Design and testing of a new High Pressure Chamber with Optical access (BOHP)

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Abstract

In the framework of the Research and Technology program, the Space Engines Division of SAFRAN Snecma develops new injection technologies for advanced liquid engine gas generators. This program aims at drastically reducing the costs associated with the fabrication and the integration of injection elements in the injection head of gas generators. The solution was to reduce the number of injection elements and therefore increase the mass flow rate per element, using the development of the tricoaxial injection technology.

Because of the high flow rates involved, tricoaxial injectors cannot be tested in the Mascotte test bench at ONERA. These injectors are typically tested at DLR P8 test bench, a co-ownership between Astrium, DLR, CNES and SNECMA. A single injection element test chamber named BUE without optical access is used to characterize: the performance, the pressures losses and the combustion stability associated to this injection element technology.

Flame and reaction zones visualizations were deemed necessary in order to better validate advanced CFD combustion models for transcritical combustion. Consequently, it was decided to design a new test chamber capable of providing optical access (BOHP) to the flames of tricoaxial injection elements covering present and future Gas Generator development needs. These needs were then translated in the specification of extreme operating conditions up to 200 bar chamber pressure and O2/H2 mixture ratio up to 1.

This paper provides a synthesis of the specifications used in the early stage of the project (2007), as well as an overview of the design phase that took place in 2008. Finally, the results of the 2009 acceptance testing campaign are summarized.

1. Introduction

Since the early developments of the tricoaxial injection elements, hot fire tests were performed at the DLR P8 test bench because the high mass flowrates per element were beyond the capabilities of the Mascotte test bench from ONERA. Tests performed at P8 used a high pressure single element chamber without optical access, named BUE [1], capable of providing a characterization of:

- the performance of the tested injection element, particularly the thermal stratification at specified axial positions,
- the injection pressure losses
- the LF (Low Frequency) and HF (High Frequency) combustion stability of the injection element.

A significant effort was produced in R&D to develop advanced CFD models for RANS (Reynolds Averaged Navier-Stockes) and LES (Large Eddy Simulation) codes capable of simulating transcritical injection and combustion at high pressure. In order to validate these models, it appeared necessary to access optical visualization of the high pressure transcritical flames associated to the tricoaxial injection elements tested at P8. This essential need was at the center of the justification of the design, fabrication and testing of a test chamber for the P8 bench, called BOHP (Boîtier Optique Haute Pression – High Pressure Optical Chamber). BOHP is a combustion chamber device dedicated to single-injector hot fire technological tests. Firstly, it allows to characterize injection technologies through pressure (high and low frequency) and intrusive temperature measurements similar to the former BUE

(Boiter Uni Element) combustion chamber. Then, the BOHP can also help in fully understanding the effects of the injectors design parameters on the flame behaviour: flame length, flame structure and propellant mixing. These results will be used for the validation/optimization of CFD tools and models. In addition the BOHP can be used to study the ignition process.

2. Specimen specifications

The BUE combustion chamber currently used by SNECMA/CNES for gas generator injection technology test campaigns is a combustion chamber dedicated to single-injector tests: Unfortunately, there is a lack of optical access to the flame thereby reducing the depth of understanding of injectors design effects on flame structure. To improve significantly the performances and design of gas generators injection element the flame structure is needed. Moreover, the flame visualizations are considered a central input necessary for the validation of transcritical CFD models. These are the main reasons that drove the need for the development of the BOHP.
Additional specifications were added. If possible, the BOHP can be adapted to the BUE and the specimen is considered as a visualization module, but it can also be used alone. It is expected to be used under cryogenic LOX/LH2 or LOX/CH4 conditions at combustion chamber pressure and mixture ratio (RM) up to 200 bars and 1 respectively. The hot test duration is approximately 30s (similar to BUE) but for dedicated tests the test duration can be increased.

2.1 Measurement specification

Specific optical diagnostics are considered in the design of the BOHP, with particular attention on the analysis of three principal phenomena:

Flame geometry:
Flame characterization (size, shape, anchorage to the injector, behavior, confinement, species distribution, temperature stratification …) under gas generator conditions (Mixture ratio <1.2) during start-up transient and steady state. The objective is to characterize the flame properties according to injection element geometry and operating point.

