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Firing Test and Program Progress of the SMSP regenerative combustion chamber

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Abstract

The Single Material Single Part regenerative combustion chamber is the result of the AVIO self-founding R&D program on the LOX/CH4 cryogenic liquid propulsion. It is design for and takes advantages by the Additive Layer Manufacturing technology, that has been used for its production. The SMSP development program consists in the design and manufacturing of the TCA using a modular configuration characterized by the igniter, the injector head, the cylindrical module and the nozzle module.

In this paper we present the results of the successful firing tests of the cylindrical module that demonstrated the design approach and the feasibility of the ALM technology. Moreover it is described the design and development activities on the nozzle module.

1. Introduction

On November 2012 the VEga Consolidation and Evolution Programme (VECEP) has entered in force, with the scope to enlarge the Vega market position for the short-medium term with the so-called Vega C configuration, moreover, during ESA Council at Ministerial level, held in Dec 2016, go-ahead for the preparation of the long term evolution of the launcher (beyond 2025) has been given with the approval of the VEGA Evolution Program (VEGA E).

AVIO is engaged in the development of the upper-stage engine for the VEGA-E launcher taking advantages by the heritage of the LYRA program that led to the successful tests of the MIRA engine, RD 1, characterized by a close engine cycle, LOx/CH4 cryogenic propellants and feeding system with turbo-pumps. The firing test campaign was performed in Voronezh in 2014, after there were activated several technological activities to develop not only the turbopumps and the injector head but also the regenerative combustion chamber, for example using the additive layer manufacturing technology, RD 2.

In this paper we present the progress of the SMSP combustion chambers, RD 5, development program, describing the design of the nozzle module and the successful firing test campaign of the cylindrical module. For the flight application the TCA is characterized by only one part, but for the development and verification phases we use a consolidated modular configuration, Figure 1. It is characterized by four parts: the igniter, the injection head module, the cylindrical module and the nozzle module. Each module has its own water cooling system. The firing test are conducted using liquid oxygen and gas methane in the FAST2 AVIO test stand, RD 4.

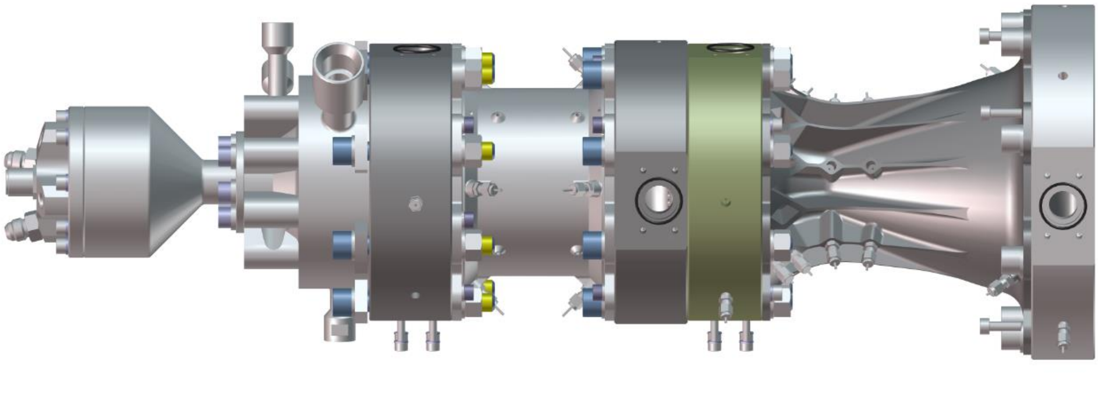

Figure 1: Single Material Single Part combustion chamber modular configuration.

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2. SMSP Nozzle Design

The SMSP nozzle design as prototype for future upper stage engine is characterized by an innovative design that takes advantages by the ALM technology, obtaining the nozzle with only one piece and only one material. The nozzle is characterized by and external shell with reinforcement to provide both strength to the design than a self-sustainable structure during the additive manufacturing process. A dedicated cooling system, illustrated schematically in Figure 2, with two manifold for the inlet and outlet of the coolant is design.

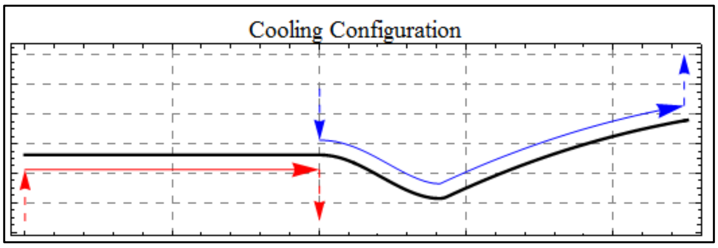

Figure 2: Cooling system configuration and geometry.

