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Development and Test of an Innovative Hybrid Rocket Combustion Chamber

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Abstract

In the framework of the European H2020 HYPROGEO program, an innovative hybrid engine combustion chamber compatible with satellite requirements (constant thrust over a very long burning duration) has to be developed. To design such an engine, a first test rig, similar to the considered innovative combustion chamber, was designed and tested. The test campaign, performed under various operating conditions, enabled to demonstrate the catalytic ignitability of this new hybrid engine and the sustainment of a stable combustion. Additionally, the main influencing parameters on the fuel regression rate law have been identified.

1. Introduction

The use of electrical propulsion systems to transfer satellites from GTO to operational GEO orbits, in addition to their current use for station keeping, seems to be the trend for future European telecommunication satellites. Nevertheless, the very long transfer duration inherent to such low-thrust technology may not be compatible with all the mission timeline requirements. One of the solutions proposed by industrials and public agencies would be to employ a dedicated high-thrust propulsion system to accelerate the transfer phase. This kick-stage module should also combine environmental-friendly chemical technology and electrical thrusters to optimize its efficiency in term of propulsive performances, mass, costs, etc.

Thanks to its advantages (safety, low environmental impact, propulsive performances, costs, etc. compared to the currents MMH/NTO bi-liquid engines), hybrid propulsion, which combines a liquid oxidizer and a solid fuel grain, could be a good candidate for this task. However, the current architecture of such an engine associated to time-dependant shift of the oxidizer to fuel ratio and variations of the fuel grain shape is not suitable with the long burning time and constant thrust required for a satellite application. An innovative combustion chamber satisfying the previous requirements has consequently to be developed.

In order to have a constant thrust, Rice *et al.* developed the vortex end-burning hybrid engine (VEBH) which provides the advantage of a constant burning fuel surface area [1]. The engine mixture ratio can be thus controlled by varying the oxidizer mass flow rate and/or the combustion chamber diameter (fuel surface area). As presented in Figure 1 left, this engine, designed for use with HTPB, consists of a ring chamber sandwiched between mating top and bottom and the gaseous oxidizer is tangentially injected through ports at the tail-end (nozzle side) of the chamber in order to create a swirl motion of the gaseous phase and to increase the fuel regression rate. Based on observations of post firing fuel grains, a counter swirling pattern of grooves, which appear to indicate flow opposite that of the

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swirl GOX injection, exists near the centre of the chamber. According to the authors, a portion of the oxygen may be spiralling along the bottom of the chamber and up to the head end in the central region where it meets the grain surface and flows back outward. In this case, the flow field might consist of two intertwined spirals in the central region of the chamber, one spinning upward and the other spinning down towards the nozzle (Figure 1 right).

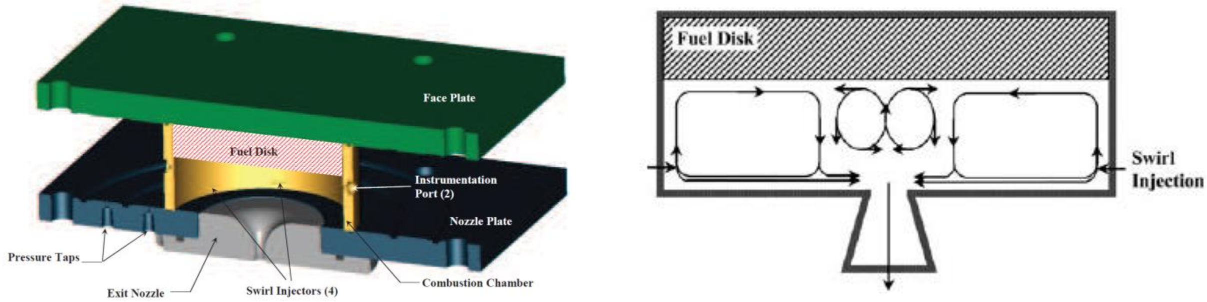

Figure 1: Vortex end-burning hybrid engine [1] (left) and flow field in the combustion chamber [2] (right)

