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Design and Commissioning of the MOUETTE Hybrid Rocket Slab Burner

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Abstract

This paper illustrates the design and development process of the MOUETTE (Moteur OptiqUe pour ÉTudier et Tester Ergols hybrides) optical access slab burner for investigation of the combustion behaviour of hybrid rocket fuels. The system has been conceived to use gaseous oxygen as oxidizer with a mass flow rate of up to 100 g/s and a maximum combustion chamber pressure of 10 bar. The test chamber features two quartz glass windows to acquire high-speed imaging of the fuel grain during the combustion process, and a graphite nozzle to adjust the operative pressure. The ignition of the solid fuel grain is provided by a pyrotechnic igniter. The burner, together with its feed system and test bench, has been manufactured and integrated. Leaking and proofing tests have been carried out, followed by ignition sequence tests to define the operating procedure. A validation campaign with a paraffin-based fuel has been carried out to verify the functionality of the system.

1. Introduction

The core of a chemical rocket propulsion system is the combustion chamber, where fuel and oxidizer are mixed and burned to generate a hot gas mass flow, which is ejected and accelerated through a nozzle, to provide the thrust required by the spacecraft. The continuous development of new propellant combinations is therefore one of the key lines of research to achieve more efficient, sustainable, and cost-effective space transportation systems. Hybrid Rocket Engines (HREs), allow great flexibility in the fuel selection, as the solid grain can be mixed with different types and quantities of additives to improve properties like combustion efficiency, regression rate and structural resistance.

The characterization of paraffin-based propellants mixed with additives is one of the activities of Université Libre de Bruxelles (ULB) Aero-Thermo-Mechanics Department (ATM). While most of the ballistics research is carried out on a 1kN thrust HRE using Nitrous Oxide (N2O) as oxidizer [1], some preliminary investigations of the regression rate of new fuel mixtures have been accomplished with the Royal Military Academy of Belgium (RMA) hybrid rocket slab burner [2], which features an optical access and is described in the next section.

A slab burner can be a privileged choice for initial fuel characterization test campaigns, thanks to the flexibility of operation enabled by the smaller size, which typically allows to run more cost effective and less resource consuming tests when compared to larger size HREs. Moreover, due to the two-dimensional burning surface, the use of a slab burner is also interesting for investigate the internal ballistics of HREs. In particular, the addition of one or more optical accesses in correspondence with the combustion chamber allows flame visualization and high-speed video imaging of peculiar phenomena such as paraffin-wax droplet entrainment and liquid layer instability analysis [3]. Visualization techniques typically utilized include Schlieren [4], OH* chemiluminescence [5], and infrared investigations [6].

To achieve these research capabilities, it has been decided to improve the RMA hybrid rocket slab burner design, which later lead to the conception of a second slab burner, named MOUETTE (Moteur OptiqUe pour ÉTudier et Tester Ergols hybrides). Starting from the analysis of the improvements planned for the RMA burner, this paper illustrates the requirements of the new system, justifying the final design. The development of the new test bench is also presented. Lastly, the results of the validation test campaign are discussed, to highlight the features and capabilities of the new system, as well as some preliminary visualization results of the solid fuel grain combustion obtained using a high-speed camera and filters for CH* and OH* chemiluminescence.

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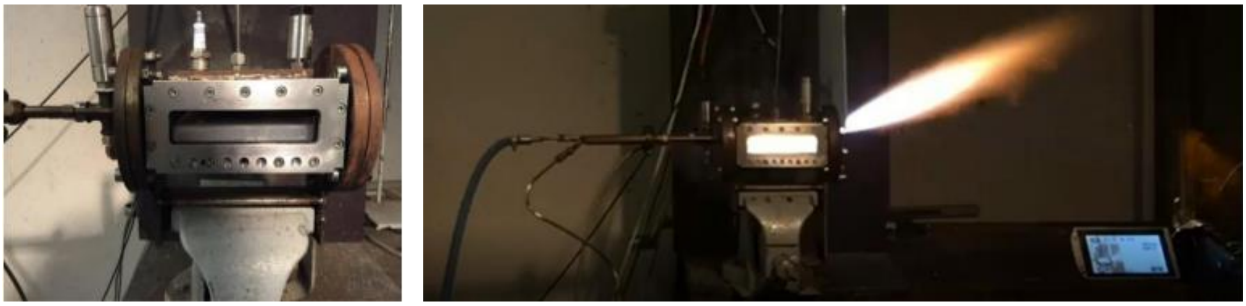
2. Slab burner design

2.1 RMA hybrid rocket slab burner

The baseline for the development of MOUETTE was the RMA hybrid rocket slab burner. Designed to be used in parallel with the main 1kN engine, the burner allowed shorter test preparation times and lean test procedure. For example, it has been used to provide initial regression rate information on a paraffin/MgB_2 fuel mixture, to trim the additive percentage and the grain manufacturing procedure before moving to the main engine [2]. Other than for parametric studies on fuel mixtures, the burner has also been used to investigate the effect of ignition on fuel grains and to gather data on liquid oxidizer injection, thanks to the optical access in the chamber.