Ignition transients:
Ignition phenomenon (kernel localization and propagation, ignition delay…). The objective is to visualize the ignition phenomenon under well mastered transient feeding conditions of the gas generator and the igniter itself. (LOX+He, LH2 for the main injector, GOX, GH2 for the igniter…).

Injection characteristic
Injector performance. The objective is to measure the pressure losses of the injection element and the temperature stratification induced in the combustion chamber.

2.2 Main functions specifications

The main functions ensured by the BOHP are:

Propellants feeding
The BOHP allow the propellants distribution from the P8 bench feeding lines interfaces (or extension lines from the bench interface to the test specimen interfaces) to the injection element.

Hot gases flow compatibility with BUE
The BOHP can be mounted upstream of the BUE. In this configuration, the hot gazes and the flame generated by the injection element can flow downstream into the BUE. In this case, the BOHP is considered as visualization module.

Optical access
The BOHP allows the use of flame visualization diagnostics, such as OH* spontaneous emission, from the exit of the injection element to the end of the flame (see figure 1).

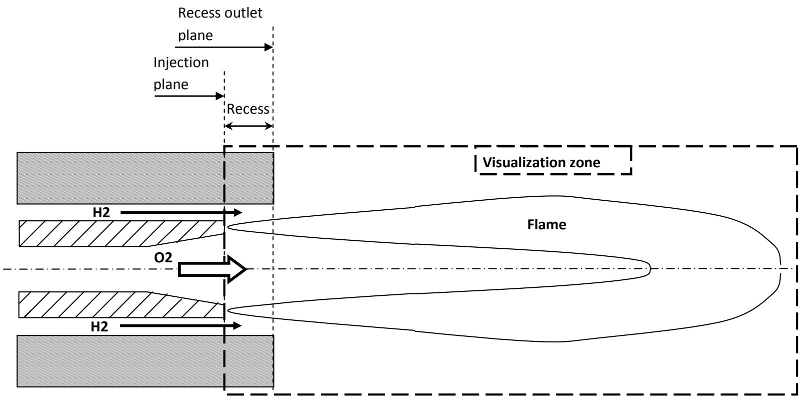


Figure 1: visualization zone (coaxial injection)

Igniter interfaces
The BOHP shall use the torch igniter developed by SNECMA.

Functional representativeness
The BOHP shall have no impact on flame expansion; neither shall modify the hot gases mixing.

BUE mechanical support
The BOHP shall me able to sustain the BUE combustion chamber when the BUE main combustion chamber is mounted downstream of the BOHP.

2.2 Life time specification

Due to the experimental objectives, it is difficult to demonstrate an operational life. Nevertheless the target of time life is:

- 100 cycles (start-up, steady state and shut down)
- 3000s of cumulated operating points

3. Design

The BOHP can be interfaced with the current BUE, which can be decomposed in seven parts, as pictured in Figure 2.

(1) Oxygen feeding line including a small LOX dome, and a gaseous helium interface for venting purposes,
(2) Injection head, including the injection element
(3) Feeding plate, including the H2 or CH4 inlet
(4) Water cooled Combustion Chamber body
(5) Throat
(6) Igniter system, designed as a torch operating with gaseous oxygen and hydrogen.
(7) Water cooling flanges