The nozzle is equipped with several measurement points in order to characterized the cooling system performance in term of coolant pressure losses and temperature rise, Figure 3. Specifically we have 10 pressure measurement (5 points on two rows) and 6 coolant temperature measurement (3 points on two rows).
Because the chamber materials are different, the cooling system design needs to be updated in term of channel number, rib height, rib width and liner thickness. The chamber design follows three steps: feasibility phase, optimization phase and verification phase. The optimization phase is carried out by means of the Avio code developed and validated in frame of the LYRA program. Main performance results are shown in Figure 4, in term of heat flux, metal temperatures, coolant pressure and coolant temperature.

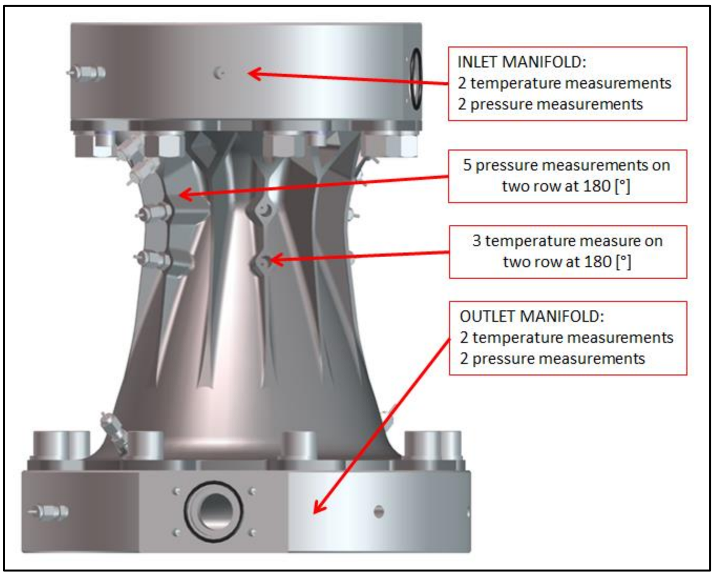

Figure 3: Nozzle instrumentation details.

The verification design phase includes a thermo-structural 3D simulation made with the commercial code MARC a 2D CFD reacting simulation to estimate the convective heat exchange coefficient on the hot gas side, and a 3D CFD simulation made with the commercial code Fluent to estimate the convective heat exchange coefficient on the cold coolant side; these are needed to confirm the structural integrity of the combustion chamber and the reliability of the boundary conditions estimated through the Q-1D preliminary design code.
With the proof test simulation up to 180 [bar] on a representative portion of the nozzle we verified that the material work in the elastic domain with a minimum Yielding Safety Factor of $SF_{y\_min} = 3.16$ and a minimum Ultimate Stress Safety Factor of $SF_{u\_min} = 4.02$, occurring on external shell. On the Liner, instead, the minimum Safety Factors are $SF_y = 4.50$ and a minimum Ultimate Stress Safety Factor of $SF_u = 5.72$. After that a Low Cycle Fatique was performed considering 5 cycles at the reference test cycle, characterized by 10 [s] of firing time each, plus the cool down phase. The minimum safety factors in time on the entire simulation domain are shown in Figure 5, while in Figure 6 are shown the image for the liner hot gas side. After 5 firing cycles, the minimum Yielding Stress and Ultimate Stress Safety Factor are respectively $SF_y = 1.11$ and $SF_u = 1.25$.

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The CFD analysis on the cooling channels show a good agreement in term of convective heat exchange coefficient with respect the Q-1D code. In Figure 7 is shown the dimensionless temperature profile respect to the maximum temperature on the liner estimated through the Q-1D code. The value is lower highlighting the conservativeness of the simulations.