The RMA hybrid rocket slab burner, shown in Figure 1, features a steel combustion chamber with a square cross section, along with a borosilicate glass window on one lateral side. The oxidizer used is liquid N_2O, in analogy with the main HRE, which is injected through a swirling injector. The fuel is ignited with a gaseous oxygen and propane torch, activated by a spark plug. The nozzle is replaced by a flat plate with a rectangular opening, that can be adjusted to modify the pressure in the chamber. Finally, a pressure transducer and a thermocouple are installed in the chamber.



(a) (b)

Figure 1: (a): RMA slab burner; (b): Firing test on the RMA slab burner (Reproduced with permission from [2]).

2.2 Design objectives

To improve the flexibility of the system and the quality of the measurements that could be acquired, it has been decided to upgrade the RMA slab burner. In particular, the objectives to achieve with the new design were:

A. Eliminate the effect of liquid oxidizer droplets and swirling flow on the fuel grain.
B. Increase the maximum operative pressure.
C. Improve the type and quality of performable measurements.
D. Improve motor handling and test preparation characteristics.

The design approach set up with a modularization of the RMA slab burner, to consent the modification and addition of several subcomponents to the existing test chamber. As the design iterations progressed, however, also the combustion chamber was completely redesign, but still maintaining the interchangeability of the components, to allow a flexible approach and keep the possibility to substitute or modify single parts if necessary. The discussion of the design objectives and the proposed solutions are discussed below.

A. Eliminate the effect of the swirling flow on the fuel grain.

As the RMA slab burner was built to evaluate in smaller scale the ballistic properties of solid fuels before performing tests on the 1kN engine, the oxidizer was kept the same, which is liquid N_2O. To allow the liquid injection droplets to break up and evaporate before interacting with the fuel, while keeping the chamber compact, N_2O is injected through a swirling injector, mounted on the forward end of the test chamber, which create a swirling movement of the flow inside the chamber increasing the residence time of the droplets before impinging on the fuel grain. As the burner has been used mostly with paraffin-based liquefying fuels, while the turbulent flows increase the regression rate of the fuel grain, this also translated in a larger quantity of entrained paraffin droplets that burn and collide on the walls of the chamber, increasing the temperature at the walls and depositing soot on the window, hindering the quality of the images acquired.

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A possible solution to this issue has been identified in the introduction of a pre-chamber, which would give enough space to the oxidizer to break up even with an axial showerhead injection plate, thus eliminating the turbulent flow induced by the swirling oxidizer flow and the accumulation of soot on the window. A second advantage of the pre-chamber is the increase in the useful volume inside the test chamber: as half of the available space is occupied by the swirling injector and torch igniter, the pre-chamber would permit to move them upstream, increasing the visibility range through the window, for more flexibility on the dimensions and geometries of grains that could be tested.

A second issue identified in the flow inside the chamber was caused by the flat plate used as exhaust discharge. The shape of the plate and the position of the opening induced a recirculation zone in the rear part of the test chamber, locally increasing the regression rate on the fuel and the temperature of the combustion gas, burning and damaging also the rear end of the chamber. The solution has been identified in the addition of a post-chamber, with the purpose of guiding the flow towards the exhaust opening.

B. Increase the maximum operative pressure and burn time

The RMA slab burner has been designed to perform tests at low pressure (< 1.5 bar absolute pressure) and of short duration (around 5 seconds). The main limitations to increase these operating parameters are the thermal and structural resistance of the borosilicate glass window, the profile and material of the test chamber (square section and carbon steel) and the exhaust plate configuration, also made in metal, which can’t sustain a high temperature flow for longer periods of time. To overcome these issues, several improvements have been introduced:

- The material selected for the new components is a low carbon stainless steel, which provides a higher temperature and structural resistance. Moreover, a round cross section has been selected for the chamber, providing higher structural resistance for a pressurized environment. The wall thickness also ensures higher thermal capacity and resistance to thermal deformations induced by the temperature of the gas, increasing the total burning time.
- The window interface with the chamber has been redesigned, to minimize the tensions induced by the thermal expansion of the glass. A new window material has been selected, namely quartz, to have higher temperature and pressure resistance [7].
- A nozzle has been introduced in the post chamber. As the objective of the burner is not to provide thrust, only a convergent section has been adopted. The nozzle was made in two parts, both in graphite, a first converging section and a throat insert. The converging section protects the post-chamber from the high temperatures of the combustion gas, increasing the useful life of the slab burner. The throat insert is a smaller piece that can be changed more often, according to the erosion, and several diameters have been realized, allowing to pressurize the chamber at different operative pressures.

C. Improve the type and quantity of performable measurements

The improvement of type and quantity of measurements has been achieved as a partial consequence of the redesign process of the previous two points.