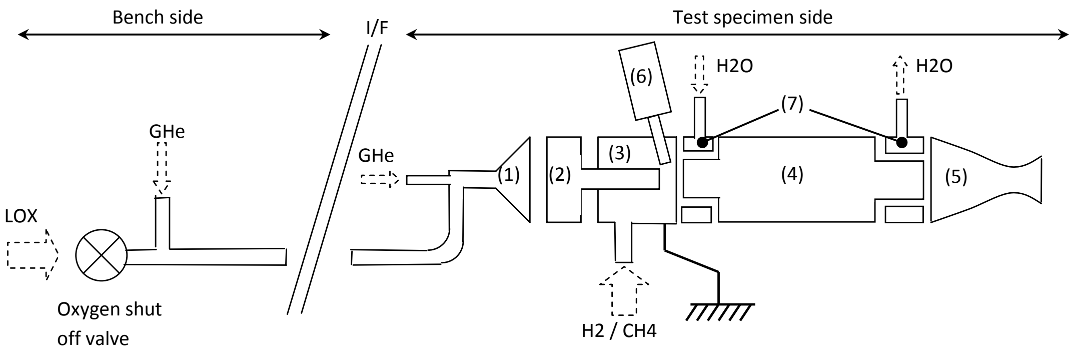


Figure 2: BUE scheme

3.1 Overview of concept trade-off

Configuration 01
In the first configuration presented in Figure 3, the BOHP is integrated in between the two parts (3) and (4). The BOHP is considered as an optical module. Two igniter positions can be used: (6) and (6'). This configuration induces very few modifications of the existing BUE hardware, but the optical access to the injection plane requires a modification of the injectors (2) and/or the injectors positioning in this LH2 flange because the optical access frame would start too downstream. This configuration could also be represented without the current BUE combustion chamber (4).

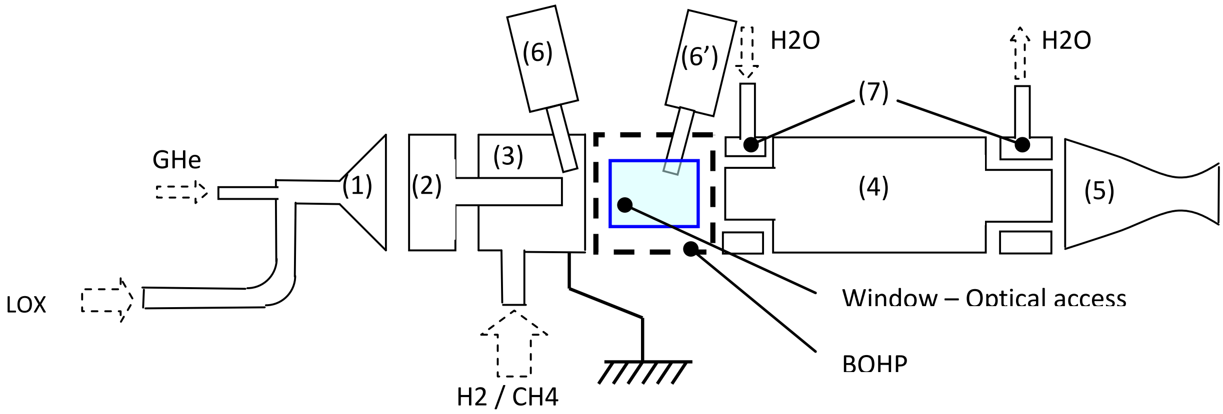


Figure 3: BOHP configuration 01 schematic

Configuration 02
In the second configuration illustrated in Figure 4, the BOHP is integrated in between the two parts (2) and (4). The LH2 flange is included in the BOHP specimen. This configuration allows a good optical access from the injection plane without modification of the injectors or injectors positioning. This configuration could also be represented without the present BUE combustion chamber (4).

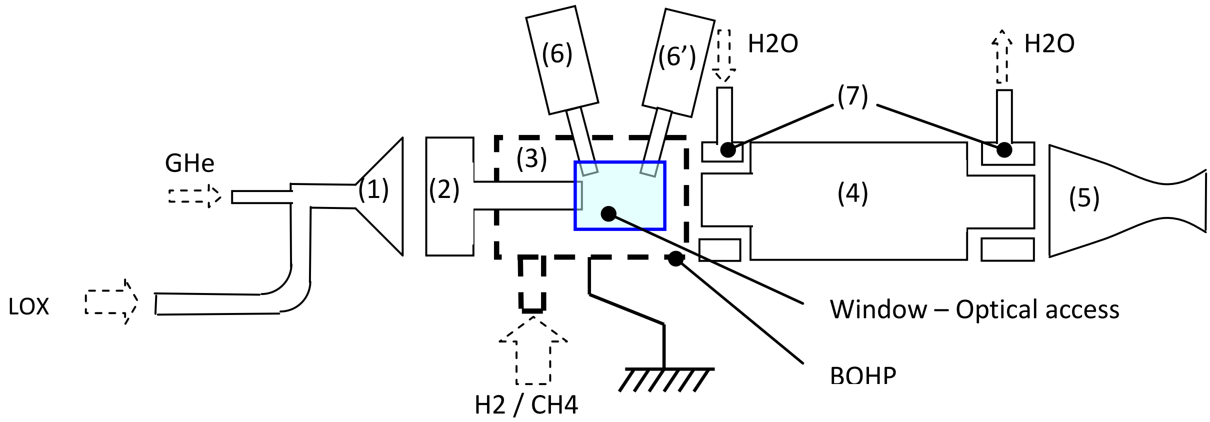


Figure 4: BOHP configuration 02 schematic

The configuration 02 has been selected because it respects the measurement specifications described on 2.1 and the BOHP can be use with or without the BUE.

