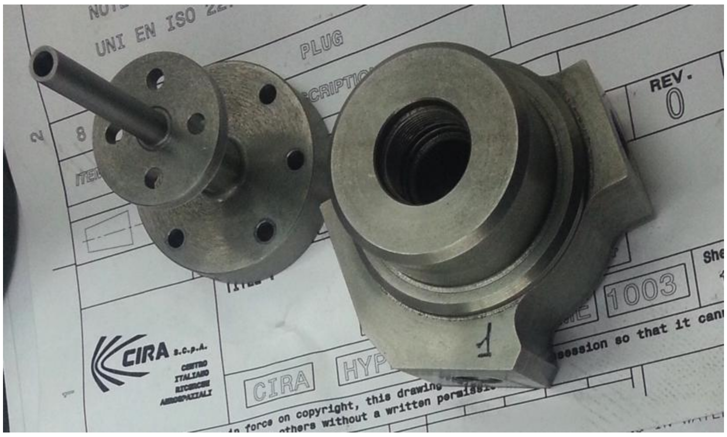


Figure 4 – Igniter head and torch outlet

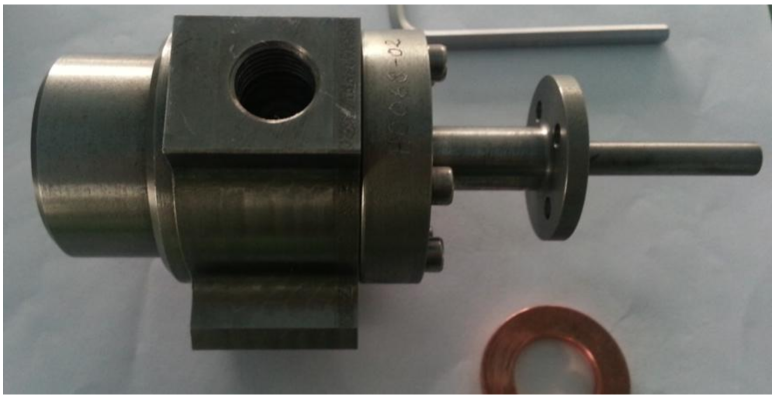


Figure 5 – Igniter assembled

2. Design Analyses

In this section the analyses made in order to validate the design of the igniter are briefly reported.

2.1 System analyses

In the following the results of system analysis made on the igniter by means of the software ECOSIMPRO [5] in order to verify design performances at steady state as predicted by the igniter design tool methodology/software developed by CIRA are reported.
The model is quite simple and is composed of two pressure and temperature inlets that simulate facility inputs, O_2 and CH_4 valves and a combustion chamber (Figure 6). In this case the combustion efficiency has been evaluated by means of RPA[6] as 0.9787. Considering this efficiency the results in terms of pressure and temperature are reported in Figure 7. The results confirm that the throat is sonic and throat pressure is about 10 bar.