- The increase in temperature and pressure resistance of the chamber allows for tests at different burning times and different pressures.
- The introduction of a throat insert allows to change the pressure in the chamber with more precision, increasing the range of test pressures achievable.
- The quartz glass window is more resistance to the operative conditions of the burner. Two parallel windows have been introduced, making possible to perform measurements with other visualization techniques other than high speed videos and OH* or CH* chemiluminescence, such as Schlieren techniques. Moreover, the windows dimensions have been increased to allow a larger optical access to the test chamber.

As a pre-chamber for flow conditioning has been introduced, it has been decided to change the oxidizer from liquid N_2O to gaseous oxygen. The use of oxygen allows faster operations, as for the mass flow rates and inlet pressure range required it can be fed directly from pressurized vessels without the use of a secondary tank which has to be filled and pressurized. Moreover, shifting to a gaseous oxidizer eliminates the effects due to break up and evaporation of liquid droplets, increasing the flexibility of the system. The length of the pre-chamber has been chosen to ensure full reattachment of the oxidizer flow after injection.

Other than optical measurements, the burner has also been equipped with four ports, that can be used to mount thermocouples or pressure transducers, both in the pre-chamber and in the post-chamber.

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D. Improve motor handling and test preparation characteristics

The outcomes of the design phase also had an advantage on test preparation time and handling of the system:

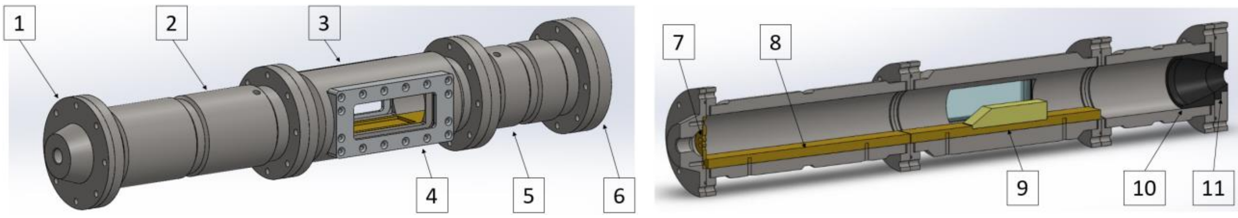
- The use of gaseous oxygen, as previously discussed, simplifies the feed system operations, eliminating filling and pressurizing procedures, as well as the tank draining at the end of the tests, considerably reducing the time required to perform tests.
- While in the RMA slab burner the fuel grains were glued directly inside the test chamber, brass grain holders have been introduced, that can be quickly exchanged between tests reducing the preparation time.
- The nozzle insert allows for a fast reconfiguration of the nozzle opening, thus several tests at different pressures can be performed over a short period time.

2.3 MOUETTE hybrid rocket slab burner

The final design iteration led to the concept illustrated in Figures 2a and 2b, which show a CAD model of the components that constitute the MOUETTE hybrid rocket slab burner. The description of the single parts according to the enumeration followed in the figures is given in Table 1. The changes from the initial design are several, responding to the design objectives given in the previous section. The MOUETTE burner features a cylindrical shape, like a conventional hybrid rocket combustion chamber, with two openings for optical measurements (n.4). The oxidizer is fed to the chamber through an injector plate (n.7) and conditioned through the pre-chamber (n.2). It then flows in the test section of the burner (n.3), namely the combustion chamber, where the solid fuel grain is placed. The combustion products then flow through the post-chamber (n.5), to be ejected through the convergent nozzle (n.10 and n.11). The space available for hosting the fuel grain in the chamber is 133 mm long, 74 mm wide and 63 mm tall.

To satisfy the requirement of optical accessibility, the burner combustion chamber presents two parallel quartz glass windows. The sealing between the cylindrical parts of the burner is achieved with NBR O-rings, while the window frame seals the optical access with NBR gaskets, which also act as interface between the quartz glass and the metallic parts, to avoid scratch and damage due to thermal expansion of the components.

The cylindrical configuration and the modular structure of MOUETTE make the system particularly versatile. With small modifications, the burner can also be operated as a conventional HRE.



(a) (b)

Figure 2: (a): lateral view and (b): longitudinal section of the MOUETTE slab burner CAD 3D model.

Table 1: Components of the MOUETTE slab burner enumerated according to Figure 2.

N.	Component	Description	Material
1	Injector head	Oxygen manifold, holds the injector plate	Stainless Steel
2	Pre-chamber	Conditions the oxidizer flow coming from the injector	Stainless Steel
3	Main chamber	Test section of MOUETTE	Stainless Steel
4	Window frame	Structural support for the quartz glass window	Aluminium
5	Post chamber	Aft part of the burner	Stainless Steel
6	Nozzle support	Holds the throat insert	Stainless Steel
7	Injector plate	Injects oxygen in the slab burner	Brass
8	Pre chamber sole	Avoids turbulence induced by change of cross-section	Brass
9	Fuel grain support	Holds the solid fuel grain	Brass
10	Convergent nozzle insert	First part of the nozzle	Graphite
11	Nozzle throat	Second part of the nozzle, with different throat diameters	Graphite