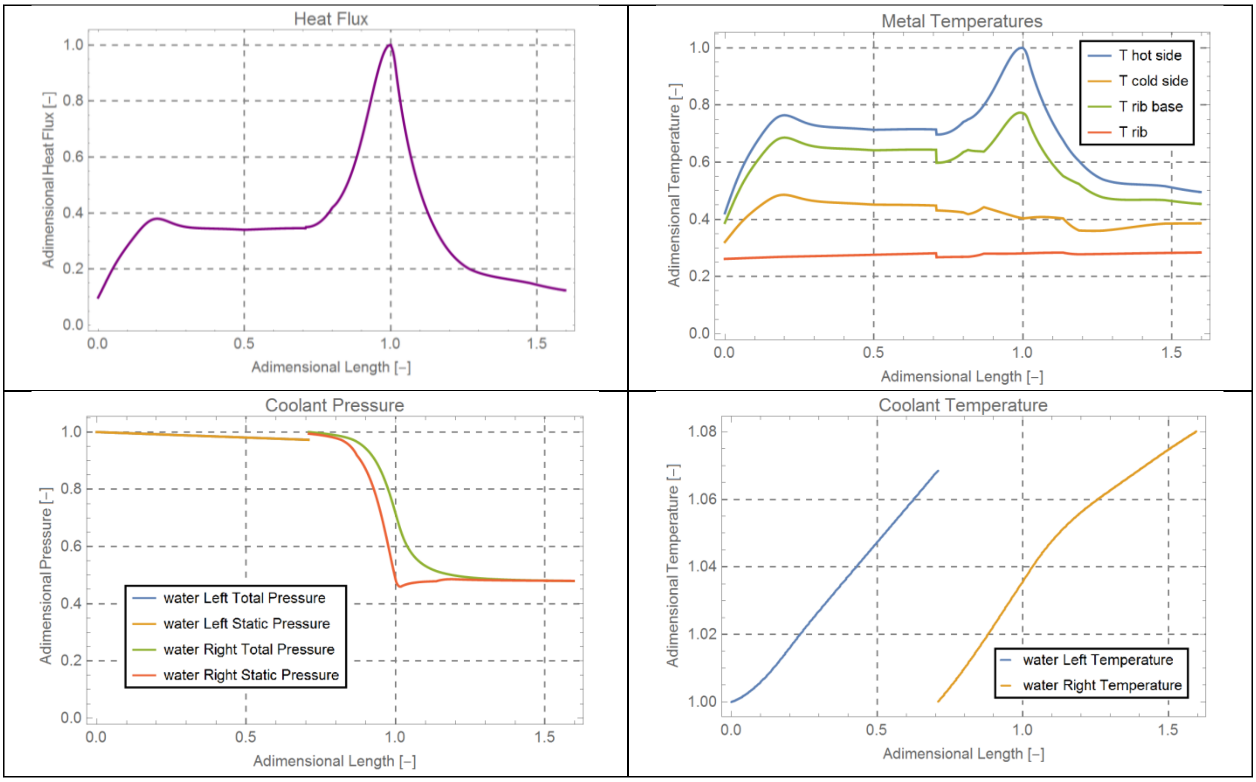

Figure 4: Q-1D analysis - Cooling system performance estimation.

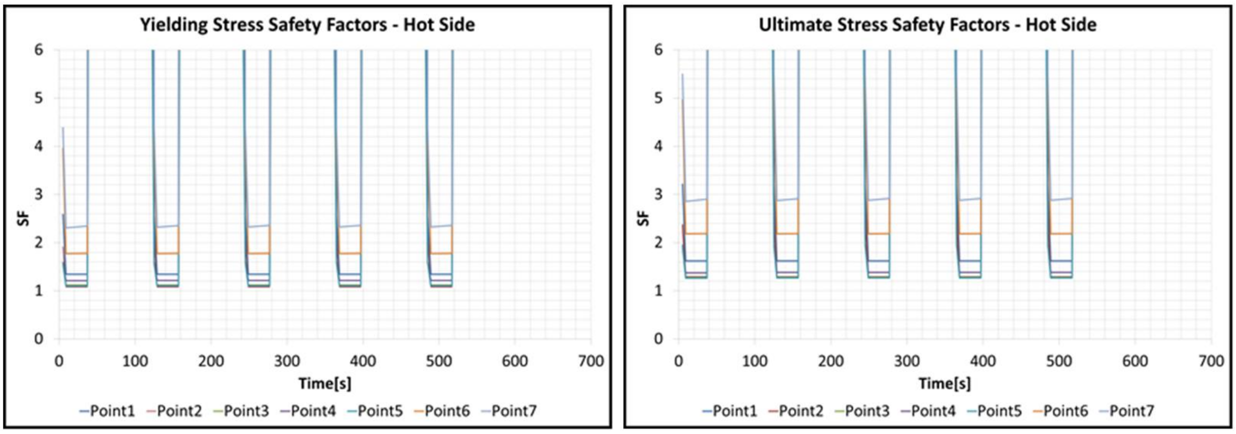

Figure 5: FEM analysis - Low Cycle Fatique analysis.