Figure 5 provides a CAD view of the BOHP assembly with the BUE and the throat (bottom left corner) in the downstream position. We can notice that two configurations of igniter are available, one close the injection plane and the second further downstream.

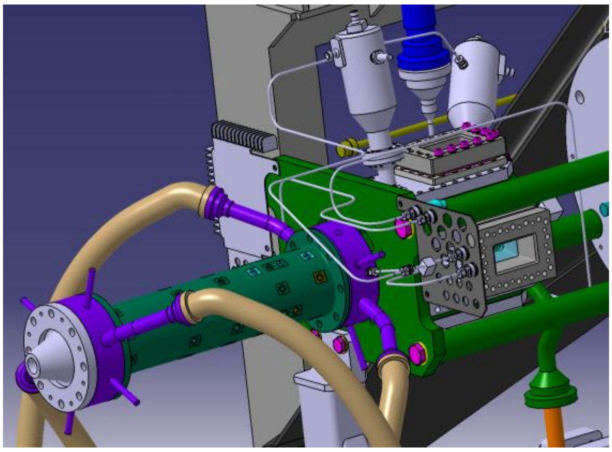


Figure 5: CAD representation of BOHP assembled upstream of BUE

3.2 Overview of thermal justification

The temperature test profile reported in Figure 6 has been applied for thermal calculation. This temperature profile is representative of a cycle: cold flow-checks, ignition and transient, steady state, and extinction with purge.

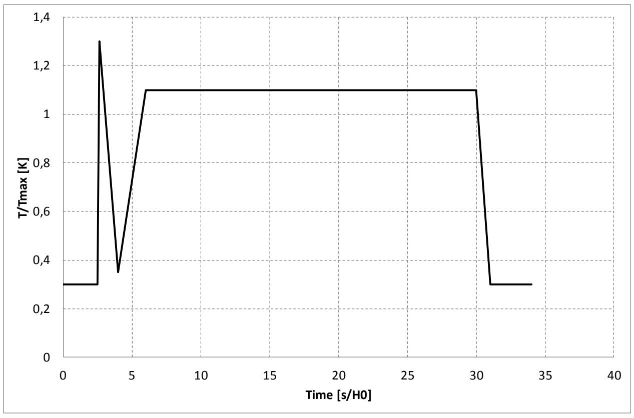
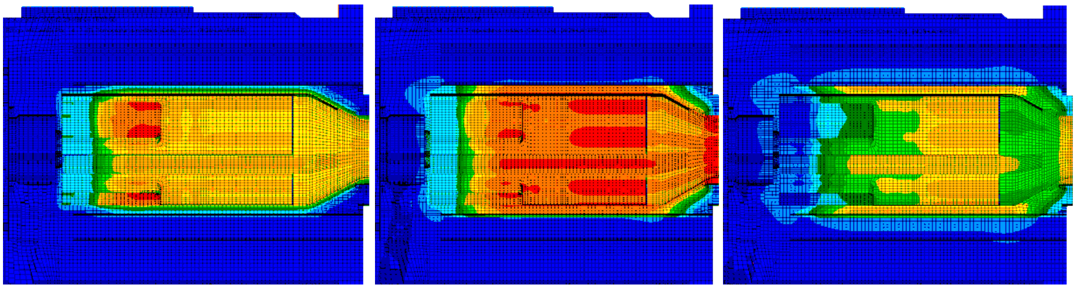


Figure 6: temperature test profile normalized by the maximum temperature.

Thermal justification of combustion chamber

The temperature maps obtained by SAMCEF thermal code are reported in Figure 7. The temperatures calculated for the BOHP combustion chamber are in agreement with the limits imposed by the material choice for the specimen.