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3. Test bench development

3.1 Feed system

As MOUETTE uses gaseous oxygen as oxidizer instead of N_2O, a new feed system had to be designed. The schematic is shown in Figure 3. The feed system consists mainly of an oxygen line and an auxiliary nitrogen line. Oxygen flows from the tank in blow down mode, while the pressure is set using a pressure regulator. An electro pneumatic valve controls the flow of oxygen, while the mass flow rate is kept constant by a chocking orifice, which also isolate the valves from pressure oscillations coming from the combustion chamber. A solenoid valve is used to drain the remaining oxygen in the line at the end of the test procedure. Pressure and temperature values are measured in different points of the line with pressure transducers and K-type thermocouples. A relief valve is mounted upstream of the motor, allowing an emergency discharge of oxygen in case of overpressure, especially for proof test operations.

The nitrogen line is an auxiliary line which mainly consists of a solenoid valve used for the purging of the burner at the end of the test. A pressure regulator is also present, to reduce the pressure for a line derivation used to actuate the oxygen electro-pneumatic valve.

Along the feed system lines, a set of manual ball valves have been positioned, which are used to isolate parts of the system during pre-test procedures, and to perform nitrogen purge during system leak tests and to drain the remaining nitrogen in the line at the end of the test.

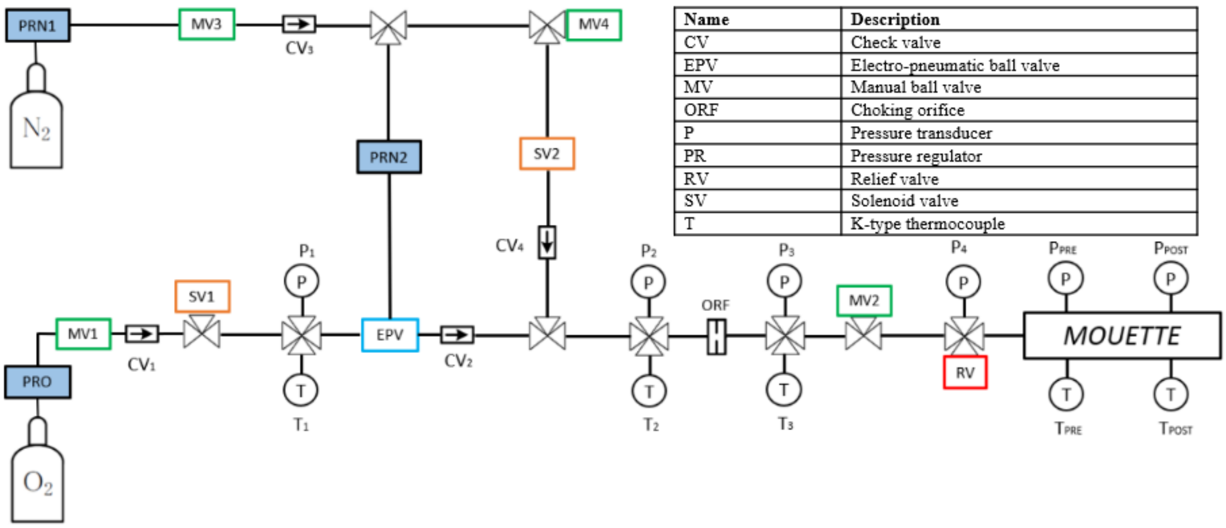

Figure 3: MOUETTE feed system schematic.

3.2 Calibration of the orifice

The mass flow rate of oxygen is set to a fixed value using a choking orifice. The mass flow passing through it can be calculated according to equation 1:

$$\dot{m} = c_D A \sqrt{\gamma \rho_0 P_0 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad (1)$$

Where $\dot{m}$ is the oxygen mass flow rate, γ the heat capacity ratio of oxygen and ρ_0 its density upstream of the orifice (both function of upstream pressure and temperature), P_0 the pressure of the flow upstream of the orifice, A the area of the orifice and c_D the discharge coefficient.

Once the c_D is known, the mass flow rate of oxidizer to the burner can be set just by selecting the desired orifice diameter and regulating the pressure upstream of it, set by the pressure regulator. The precise value of the mass flow can then be calculated after the test, as the pressure and the temperature upstream of it are measured.

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Different orifice diameters have been realized, allowing to operate the motor at different mass flow rates. The interface with the feed system has been designed with a modular structure so that the diameter can be easily adjusted between tests to the required value.

An initial characterization campaign of the c_D has been carried out using the equipment of the ATM department. In particular, the orifice has been installed on the air supply line of a test bench for multiphase flow investigation. The working flow of the system is dry air, supplied by an air compressor. Upstream of the orifice, a pressure transducer and a thermal mass flow meter are used to measure the pressure P_0 and the mass flow rate $\dot{m}$ in the line. The temperature of air is also measured. The orifice then discharges the airflow in the environment.

Using Equation 1, and the density and heat capacity ratio of dry air calculated for the pressure and temperature upstream of the orifice, the discharge coefficient could be inferred. Figure 4 shows a plot of experimental data acquired for three orifice diameters, namely 2.4, 2.7, and 3.0 mm. The calculated discharge coefficients are 0.67, 0.61, and 0.57, respectively.