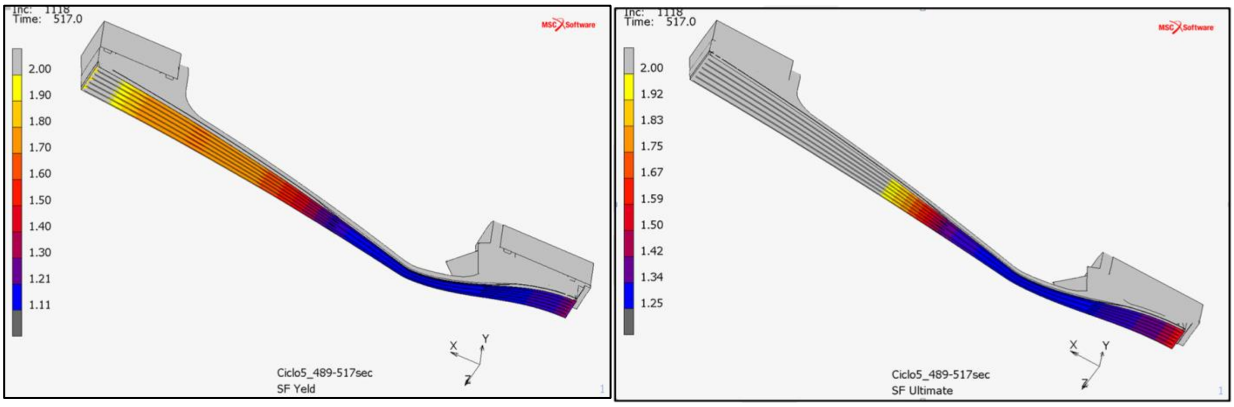

Figure 6: FEM analysis - Safety factor on the liner hot gas side.

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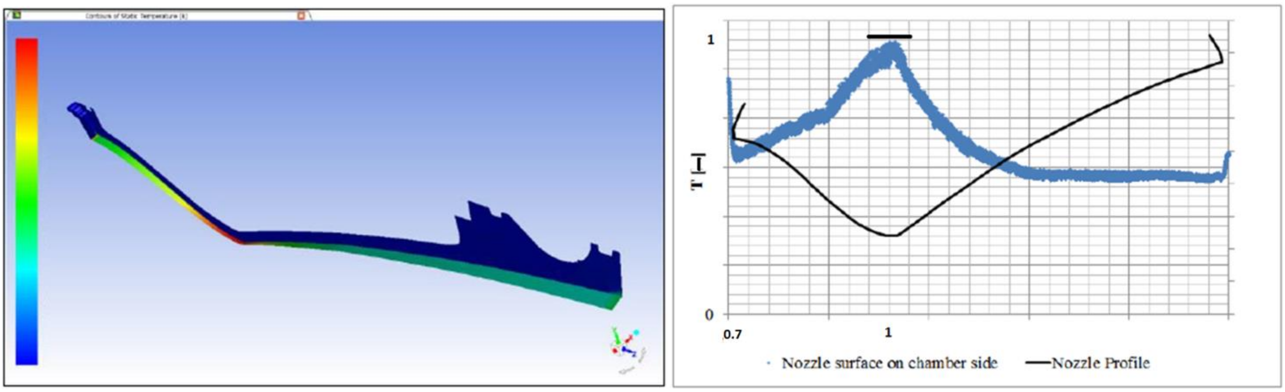

Figure 7: CFD analysis - Temperature profile on the hot gas side.

3. Manufacturing

For the manufacturing of the SMSP cylindrical module, RD 2, we investigated the ALM limits in terms of dimensional and shape tolerances with several sub-scale samples. Different thickness of the liner and channels ribs have been produce in order to define the best capability of the technology, investigating also the metallographic structure of the material through samples cutting, optical magnification, SEM analysis. The computerized tomography was tested and set-up for our specific application. The first prototype of the cylindrical module, Figure 10, was successfully manufactured and we present the firing test campaign results in the next chapter.

For the SMSP nozzle module we apply the same manufacturing procedure defined in the previous activity, in term of ALM machine, Figure 8, powder specification, fusion parameters, NDI control, thermal heat treatment and acceptance tests. To verify the manufacturing procedure on the new geometry a representative sample of the nozzle has been produced and controlled, Figure 9, after that it was authorized the manufacturing of the entire nozzle, Figure 11.