However, this concept is not compatible with the long burning time required for a satellite application since the distance between the injection location and the fuel surface evolves which may cause combustion stability and ignition issues with the time. In order to solve this problem, an interesting solution is the end-burning swirling-flow hybrid rocket engine (named SOFT for swirling oxidizer flow type) using paraffin wax developed by Hayashi and Sakurai for a first stage application [3]. This concept is similar to the one of Rice *et al*. in terms of overall dimensions, oxidizer type and injection but is besides equipped with an actuator to push the fuel grain axially toward the nozzle side in order to keep the volume of the combustion chamber constant during the burning. As in the previous study, the authors observed that the fuel regressed axially with a high regression rate region close to the centre of the fuel grain. According to Volchkov *et al.*, the convection coefficient on the surface is maximal at the axis level because of the phenomena induced by the swirl injection [4]. Hayashi and Sakurai concluded that the formation of a crater at the centre of the fuel grain was provoked by these same mechanisms since the energy input was higher.

Although this concept was interesting, the actuator was not useful with regard to the very short burning duration (only two seconds). Moreover, the fuel employed for this study was not suitable for a satellite application due to its high regression rate. To make this engine compatible with regards to the requirements in terms of burning duration, the needed length would not be compatible with spacecraft accommodation constraints. Dedicated studies on pancake hybrid engines were performed in order to satisfy these constraints [5][6] but these concepts lead to a time-dependant shift of the oxidizer to fuel ratio and variations of the fuel grain shape which are not suitable with the satellite requirements.

In the framework of the European H2020 HYPROGEO project, a hybrid engine compatible with a long burning duration (about 5000 s) and with a constant thrust at the required level (250 N) for a satellite application has to be developed [7]. To reach these objectives, the idea was to design an end-burning swirling-flow hybrid engine combined with a passive actuator to compensate the fuel regression and operating with high density polyethylene as fuel and 98% hydrogen peroxide as oxidizer. This type of fuel is compatible with a satellite accommodation due to its very low regression rate. In addition, catalytic injection combining start and stop capabilities is made possible by the choice of this oxidizer.

However, in order to better define this new engine and to investigate potential difficulties, such as ignition, oxidizer injection, the definition of the operating conditions to have the required oxidizer to fuel ratio and chamber pressure, etc., the MHYCAS hybrid engine, a French acronym for hybrid engine compatible with satellite applications, was first designed and tested as an intermediate step. After a brief description of the architecture of this new hybrid engine, this article will present the test results and an analysis of the main parameters influencing the fuel regression rate in such a concept.

2. Description of the test facility

The MHYCAS test facility is composed of a pressurized tank, feeding lines and of the MHYCAS hybrid engine (Figure 2). The tank pressure is maintained at a constant level during the firing tests. This keeps the oxidizer mass flow rate, and hence operating conditions, constant during operation.

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2.1 Description of the MHYCAS engine

The MHYCAS engine (Figure 2 left) is designed to be very close to the one envisaged for the final HYPROGEO breadboard. This engine is composed of a fuel tank containing the fuel grain, an annular ring providing a swirl injection on which are plugged six decomposition chambers filled with the catalyzer and alimented with 87.5% hydrogen peroxide, six injector ducts manufactured using additive layer manufacturing, a combustion chamber of 200 mm in-diameter at the fuel location and a nozzle with adaptable throat section. The modular design of this hybrid engine enables the operator to easily change the number of active decomposition chambers, the initial position of the fuel grain with respect to the location of the oxidizer slots, the shape of the fuel grain and the operating conditions in terms of chamber pressure, oxidizer mass flow rate and mass flux (calculated at the oxidizer injection).