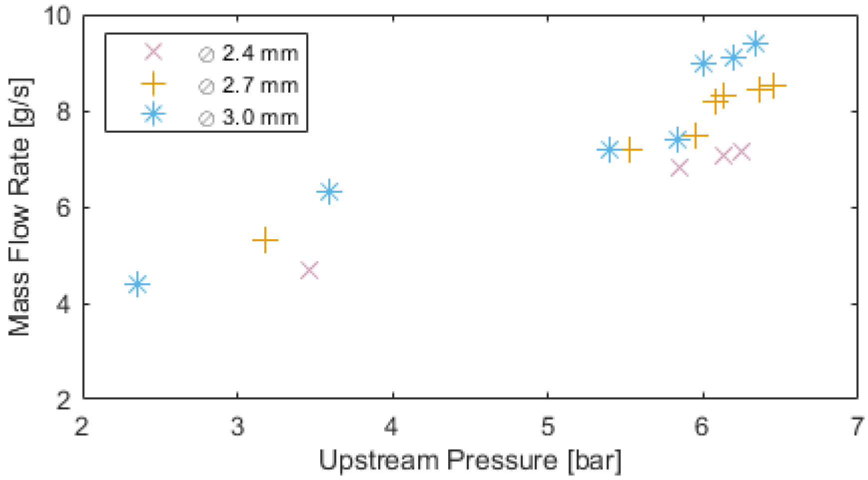
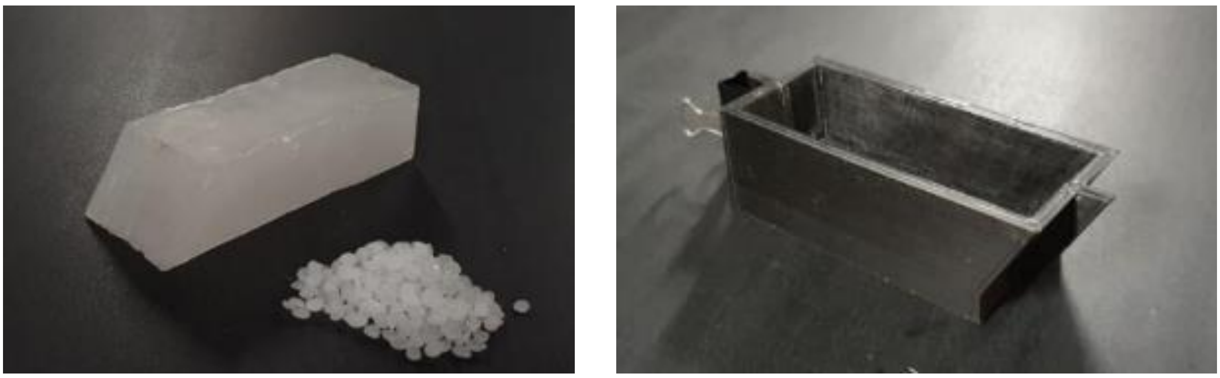


Figure 4: Experimental data of orifices cold flow test characterization.

3.3 Fuel grain

For the commissioning campaign, a series of fuel grains have been made, using paraffin Tudamelt 52/54, supplied by H&R group. The fuel grain shape chosen for the commissioning campaign has a chamfered leading edge, chosen as in [8], and is shown in Figure 5. The manufactured grains have a mass of around 90 grams, with average length of 100 mm, width of 40 mm and height of 30 mm.

The paraffin, supplied in pellets, is melted and casted in a mould, where it solidifies acquiring the form required. The mould has been 3D printed in PLA in three pieces and with chamfered walls, to guarantee easy removal of the grain when solidified.



(a) (b)

Figure 5: (a): Paraffin fuel grain; (b): Fuel grain mould.

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3.4 Ignition

For the ignition of the MOUETTE fuel grains a simple pyrotechnic ignition device has been chosen. The igniter is a small solid propellant grain, composed by 40% sugar and 60% potassium nitrate. The charge is positioned close to the fuel grain and activated with a nichrome wire. Once electricity is supplied to the wire, it heats up through Joule effect, igniting the solid propellant. The product gas generated by the solid propellants provides the heat required for the fuel grain ignition, once the oxygen main valve is opened.

3.5 Data acquisition and control system

The data acquisition system selected for MOUETTE is a National Instruments (NI) DAQmx USB 6218, managed by a dedicated LabVIEW program. The system allows the users to collect and record sensors data, manage the ignition and the valves opening and closing (both manually and through an automatic test sequence), actuated and powered by a separate power supply and control box.

The test sequence is defined and controlled through an automatic procedure, which can be initiated only after the activation of switches that follow the pre-test procedure and guarantee the safety of the test operators. The sequence is divided in three main steps:

1. Ignition of the pyrotechnic device.
2. Opening of oxygen main valve.
3. Purging of the chamber with nitrogen.

4. Commissioning campaign

4.1. Manufacturing, Assembly, and Integration

After the critical design of all the system has been completed, the procurement and manufacturing of the single subsystems and components has been divided between the ATM department and external suppliers.