7s 24s 34s

Figure 7: temperature map of the BOHP combustion chamber at 7s, 24s and 34s

Thermal justification of the silica window and the window flange

The temperature maps reached at the end of the steady state operation (t=29 s) are presented in Figure 8: for the silica window on the left and for the window flange on the right. The maximum temperatures and gradients are acceptable for the selected materials.

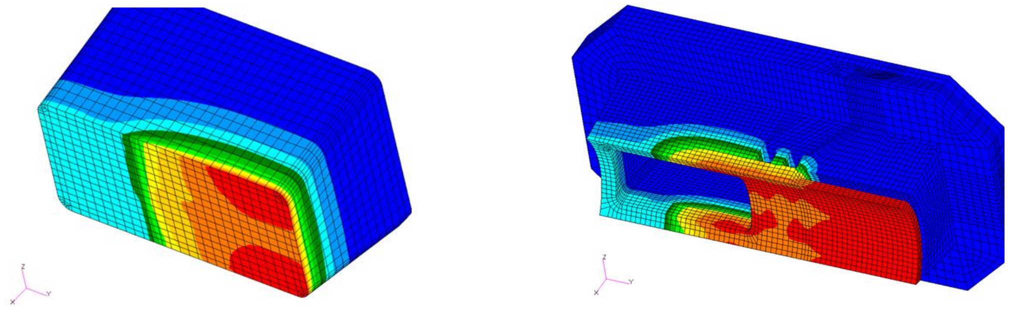


Figure 8: temperature map of silica window (left) and window flange (richet) at 29s

3.3 Main features

The BOHP is a system that provides four visual accesses (figure 9). This optical device is expected to work at pressure up to 200 bars. Because the optical access module (BOHP) is not water cooled, the duration of the test is limited to 40s. The BUE (Boitier Uni Element) combustion chamber can be mounted downstream the BOHP body to increase significantly the combustion chamber length.

The BOHP has several features detailed next: modular widow arrangement, adjustable streamtube and modular ignitor position.

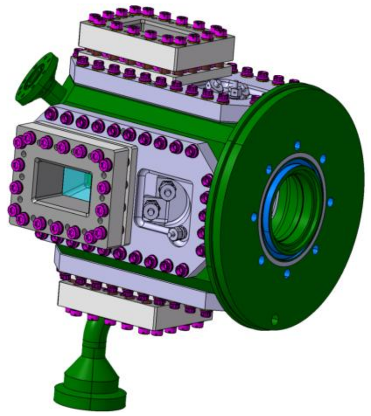


Figure 9: BOHP and optical access view

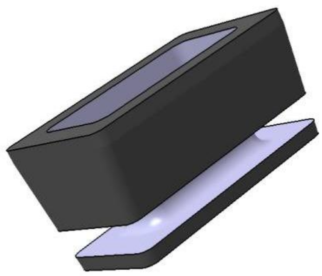


Figure 10: dummy window

A Modular window

The BOHP is a module that can be equipped with four silica window or metallic windows, the former being used for visualizations, the later for additional temperature sensors.

Two window configurations exist. With the first configuration, the window is placed close to the exit of the injector. With the second configuration, the window is mounted at the end of the combustion chamber. Consequently, the use of the both configurations simultaneously allows characterizing the global flame structure.

When the silica window is replaced by a dummy/metallic window (figure 10), it is equipped with one intrusive thermocouple in order to measure the hot gas temperature close to the wall.

B Adjustable stream tube

The BOHP is roughly a cylindrical combustion chamber. A specific silica combustion chamber can be installed inside the BOHP. Its shape is a cylindrical tube with an internal diameter similar to the BUE. This silica tube is maintained by metallic tubes (see Figure 11). This concept is called *reduced streamtube*. There are two versions of the *reduced streamtube concept*: on in silica to allow good flow visualization, and one in Inconel that can be used with a specific dummy window equipped with a dynamic pressure sensor to study the impact of the combustion diameter on the ignition pressure peak.