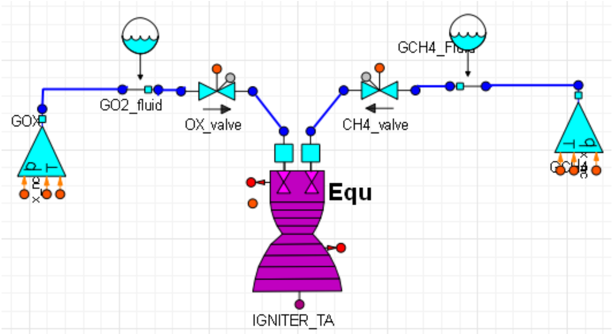


Figure 6 – ECOSIMPRO Igniter Schematics

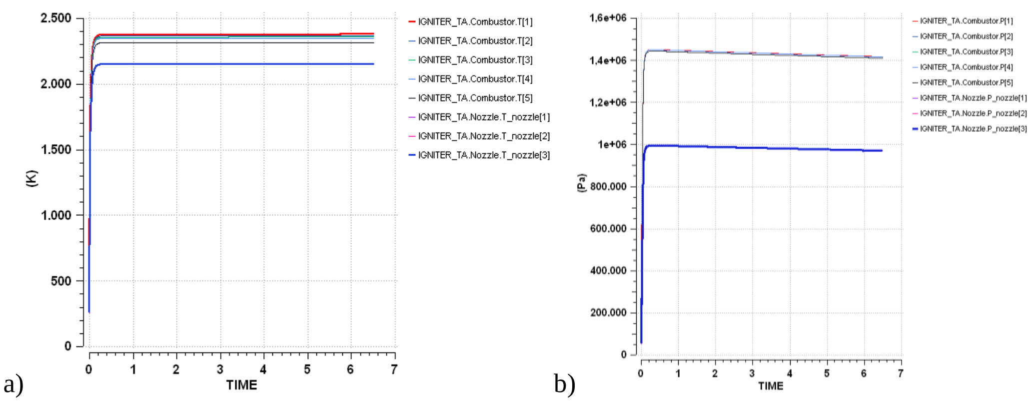


Figure 7 – Design verification results a) temperature b) pressure at different axial stations

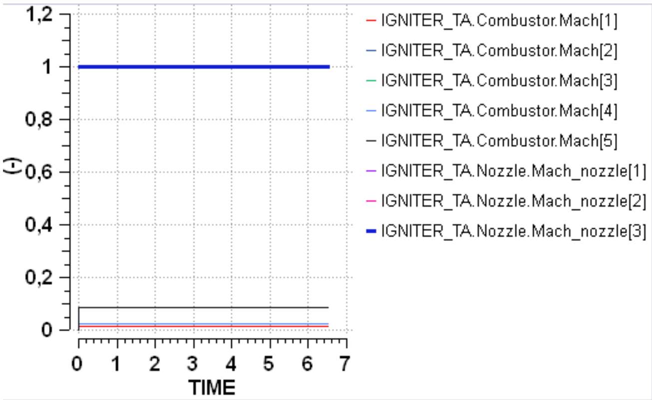


Figure 8 – Mach number at different stations

2.2 CFD & Thermo-structural analyses

The main objective of the CFD simulation is to obtain heat loads for the analysis on the igniter and on the SSBB combustion chamber where the igniter jet impinges. The simulations conducted using FLUENT® are for fully reacted flow where the species distribution and temperatures are given at the inlet represented by the chamber section obtained by chemical equilibrium simulations [6]. A 2D axisymmetric grid is generated for the ignition chamber and igniter nozzle and rocket chamber section. This modelling is viable since the heat fluxes along the igniter chamber and nozzle walls and on the rocket chamber wall opposite the igniter outlet are of principal interest. Figure 9 shows a sample pressure distribution and Figure 10 shows heat loads along the igniter wall and engine chamber right hand wall respectively. These simulations confirm the results of the ECOSIMPRO analysis and are used to give the thermal input to the thermo structural analyses.

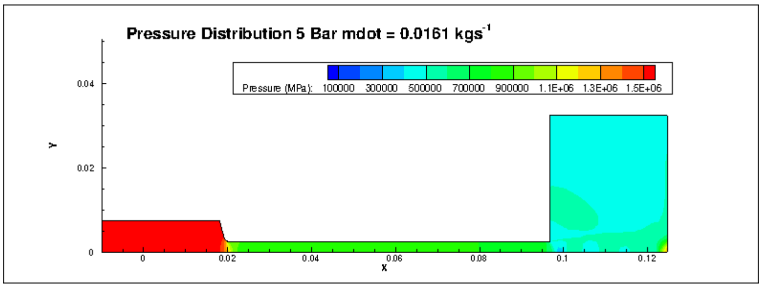
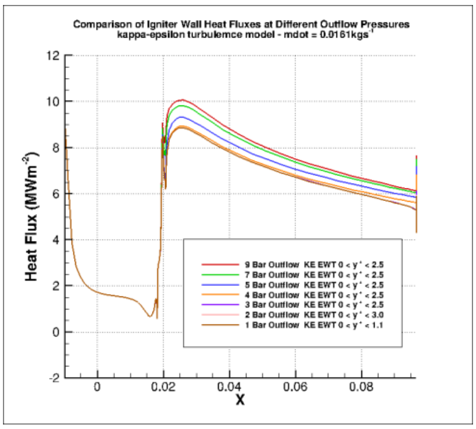


Figure 9 – Pressure distribution with 5 bar exit pressure.