Before proceeding to the commissioning test campaign, the following intermediate steps have been followed:

1. Quality check of every manufactured component.
2. Assembly of feed system and of the slab burner.
3. Integration of the feed system and slab burner on the test bench.
4. Leak test of the feed system and slab burner interfaces.
5. Proof test of the slab burner.
6. Ignition test, to evaluate the time required by the nichrome wire to ignite the solid propellant grain and the total delay before the oxygen main valve opening.

4.2. Test setup

For the commissioning test campaign, the feed system and slab burner have been instrumented with Heim 100 bar gauge pressure transducers and K-type thermocouples. The position of the sensors relative to the feed system schematic is shown in Figure 3. A Photron FASTCAM SA4 has been used to record high-speed videos of the combustion process. The camera is aligned to one of the two optical accesses, and it has been equipped with filters for OH* or CH* chemiluminescence.

A jet engine trim pad facility of the Beauvechain Air Base has been used to host the design validation test campaign. The slab burner and its feed system are inside a blast proof room, while an opening on the roof and an exhaust tube on one side allow air recirculation and evacuation of combustion gases. An adjacent control room hosts the data acquisition system, and a ballistic glass consents to observe the burner behaviour during the tests and to assess the safety of the room at the end of it.

The final test setup is shown in Figure 6. In the photograph, the MOUETTE can be seen mounted on the movable test bench, that also hosts the feed system and the power supply for valves and sensors. The mobility allows more flexibility between test campaigns, to maximize the exploitation of the test room, which is used also for the 1kN engine.

A rigorous pre- and post-test procedure has been implemented, to guarantee both the safety of the personnel involved as well as the repeatability of the tests.

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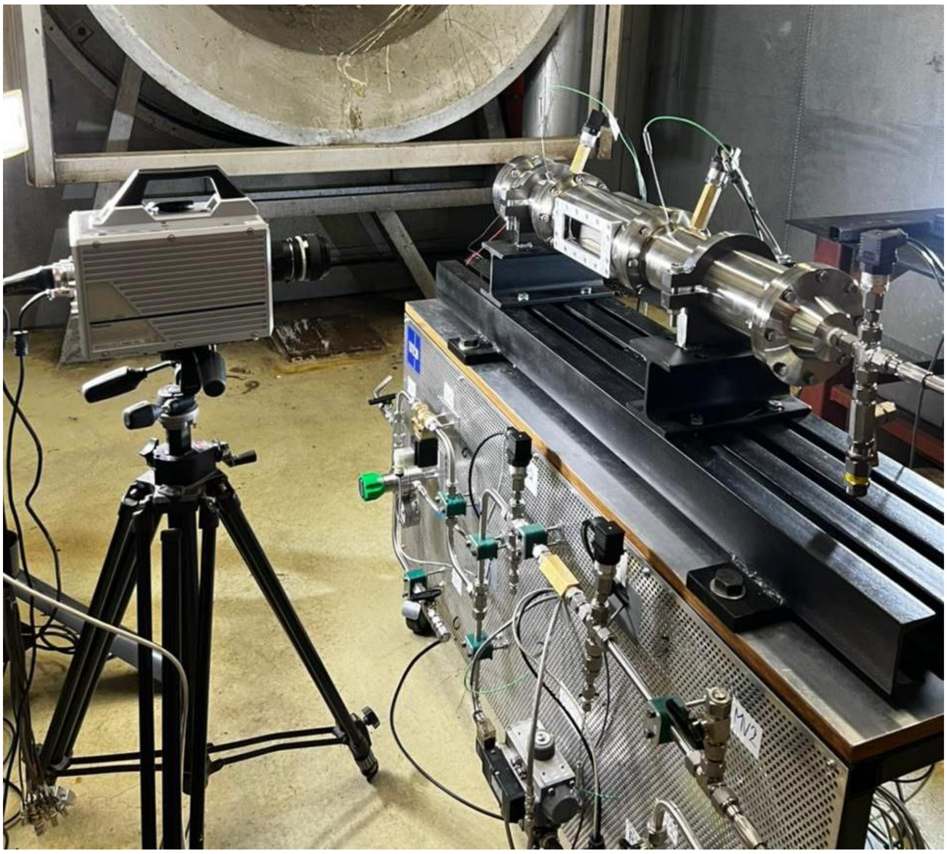

Figure 6: MOUETTE test setup.

4.3. Test campaign overview

The test matrix has been conceived to provide results at different pressures and different mass flow rates, to have a complete overview of the burner capabilities. The tests have been implemented to evaluate the performance of the burner in the different operating points, and to improve the procedures adopted during tests preparation and execution.

In particular, the two main parameters which have been modified among tests where the mass flow rate, through the choking orifice, and the combustion chamber pressure, through the nozzle throat insert. For the initial validation campaign of the system, 25 successful tests have been executed successfully.