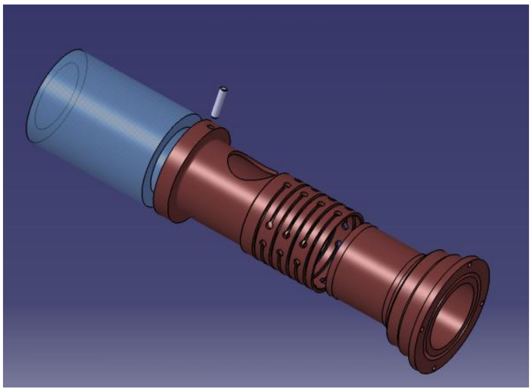


Figure 11: *Reduced streamtube concept*

C Modular Igniter position

There are two positions of the GH2/GOx torch igniter (Figure 12):

- close the exit of the injection element. This configuration is currently used because the ignition is easier. It is well adapted for injection elements validation.
- Further from the exit of the injection element. This configuration is used for understanding the flame propagation during start-up transient. This igniter position is compatible with the *reduced streamtube concept*.

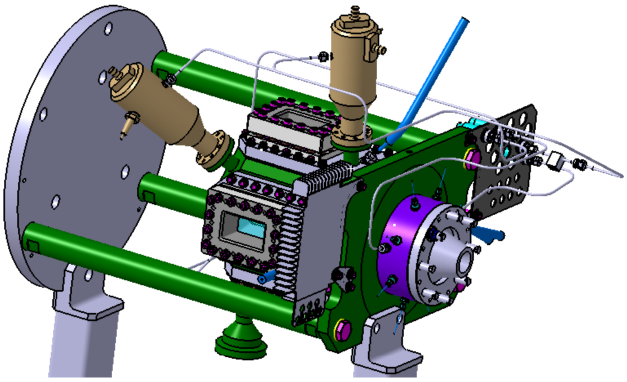


Figure 12: view of the two igniter configurations

D Injection element

Several injector designs can be tested on the BOHP because the injection head is not integrated on the BOHP specimen.

E Combustion chamber Instrumentation

As show in Figure 13, a measurement section is implemented at the end of the combustion chamber, just before the nozzle exit (section C). This section enables to measure the hot gases temperature using 8 intrusive thermocouples. The intrusiveness of each thermocouple is different, thereby providing a good characterization of the thermal stratification generated by the tested injection element at the specified measurement plane.
Two static pressure sensors are also used to measure the pressure inside the chamber. In addition, one dynamic pressure sensor is mounted at the exit of injector level.

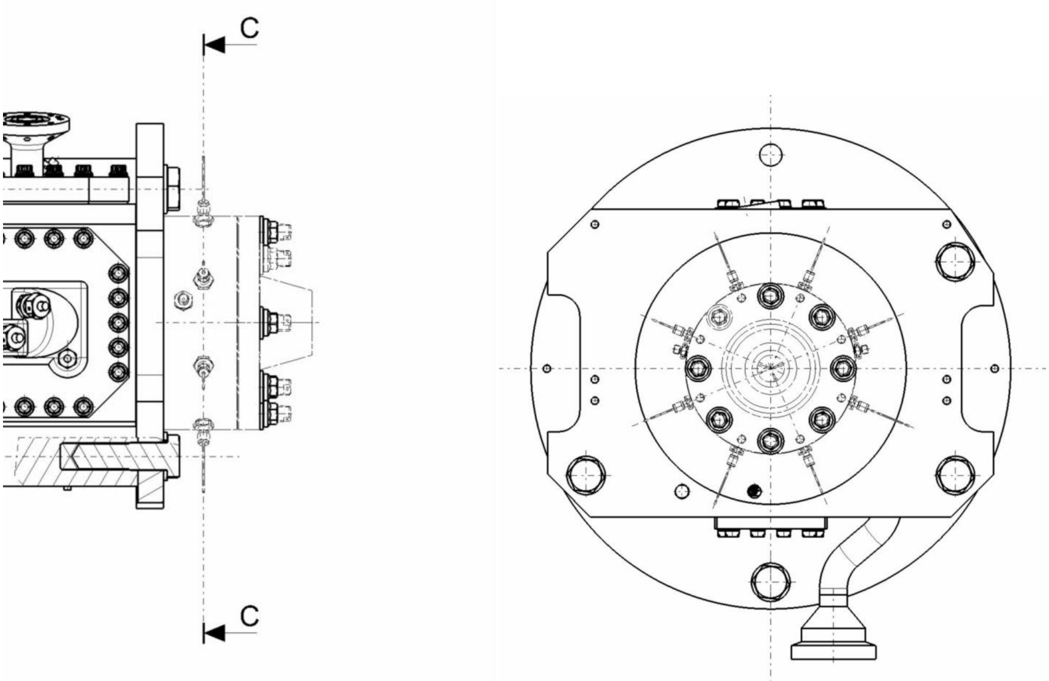


Figure 13: view of combustion chamber instrumentation

F Injection head Instrumentation

The injection head is instrumented with:

- one oxygen temperature sensor (range [90-300K], low acquisition rate : 125 Hz)
- one oxygen high frequency pressure sensor (range [-100-+100 bars], high acquisition rate : 100000 Hz)
- one oxygen static pressure sensor (range [0-300 bars], low acquisition rate : 1000 Hz)
- two hydrogen temperature sensors (range [35-300K], low acquisition rate : 125 Hz)
- one hydrogen static pressure sensor (range [0-300 bars], low acquisition rate : 1000 Hz)

4. Acceptance test

In 2009, the BOHP has been validated during a dedicated test campaign. The objectives of these acceptance tests were to:

- Verify the thermo mechanical resistance of the BOHP
- Verify the silica window resistance
- Validate the start-up transient using a deported igniter configuration (furthest position downstream of the injection plane)
- Validate the quality of the optical access through dedicated visualizations in the visible range and the UV range for OH* spontaneous emissions.

After validation of start-up transient with dummy windows (pressure peak at ignition), two test runs have been performed.

First, a test run dedicated to low combustion chamber pressure was performed, as indicated in the Figure 14. During this test, the steady state chamber pressure was increased from 105 to 120 bar, while the mixture ration O/F was kept nearly constant at about 0.9.

Then, a test run was dedicated to combustion chamber pressure up to nearly 200 bars as indicated in Figure 15. The temperature measured close to the wall of the dummy window is compatible with the use of silica window. The domain covered during the campaign is reported in Figure 16. The pressure range is from 100 to 190 bars. The mixture ratio called RM is measured between 0.7 and 1. The cumulated hot fire test time is 310s.