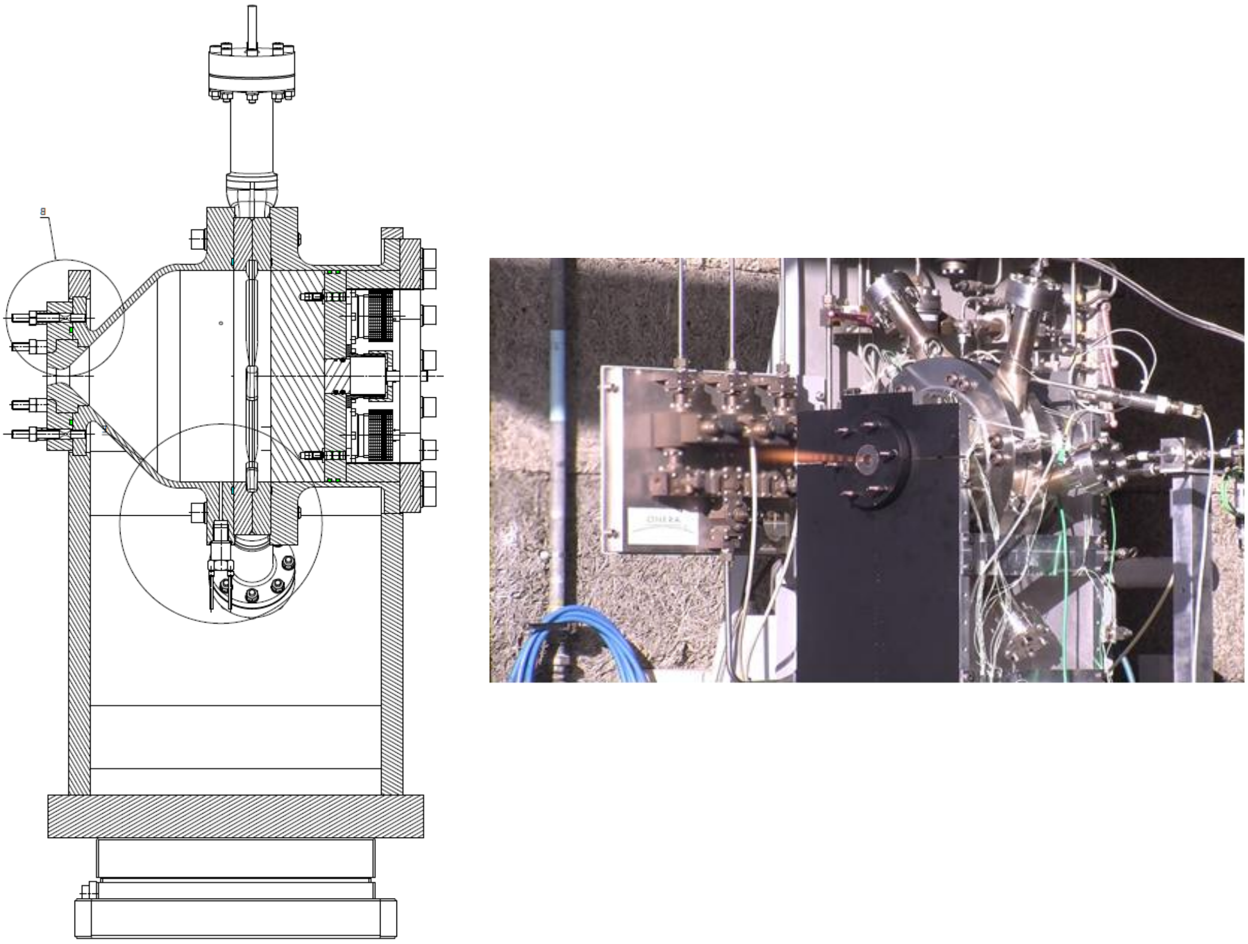

Figure 2: Drawing of the MHYCAS engine (left) and MHYCAS hybrid engine during a firing test (right)