a) 

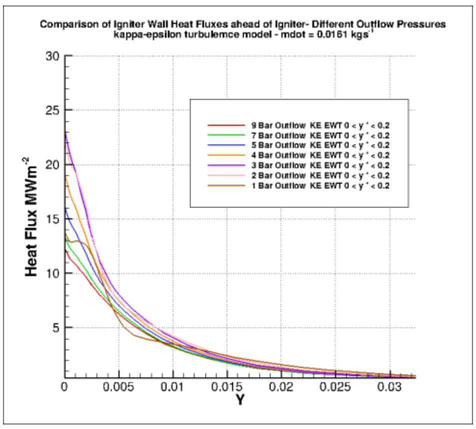
b) 

Figure 10 – Igniter wall heat fluxes (a) and heat fluxes on impinging chamber wall (b) at different conditions

An axisymmetric FEM model has been considered in this analysis using ANSYS®. Radiative effects have been taken into account in the gap between the TZM alloy structure and the Inconel 718 structure. A schematic representation of the geometric model considered for the FEM analyses is illustrated in Figure 11. Figure 12 shows the temperature distribution in the TZM alloy igniter structure after 1.5 seconds. The maximum temperature 1692 K is satisfactory since it is lower than the maximum allowable value for the TZM alloy.

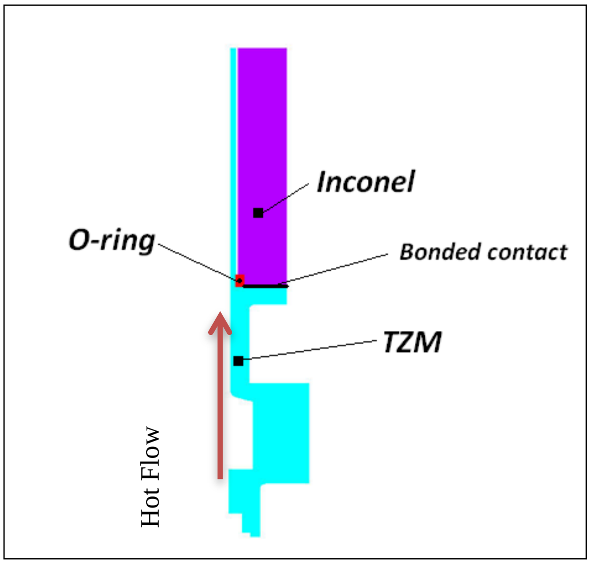


Figure 11 – Geometry considered for the FEM analyses

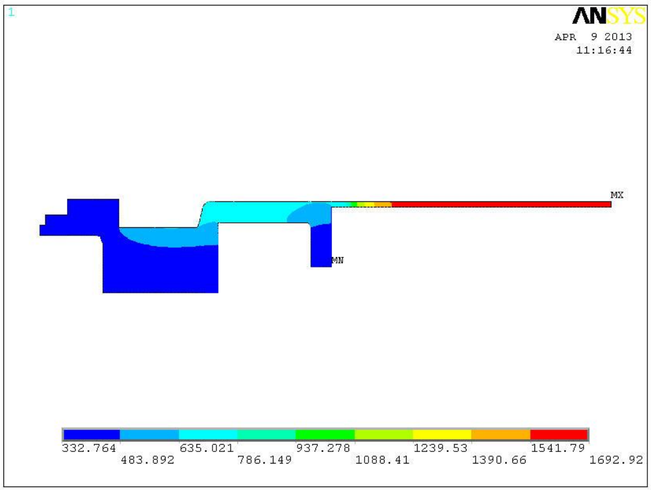


Figure 12 – Temperature contour plot after 1.5 seconds

Figure 13 shows the equivalent plastic strain after 10 thermo-mechanical cycles. The maximum value is 0.93% which is considerably lower than that for elongation breakage strain for the TZM alloy. The shelf life calculated is equal to 102 cycles without considering any safety factor.