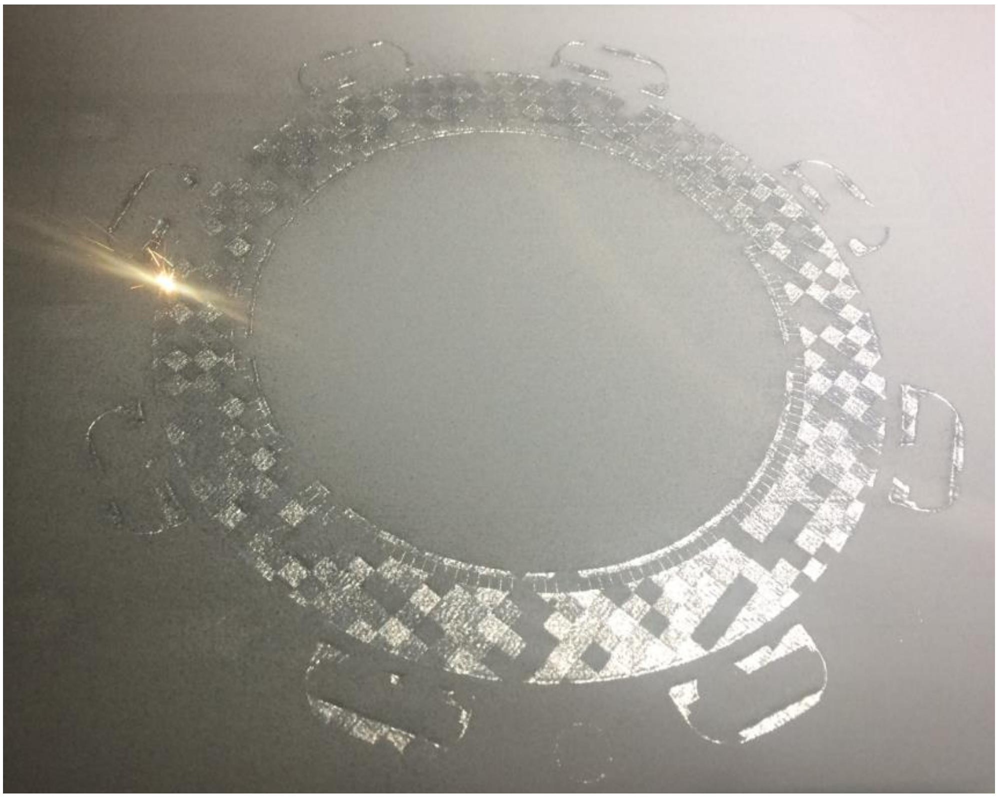

Figure 8: Concept Laser print phase of the SMSP nozzle.

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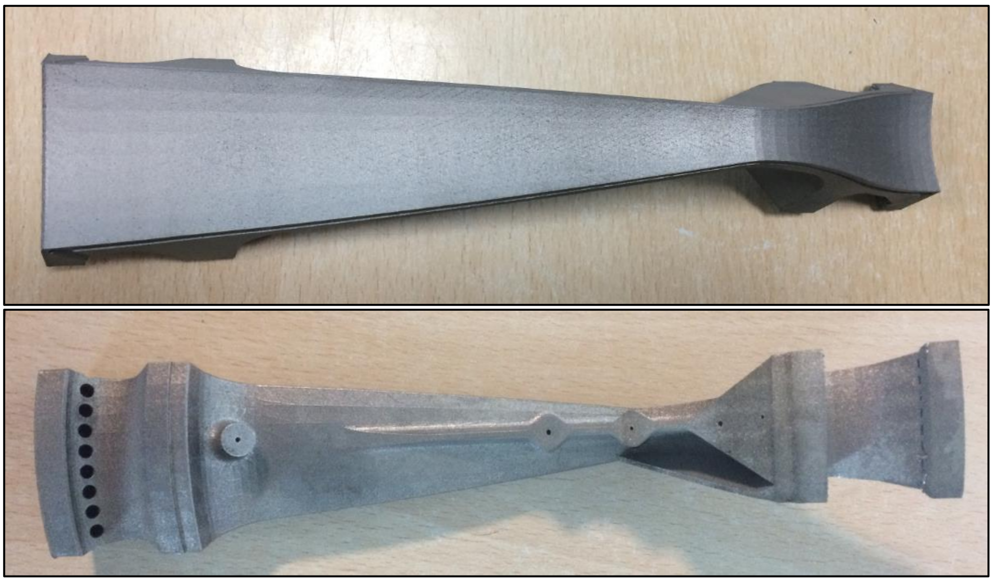

Figure 9: First feasible tests for the sample of the SMSP nozzle.

Figure 10: SMSP cylindrical module.

Figure 11: SMSP nozzle module semifinished.