However, contrary to the VEHB and to the SOFT engines, the oxidizer injection is located very close to the fuel grain to ease the catalytic ignition of the engine. Moreover, since the oxidizer injection and the gaseous flow have a major impact on the fuel regression rate, the injection ring was designed with the help of CFD analysis. The goal of these fully 3D numerical simulations with a k-ω SST turbulence model was focused on two inter-related aspects of the design process: the design of the combustion chamber and the design of the decomposition chamber. Regarding the combustion chamber, it was important to obtain a temperature distribution that would not compromise the chamber wall, whilst, at the same time, providing a reasonably uniform flow-field near the fuel grain. Regarding the decomposition chamber, the point was to avoid hot spots between the ducts and to ensure that the hot combusting gases do not create a near-stagnation region at the end of the ducts. This analysis led to the selection of six "continuous" ducts which inject the oxidizer tangentially to the combustion chamber to generate a swirl motion (Figure 3). This choice was made to provide a uniform temperature distribution across the fuel grain, a broader combustion zone near the thrust axis but also only small and located stagnation regions where the combustion gases impinge on the inside wall of the injector slots.

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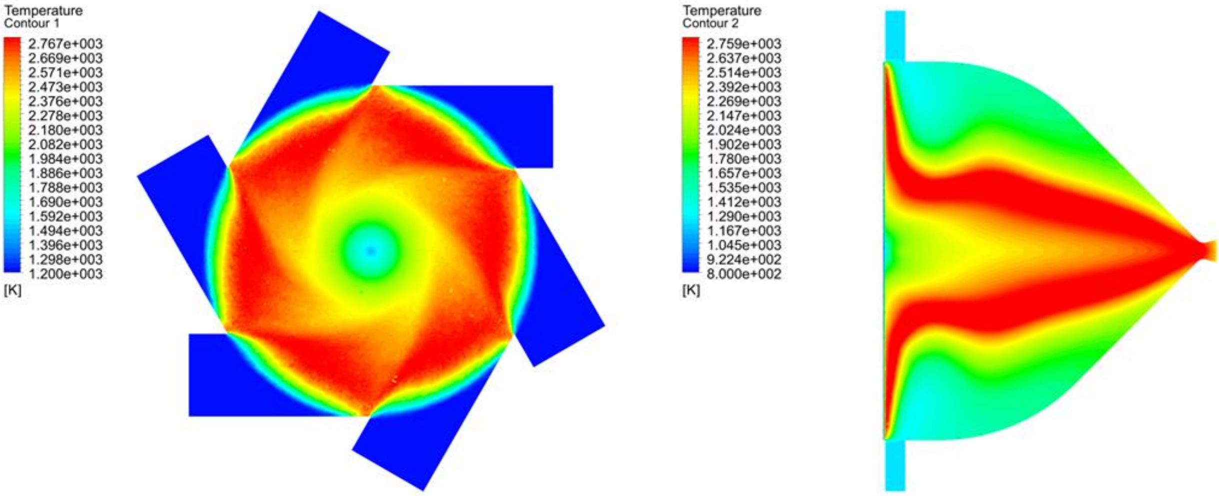

Figure 3: Temperature fields obtained by the numerical study for six “continuous” injection slots

2.2 Instrumentation

The MHYCAS engine is instrumented with temperature and pressure probes located at the end of one of the sixth decomposition chambers, three unsteady pressure probes placed around the combustion chamber and four ultrasonic sensors located on the external fuel grain surface. The ultrasonic sensors coupled to a dedicated electronic system enable to track the instantaneous travel time of the ultrasonic waves within the fuel grain and hence to deduce, after analysis, its instantaneous regression rate. The engine is also placed on a thrust bench to measure the propulsive performances. However, it should be noted that the nozzle was not adapted to the ambient pressure since the nozzle throat was only modified to target different values of combustion chamber pressure.

To complete these measurements, thin thermocouples are welded onto the external wall of the engine (Figure 4); 14 are placed on the combustion chamber, one placed at the end of each decomposition chamber and two located on the fuel tank. Thanks to a back integration method, these temperature measurements enable to deduce an evolution of the inside temperature wall and thermal flux along the combustion chamber.

Finally, the instrumentation for the test facility includes a Coriolis mass flow-rate meter and temperature and pressure transducers for the liquid oxidizer upstream of the oxidizer distributor. The latter distributes the oxidizer from the main supply line to the six secondary ones, each one being connected to a single decomposition chamber.