Test have been first divided according to the mass flow rate of oxygen controlled through the choking orifice. Starting from the lowest mass flow rate, provided by the smallest orifice, the performance of the burner has been assessed, before increasing the diameter of the orifice and therefore the mass flow rate. For the commissioning campaign, three orifice sizes have been used. The same approach has been adopted for the combustion chamber pressure, increasing it by changing the graphite nozzle to reduce the throat diameter as the performance at a lower pressure has been confirmed.

An overview of the tests performed is given in Table 2, with the average chamber and tank pressure measured, the burning time, and the calculated mass flow rate. Data of the solid fuel grain regression rate have also been gathered, but their analysis and correlations will be discussed in future works. A photograph of a test (Test 22) is shown in Figure 7, where the glowing combustion chamber window and the nozzle exhaust plume can be seen.

All the tests discussed in this section have been performed with the paraffin wax fuel grain described in Section 3.3. Nevertheless, both the geometry and the chemical formulation of the fuel have been modified in some tests, to exploit the commissioning campaign also to satisfy other research questions. Tests 13, 14 and 16 to 18 have been carried out with fuel grains doped with metallic particles in different mass fractions, as described by Bertoldi *et al.* in [9], while tests 15 and 23 preliminary investigate the effect of different geometries of the fuel grain on its regression rate characteristics, as discussed by Glaser *et al*. in [10]. As these tests are analysed in other works, they are not examined in this document.

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Table 2: MOUETTE test campaign overview.

Test Number	Burning Time [s]	Tank Pressure [barg]	Chamber Pressure [barg]	Mass Flow [g/s]	Inlet Mass Flux [g/cm^2]	Notes
1	5.32	37.46	0.11	54.63	1.27	
2	5.31	36.54	0.09	53.17	1.24	
3	5.22	36.65	0.34	53.47	1.24	
4	5.18	36.64	1.91	53.45	1.24	
5	5.38	36.54	3.05	53.31	1.24	
6	5.28	36.50	3.20	53.26	1.24	
7	[-]	[-]	[-]	[-]	[-]	Error in data acquisition
8	5.56	36.84	2.75	53.77	1.25	
9	5.25	37.22	2.88	54.33	1.26	
10	[-]	[-]	[-]	[-]	[-]	Error in data acquisition
11	5.52	34.92	2.23	81.20	1.89	
12	5.61	34.86	2.28	80.93	1.88	
13	5.41	34.62	2.52	80.51	1.87	Paraffin + metallic additives
14	5.64	34.58	1.78	80.36	1.87	Paraffin + metallic additives
15	5.46	34.45	2.48	79.20	1.84	Different fuel grain geometry
16	5.58	35.87	2.49	83.37	1.94	Paraffin + metallic additives
17	5.64	35.15	2.57	81.69	1.90	Paraffin + metallic additives
18	5.54	35.00	2.04	81.38	1.89	Paraffin + metallic additives
19	5.46	33.67	2.96	98.66	2.29	
20	5.56	33.46	4.76	98.12	2.28	
21	7.30	33.12	6.23	97.14	2.26	
22	7.24	32.89	6.58	96.49	2.24	
23	7.24	32.26	3.33	95.85	2.23	Different fuel grain geometry
24	5.58	31.62	4.54	92.80	2.16	
25	5.55	31.31	4.69	91.94	2.14	

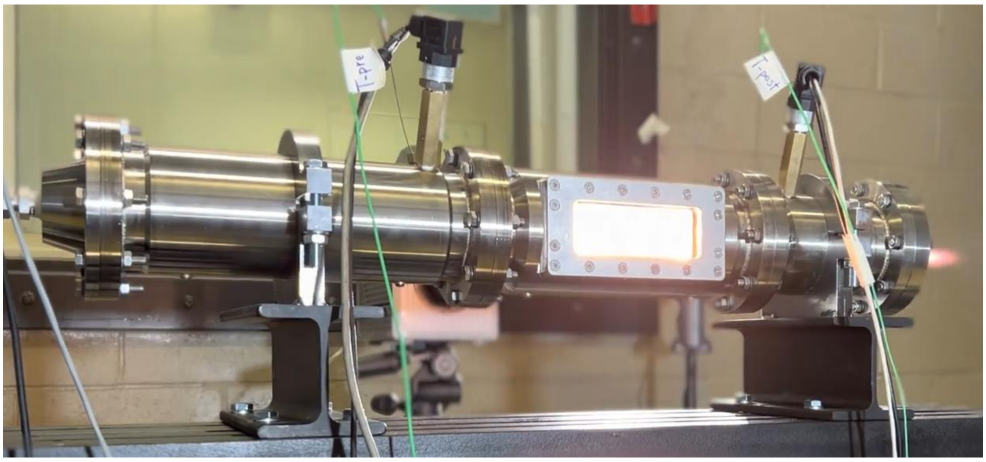

Figure 7: Photograph of MOUETTE during a firing test.