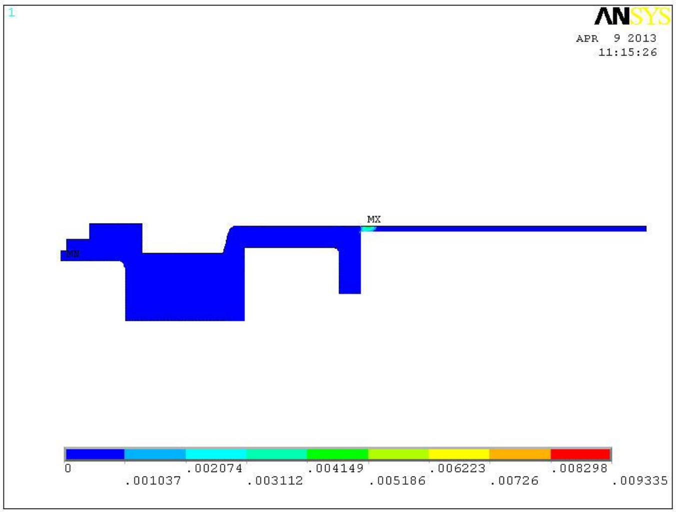


Figure 13 – Equivalent plastic strain contour plot after 10 cycles

3. Test results

In this section the results of the preliminary firing test on the igniter are presented and briefly discussed. The igniter was preliminarily mounted for leak test and cold flow testing, after this phase; the firing tests have been executed. In Figure 15 different images from firing sequence are shown. It should be noted that the stem and throat parts of the test article during the fire test radiated light, thereby qualitatively confirming the temperature levels predicted by means of the thermal analyses shown in the previous section.

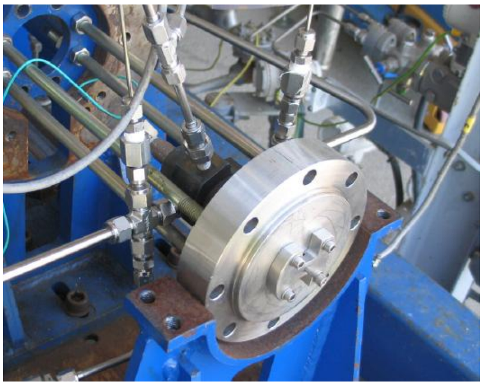


Figure 14 – Igniter mounted on test bench for leak testing

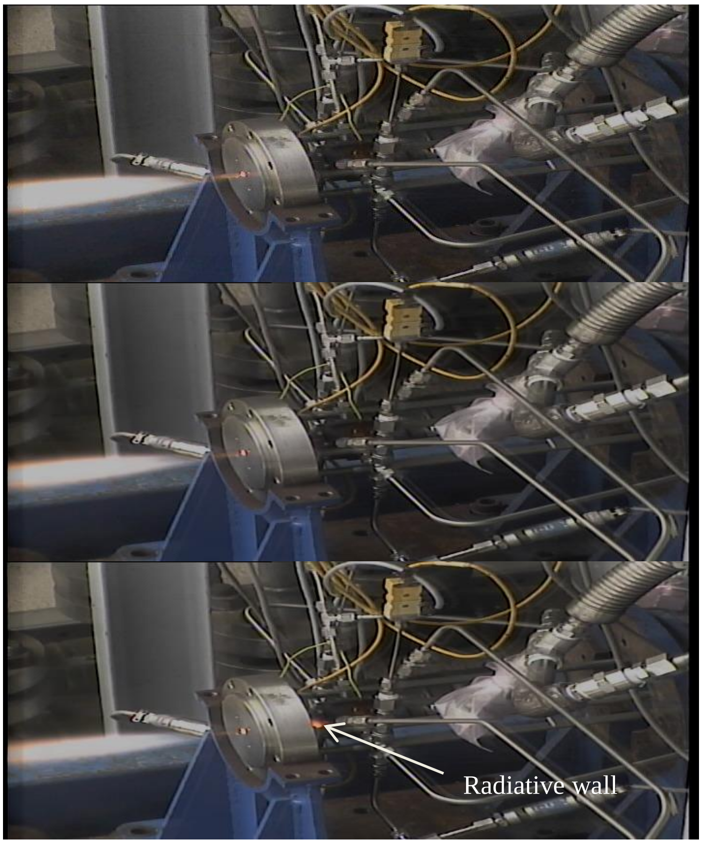


Figure 15 – Firing test images at 0.5s, 0.8s, 1.2s

In Figure 16, the data from the pressure sensors installed on Oxygen and Methane inlets as well as on the combustion chamber wall are reported. The pressure profile shows that the pressure in the chamber is slightly higher than that of the design, which could be explained by higher combustion efficiency.