Figure 4: Thermocouples welded on the MHYCAS engine

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3. Firing test campaign and results

3.1 Procedure of the firing tests and methodology for their analysis

As presented on Figure 5, the first phase of the firing tests corresponded to a blipping sequence of the oxidizer injection which enabled to fill the oxidizer lines and to slowly warm-up the decomposition chambers to avoid any catalyser damages. This sequence was followed by a continuous oxidizer injection phase which can be split into two parts: a mono-propellant phase whilst the combustion process was not started and a hybrid phase as soon as the engine ignited. Finally, after the firing test, a drain phase, which consisted of a continuous nitrogen injection, was employed to avoid thermal lag and degradation of the engine. This phase was also composed of two distinct parts: the first one coincided with the flush of the hydrogen peroxide contained in the feeding lines (associated with an increase of the chamber pressure since the hybrid engine ignited again) whilst the second one was the injection of pure nitrogen in the engine.

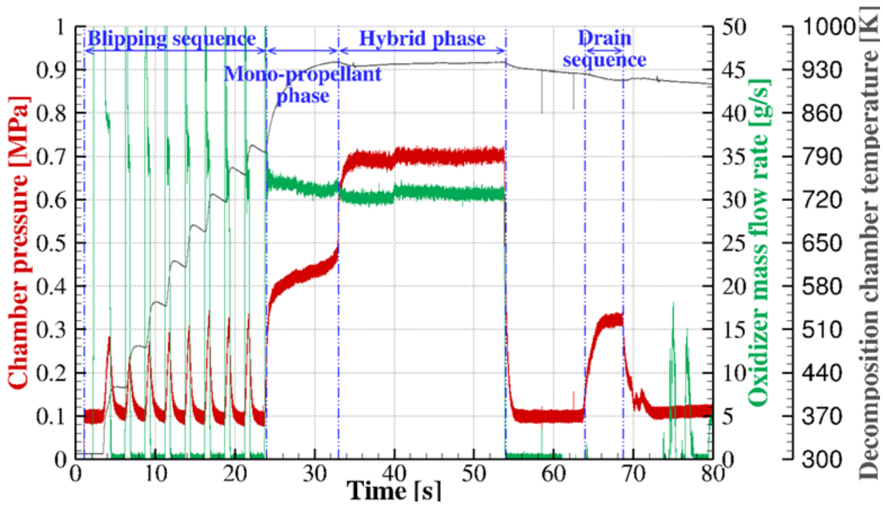

Figure 5: Example of the different firing test phases

To avoid transient effects of the engine ignition, which could have a significant impact on the data averaging for small duration tests, all the values provided were averaged over the last three seconds of hybrid phase duration. Moreover, due to the use a catalytic ignition, which involved a short monopropellant phase, the analysis of the ultrasonic sensor measurements needed to consider the temperature increase in the fuel grain during this phase. The post-treatment of these measurements is consequently very complex and is still under progress. The regression rate data coming from the ultrasonic sensor will therefore not be presented in this article. The fuel regression rates values are only based on the fuel mass loss and on the total firing duration corresponding to the hybrid phase duration and to a part of the drain phase, when the engine re-ignited due to the hydrogen peroxide flush. The total firing duration considered is consequently written according to the following relation:

$$\Delta t_{firing} = \Delta t_{hybrid} + t_{factor} \Delta t_{drain} \quad \textbf{(1)}$$

with Δt_{hybrid} the hybrid phase duration, Δt_{drain} the hydrogen peroxide injection duration during the drain phase, and t_{factor} a corrective factor for the drain phase.