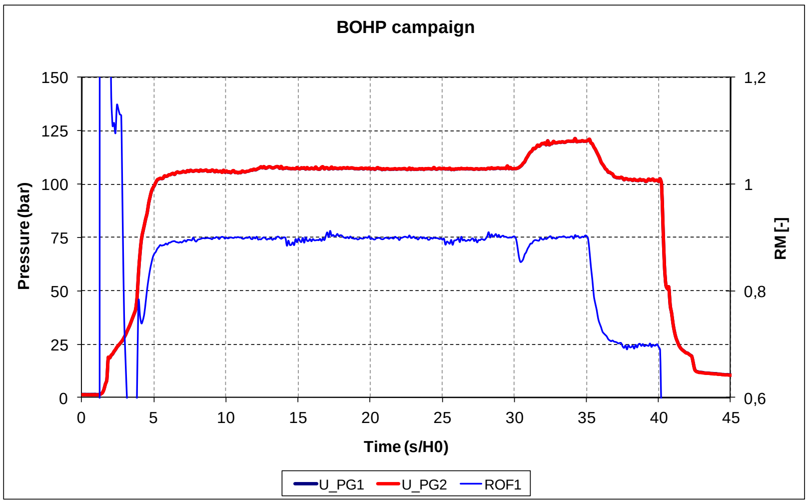


Figure 14: low pressure test profile

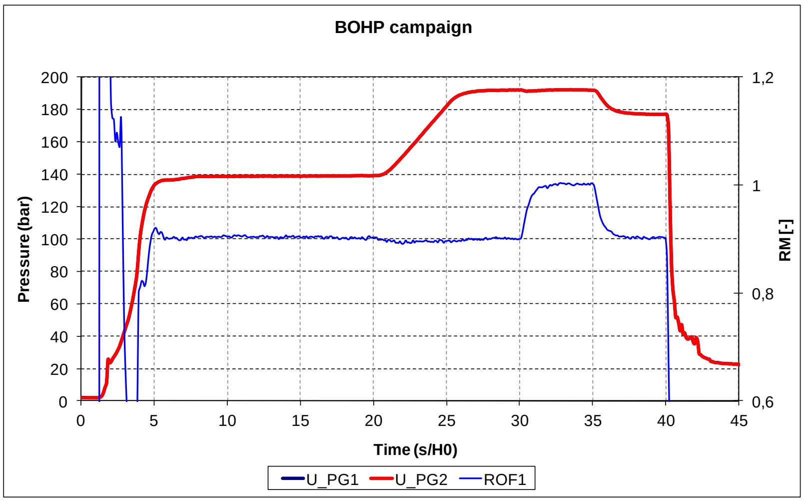


Figure 15: High pressure test profile

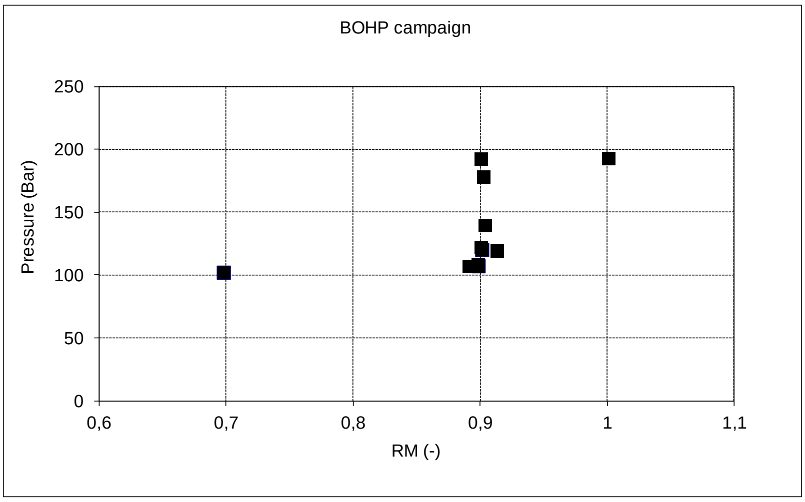
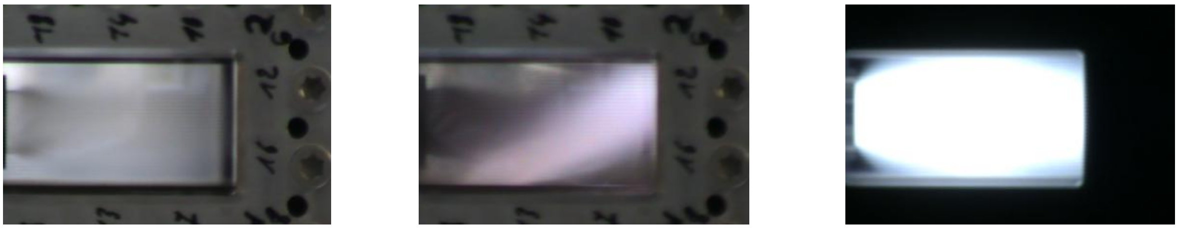


Figure 16: pressure-mixture ratio domain covered during the campaign

Two injection elements inducing two levels of pressure oscillations in the combustion chamber have been tested in order to validate the resistance of the silica windows. Several images from a standard camera are presented in Figure 17. We can clearly notice the LH2 injection during chill-down, then the LOX/LH2 injection with the hot gases coming from the igniter and finally, a stabilized flame anchored at the injection element exit.



Chill down *Ignition* *Flame at steady state*

Figure 17: Visualizations at the exit plane of the injector during chill down, ignition, and steady state.

No damage has been identified after the campaign. Consequently, the BOHP combustion chamber and the silica window concept were validated.

5. Conclusions

The need to obtain high quality visualizations of the flame structure associated to the tricoaxial injection element was driven by: the need to further our understanding of this technology capable of good performance and high mass flow rates, and by the need to validate the advanced real gas models and combustion models for CFD (RANS and LES). During the different design phases, the BOHP gained in modularity allowing a good visualization of the entire flame length. Advanced CFD and thermo-mechanical models were used during the design and justification phase of this project. The acceptance tests were successful since all the objectives were demonstrated. A significant amount of flame visualizations were acquired at high speed to characterize the ignition process. The BOHP continues to provide important data to help validating advanced CFD model as well as designing and validating new injection elements.

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