4. SMPS Cylindrical Module Test Campaign

To fully understand the phenomena involved in this kind of application and to confirm the design methodology, the test article was instrumented with pressure transducers and thermocouples. In particular the following measuring point are located on the test article:

- Inlet manifold pressure (2 measuring points).
- Inlet manifold temperature (2 measuring points).
- Outlet manifold pressure (2 measuring points).
- Outlet manifold temperature (2 measuring points).
- Cooling system inlet pressure (4 measuring points).
- Cooling system outlet pressure (4 measuring points).
- Liner metal temperature close to combustion surface (16 measuring points).

The cooling system pressure measurement are positioned close to the inlet and outlet section. The liner metal temperature are inserted into the liner rib and are positioned as close as possible to the hot gas wall.

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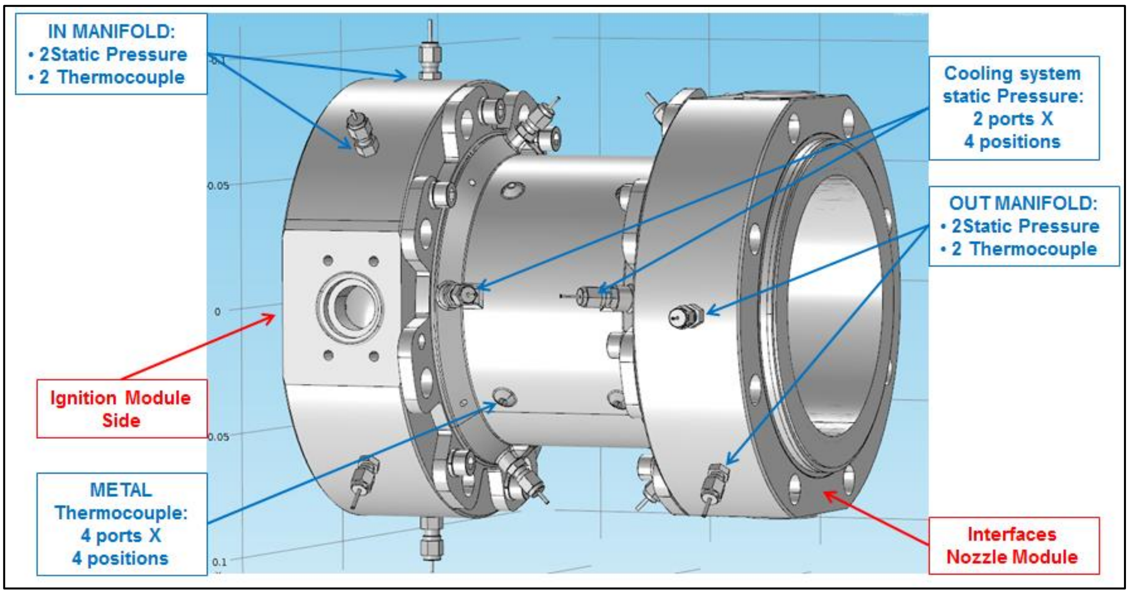

Figure 12: SMSP Cylindrical chamber instrumentations.

Five firing tests have been performed on the SMSP cylindrical combustor. The firing test matrix is listed in the following, together with the reached operative points. Conditions of Test FS05 correspond to the Design Point of the SMSP Combustion Chamber. The test logic is to progressively approach the design operating point to mitigate the risks during the tests execution reducing as much as possible the uncertainties of the performance prediction codes.

Test ID	Pcc [bar]	MR [-]	Firing Duration [s]
FS01	40±10%	3.4±20%	> 5.0
FS02	45±10%	3.4±20%	> 5.0
FS03	45±10%	3.4±20%	> 5.0
FS04	45±10%	3.4±20%	> 5.0
FS05	50±10%	3.4±20%	> 15.0

Table 1: SMSP cylinder test plan.

Test ID	Pcc [bar]	MR [-]	Firing Duration [s]
FS01	39	3.25	5.3
FS02	46.5	4.77	6.4
FS03	44.9	3.5	6.2
FS04	47.3	3.71	6.7
FS05	49.8	3.32	16.5

Table 2: SMSP cylinder testing point results.

All the firing tests reached the success criteria, specifically:

1. No damages of test article (checked by visually inspection and leak test);
2. Nominal ignition;
3. Expected Chamber pressure within the prescribed tolerance of ± 10%;
4. Expected Mixture Ratio within the prescribed tolerance of ± 20%.

A comparison between the results obtained by the tests and the results obtained from the design code, has been performed in term of outlet pressure and temperature at the outlet manifold and liner temperature, estimating the average experimental heat flux, convective heat exchange coefficient on the cold and hot side.