The drain phase has to be corrected since the oxidizer mass flow rate during this phase is different from the hybrid phase, which will modify the fuel regression rate. Based on the classical regression rate expression and on the definition of the consumed fuel mass, the corrective factor becomes:

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$$t_{factor} = \frac{v_{reg,drain}}{v_{reg,hybrid}} = \left(\frac{(\rho u)_{ox,inj,drain}}{(\rho u)_{ox,inj,hybrid}} \right)^b \quad \textbf{(2)}$$

where v_{reg} is the fuel regression rate, $(\rho u)_{ox,inj}$ is the oxidizer mass flux (evaluated at the oxidizer injection) and b is the regression law exponent.

The corrective factor can then be determined since the oxidizer mass fluxes are known (using the Coriolis oxidizer mass flow rate measurement and the known injection surface) and the b coefficient is evaluated by an extrapolated law based on the results of all the firing tests.

3.2 Description of the firing test results

The objectives of the first four tests were to ignite the hybrid engine and to maintain a stable hybrid mode over several seconds. These tests revealed that the engine was able to ignite but also that the fuel grain position regarding the oxidizer injection location had a major influence on the ignition delay. This distance was set to 12.5 mm for the first two firing tests and was then fixed at 1 mm for the rest of the test campaign in order to minimize the monopropellant phase duration.

Several configurations have been tested over the campaign regarding various operating conditions in terms of pressure or mass flow rate. In order to increase the oxidizer mass flux at the injection, two solutions were employed: the first one consisted of reducing the number of active decomposition chambers (and consequently, the number of active decomposition injectors); the second one consisted of adding a circumferential plate around the fuel grain to reduce the cross sectional area of the active injectors. The results of the main tests are presented in Table 1.

Table 1: Firing test results

MHYCAS test number	**02**	**05**	**07**	**09**	**12**	**15**	**16**	**17**	**22**
Number of active decomposition chamber	6	6	6	3	3	6	2	2	6
Firing duration (s)	12.7	18.0	28.8	36.2	29.1	23.8	25.3	22.9	16.0
Chamber pressure (bar)	7.87	8.24	17.89	8.54	18.26	11.03	7.67	7.02	5.62
Oxidizer mass flow rate (g/s)	51.7	52.1	103.1	41.4	44.1	107.9	36.2	30.6	30.3
Oxidizer mass flux (kg/m^2/s)	16.4	16.5	37.7	26.3	28.0	34.3	34.4	87.5	40.4
Oxidizer to fuel mass ratio (-)	34.5	21.3	27.5	13.9	16.2	29.2	11.7	7.4	8.1
Regression rate (mm/s)	0.050	0.082	0.126	0.100	0.092	0.124	0.104	0.142	0.132
Combustion efficiency (%)	89.2	82.9	96.8	96.0	93.0	100.0	93.7	89.9	73.9

The first firing tests were conducted with high oxidizer to fuel mass ratios compared with the target value of 7.4, which corresponds to the optimal value for a hybrid engine operating with 98% hydrogen peroxide and high-density polyethylene as propellants. Values very close to this target were however reached with the firing test MHYCAS_17 (two active decomposition chambers) and MHYCAS_22 (six active decomposition chambers) proving that reaching an optimum value of oxidizer to fuel ratio was feasible with such a hybrid engine.

The combustion efficiencies range from 75 to 100 % (for very high oxidizer to fuel ratios), which is satisfying since this engine was not designed to get the maximum efficiencies. However, the mixing processes due to the swirl injection and the thermal losses of the engine should be studied in order to improve the combustion efficiency and oxidizer to fuel ratio.

3.3 Firing test analysis

The analysis of the firing tests presented in Table 1 will only be focused on the fuel regression rate behavior since this parameter has a major role on the oxidizer to fuel ratio and on the propulsive performances, which are two important criteria to optimize regarding the targeted mission.

The distance between the fuel grain surface and the oxidizer injection has a significant influence on the ignition delay. Consequently, it seems that the heat transfers between the gaseous flow and the fuel grain are increased when

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this distance decreases. It is confirmed by the comparison between MHYCAS_02 and MHYCAS_05 firing test results, for which the fuel regression rate has been significantly increased by reducing the fuel surface / injector distance.