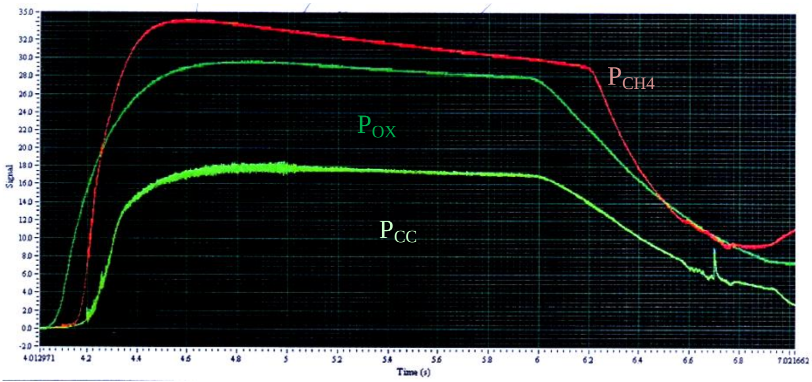


Figure 16 – Experimental pressure plots (bar)

In particular, different simulations have been performed using the ECOSIMPRO model (Figure 6) using different combustion efficiencies that show their effect on chamber pressure. For the test under examination it could be concluded that combustion efficiency is close to 1.

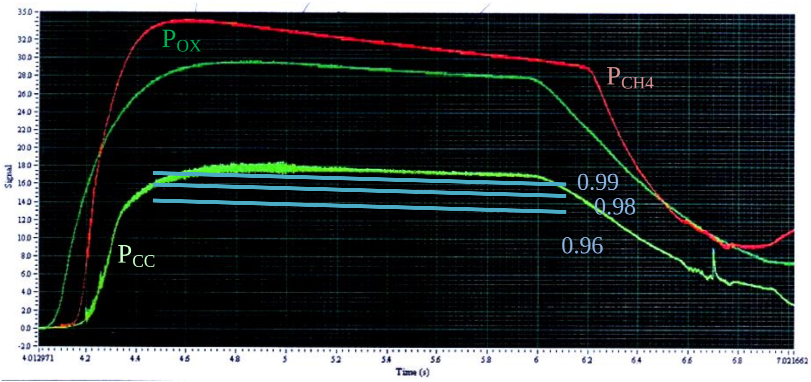


Figure 17 – Experimental pressure plots (bar) compared with ECOSIMPRO results with different combustion efficiencies

After firing the hardware was inspected and no particular problems were noticed. In particular, the diameters of the stem part (the hotter part) were checked, before and after firing and no variations in dimension were observed. A discoloration of the external wall was identified probably due to the vaporization of the solution used for the leak test (Figure 18).

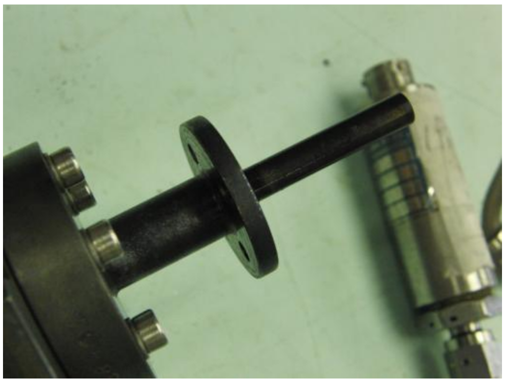


Figure 18 – Hardware after firing

Conclusions and Future work

In this work the main results of design and testing activities conducted in the framework of the HYPROB BREAD Program for the SSBB Igniter are presented. Preliminary experimental tests performed in AVIO FAST2 facility confirm the design predictions highlighting the fact that the combustion efficiency of the hardware is slightly better than expected. Future tests will demonstrate shelf life and continued reliability of the hardware. Additionally an impingement experiment to validate heat fluxes produced by the igniter at 5 bar chamber pressure will be performed. For what concerns future design work a cooled version of the igniter will be manufactured by the end of the year.

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