The results shown how the SMSP Combustion Chamber was designed with a margin of about 6% on the heat flux, convective heat exchange coefficient and coolant temperature increase inlet-outlet, while the gas side wall temperature has a design margin of about 2.5%; moreover, pressure losses are overestimated by 3% due to uncertainties of the internal roughness. It can be stated that the SMSP cylindrical module was successfully designed with a conservative approach.

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Finally, there are presented the combustion chamber pressure trends for the 5 performed tests, in the following Figure 13, Figure 14, and Figure 15. A picture of the firing test FS05 is also shown in Figure 16.

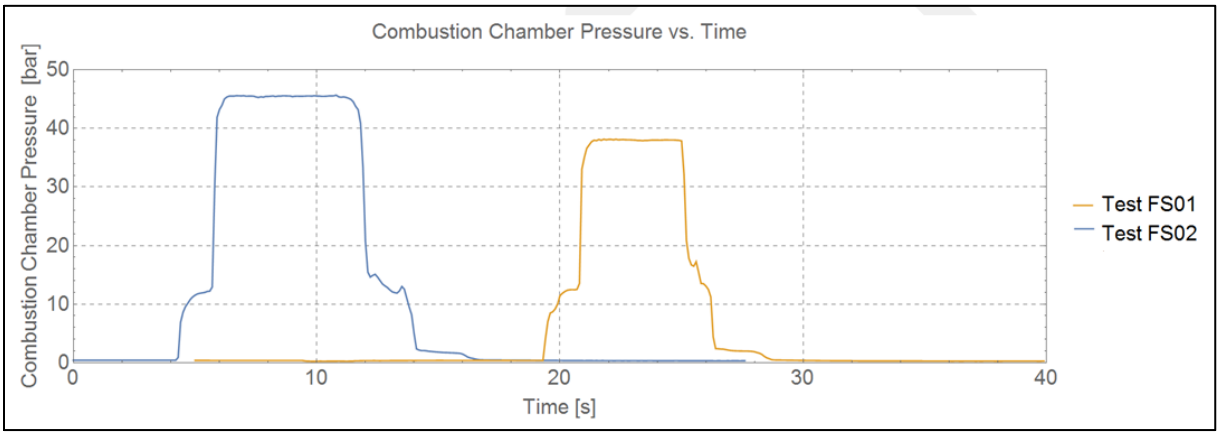

Figure 13: FS01 & FS02 Combustion chamber pressure.

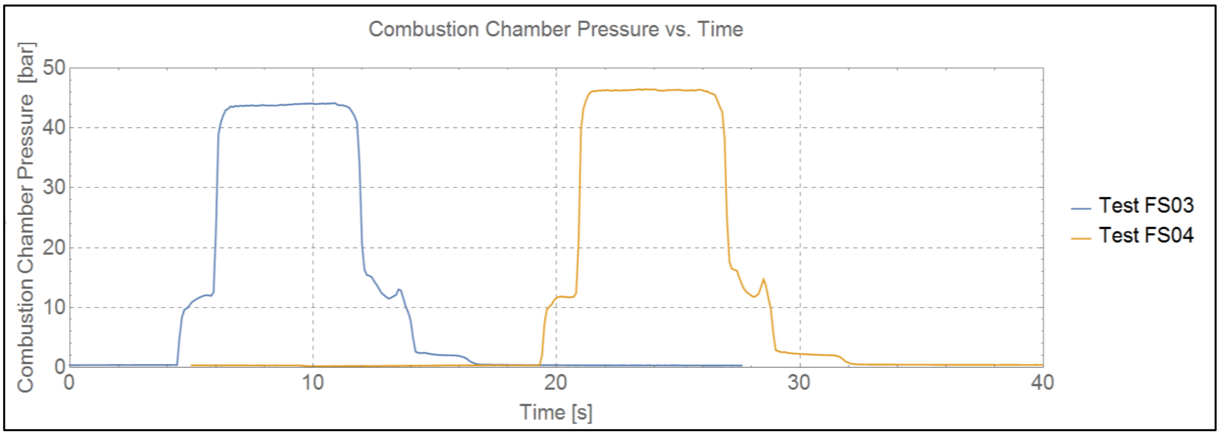

Figure 14: FS03 & FS04 Combustion chamber pressure.