In a classical hybrid engine, pressure has no significant influence on the fuel regression rate. In order to verify if this assumption is correct with the MHYCAS engine, the firing tests numbers 07 and 15 as well as numbers 09 and 12 can be compared in pairs since they have similar oxidizer injection conditions regarding mass flow rates and mass flux but strong differences in combustion chamber pressures. It can be seen that the fuel regression rate is not modified when the pressure changes. This conclusion is verified whatever the value of the oxidizer mass flow rate, since it is true for high mass flow rate (> 100 g/s) or low mass flow rate (< 45 g/s). Note that these comparisons were performed on firing tests with the same number of active injectors. These results tend to show that the combustion chamber pressure has a negligible effect on the fuel regression rate.

The last main element which could have an important impact on the fuel regression rate is the oxidizer injection, which is well known for classical hybrid engine geometries. This general notion can be separated into various parameters such as the mass flow rate, the mass flux, the injection velocity and the injection geometry (number of active decomposition chambers).

Considering two firing tests with the same mass flow rates and mass fluxes, the only solution to obtain different oxidizer velocities is the change of the oxidizer density which can be reached by modifying the chamber pressure. However, as presented before, the pressure and consequently the injection velocity of the oxidizer don't have a significant influence on the regression rate. Then, based on a comparison of test numbers 16-17 and 15-22, at a given number of active decomposition chamber and similar oxidizer mass flow rates, an increase of the mass flux improves the fuel regression rate. Finally, the number of active decomposition chamber has a major impact on the fuel regression rate since even with a similar oxidizer mass flow rate and a different oxidizer mass flux, firing tests number 17 and 22 provided oxidizer to fuel ratios very close. It seems that for an oxidizer mass flux value, the increase of the number of active decomposition chambers increases the fuel regression rate.

3.4 Fuel grain surface shape

The fuel grain regression has been supposed to be parallel to the initial surface and uniform in order to simplify the analysis. In practice, it has been observed for almost every firing test that a well-defined depression was created at the center of the fuel grain surface (Figure 6). This means that the thermal fluxes at this location were higher than in the external part of the surface, as observed by Rice *et al.* [1] and by Hayashi and Sakurai [3], and is certainly caused by the same physical phenomena even if the injection location is not the same.

Figure 6: Fuel grain shape after the MHYCAS_17 firing test

In order to study more precisely the shape evolution and the distribution of the fuel regression rate, the fuel grain length has been measured at different locations for the firing tests number 17 and 22, both with an oxidizer to fuel ratio close to the optimal value (Figure 7).

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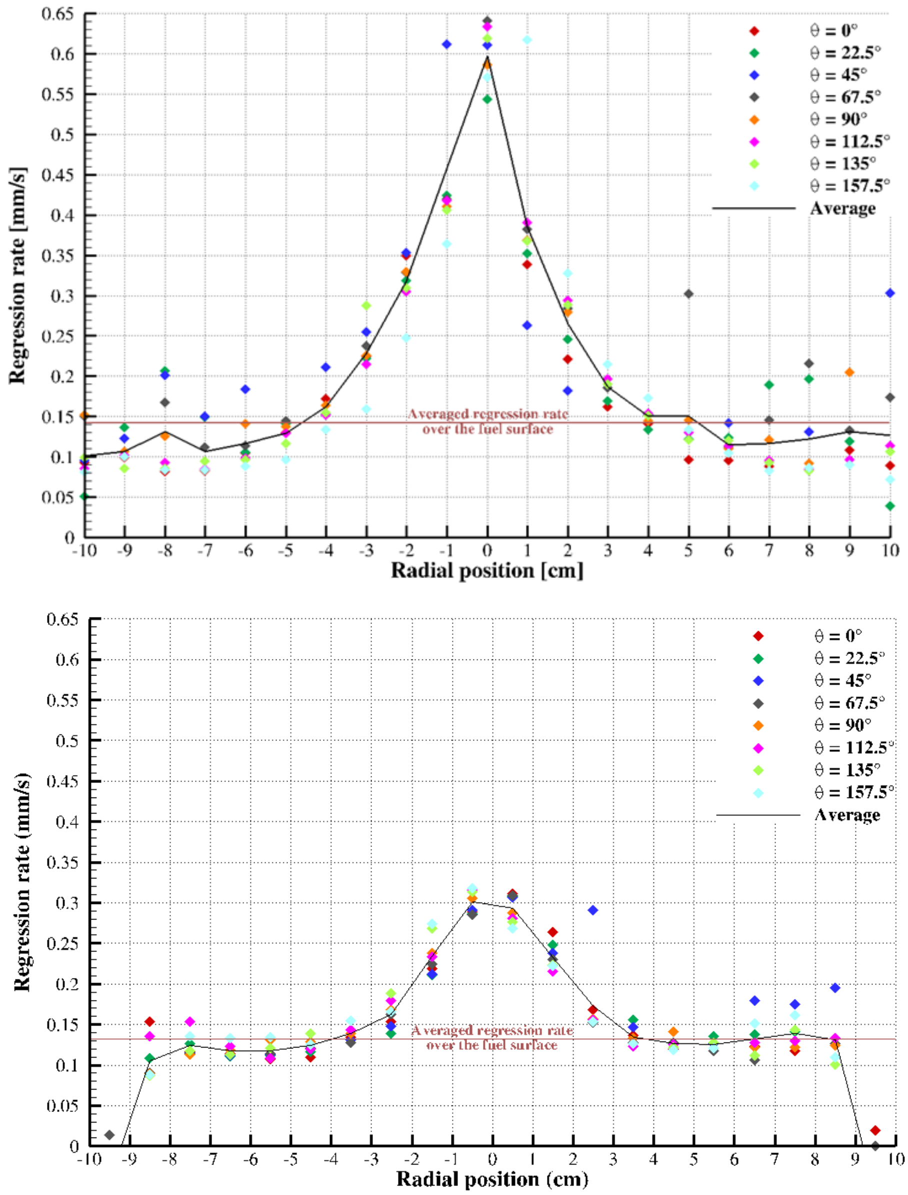

Figure 7: Regression rate distribution for MHYCAS_17 (top) and MHYCAS_22 (bottom) firing tests

Regarding MHYCAS_17 firing test, the regression rate distribution is close to be axisymmetric even if the firing test was performed with only two active decomposition chambers. However, there is an important difference between the center and the external part of the surface. It is clear that the regression rate is almost uniform at high radius values (> 40 mm) but this is not true for the central part. The fuel regression rate distribution seems more uniform when all decomposition chambers are active. This difference is nevertheless still unexplained but seems to indicate that in order to obtain a more uniform regression of the fuel grain surface, it would be better to employ six active injectors rather than two.

4. Conclusion and way forward

This paper presented the first tests for the development of a new hybrid engine architecture compatible with satellite requirements (long burning duration and associated with a constant thrust). The test campaign was successful and achieved all the initial objectives. The catalytic ignitability of the fuel was demonstrated for various operating conditions: low and high oxidizer mass flow rates (from 30 to 110 g/s), low and medium combustion chamber pressure (from 5 to 20 bar), various numbers of active decomposition chambers, etc. The previous analysis revealed that the combustion chamber pressure has no significant influence on the fuel regression rate and that the main

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parameters influencing this regression rate are the number of active decomposition chamber and the oxidizer mass flux. The control of this last parameter allowed reaching oxidizer to fuel ratio very close to the targeted values (7.4) associated with very low regression rate, an important requirement for a satellite application regarding its accommodation.

The next step in this development will consist of adding a passive displacement system to the MHYCAS engine in order to compensate the fuel regression rate and to keep the distance between the fuel burning surface and the oxidizer injection location constant. In this condition, the thermal fluxes will be constant with time and the firing test duration will have no influence on the averaged fuel regression rate, which is contrary to the present study. Finally, the passive displacement system, when used in conjunction with 98% hydrogen peroxide, should allow very long burning durations (about 15 minutes) as required for future satellite missions.

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