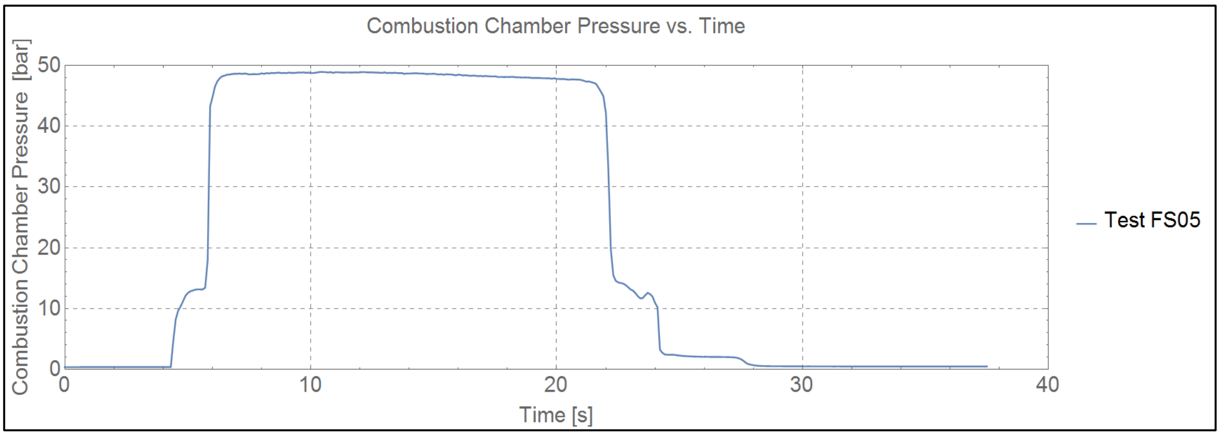

Figure 15: FS05 Combustion chamber pressure.

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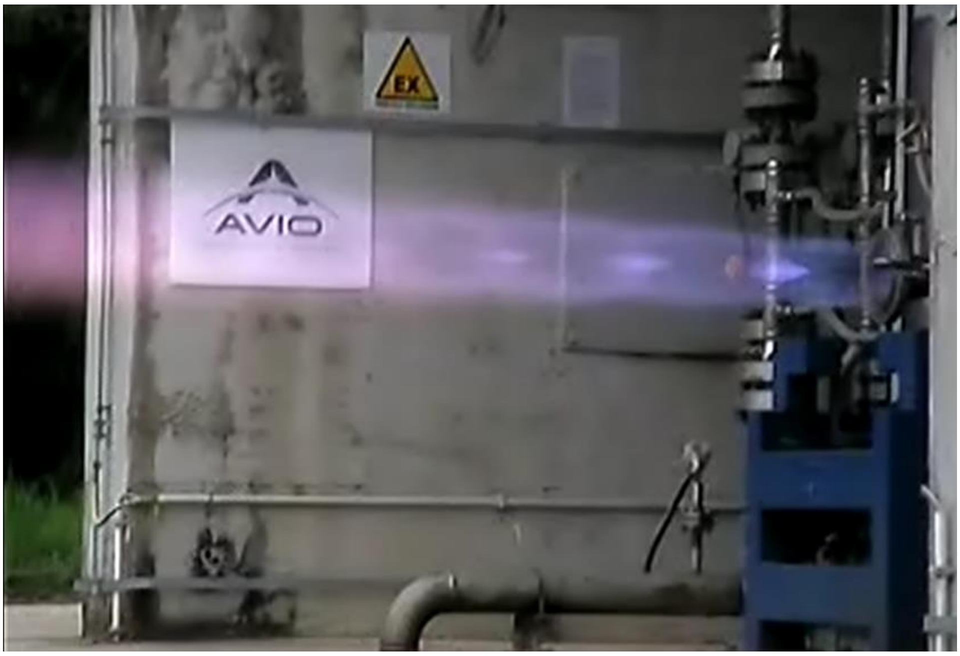

Figure 16: Picture of the FS05 firing test.

5. Conclusion

The SMSP program consist in the development of an innovative combustion chamber made with only one material and only one part that includes both liner and close-out. We accomplished several phases of the program including the investigation of the Additive Layer Manufacturing technology, the realization and the successful firing tests of the cylindrical module in the AVIO FAST2 facility, obtain the first experimental validation. Available firing test results allowed to validate AVIO customized mathematical models and confirmed feasibility of the SMSP patented combustion chamber.

SMSP nozzle module design has been completed taking into account models calibration data. The module has been produced. Actually the final machining is in progress. Firing test are foreseen to be completed within 2017.

6. Nomenclature

ALM	Additive Layer Manufacturing
CFD	Computational Fluid Dynamic
FEM	Finite Element Method
NDI	Non Destructive Inspection
SMSP	Single Material Single Part
TCA	Thrust Chamber Assy

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