4.4. Test results discussion

Figure 8 shows the chamber pressure curves of Tests 1, 2 and 3. The pressure plotted is the average between the measurements of the transducers in the pre-chamber and post-chamber. All three tests have been executed at a nominal mass flow rate of 50 g/s. The first two tests have been performed with a nozzle throat diameter of 20 mm, and the resulting combustion chamber pressure is quasi-atmospheric, oscillating around 0.1 bar gauge. Test 3 has a throat diameter of 15 mm, which allowed to increase the pressure to 0.3 bar gauge. All three tests pressure trends present a transitory ramp up to a peak, to then decrease and oscillate around the steady state value. The ramp is due to the

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transitory filling of the lines, injector manifold and chamber after the main valve opening, as well as the ignition transient of the fuel grain, while the peak can be explained by the ignition transient, when the pyrotechnic igniter which is still in the combustion chamber during the start of the oxygen flow increase its burning rate and the pressure in the chamber, before completely burn or being expelled through the nozzle. Tests 1 and 2 plots are similar, confirming the repeatability of the tests.

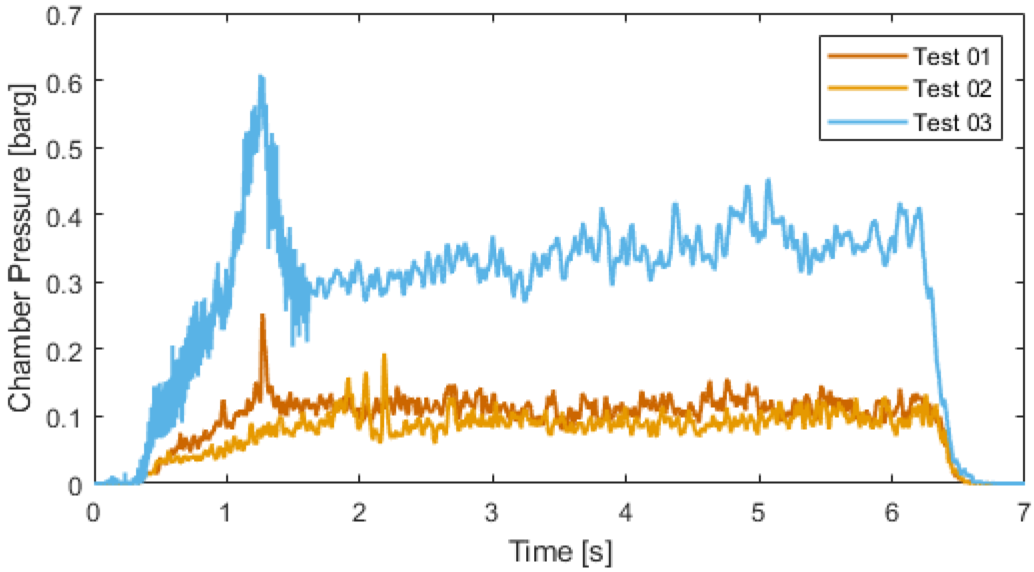

Figure 8: Chamber Pressure of tests with 50 g/s oxygen mass flow rate, without chocked nozzle throat.

After the first three successful tests, the consecutive tests have been executed with smaller throat diameters, to reach choking condition in the nozzle. Figure 9 shows the pressure trends for Tests from 4 to 9, while data for Test 7, executed in the same conditions, have been lost, due to an issue in the LabVIEW program. All tests have a nominal mass flow rate of 50 g/s. Test 4 has a nozzle throat diameter of 10 mm, which allowed to reach a pressure of 2 bar gauge, while Tests 5 to 9 have a nozzle throat of 8 mm, for a chamber pressure of 3 bar gauge.

All tests present again a pressure ramp in the transitory start-up phase, with again a strong peak, especially in Test 5, due to the igniter interaction with the fuel and the oxygen flow. Test 4 presents a peculiar behaviour, where the pressure seems to stabilize around 1 bar gauge, before a sudden pressure jump set it to a 2 bar gauge value. The first tests have been of utmost importance also to define and learn the correct operational procedures of the burner. Both the igniter and the nozzle positioning in the chamber where not completely defined yet. During Test 4, the igniter moved, and the wires, which enter the chamber through the nozzle throat, slightly moved the graphite insert out of position, increasing the area of passage for the product gas. About two seconds after, a nonuniformly operation occurred on the fuel grain, where the oxidizer flow started flowing also underneath the grain, detaching it from the holder. The sudden increase of mass flow and pressure due to the event moved the nozzle throat to the correct position, thus consenting the burner to work at the nominal pressure. The movement of the fuel grain has been documented with a high-speed camera video and is discussed in the next section. The results are interesting for the designer point of view, as they allowed to improve both the igniter and nozzle throat positioning and the grain fixing in the combustion chamber.

To reduce the pressure peak induced by the ignition phase, a smaller igniter has been adopted from Test 6 onwards, which is almost completely consumed before the injection of oxygen in the chamber, as well as a new procedure to correctly define its mass and position it in the chamber. These design tweaks allowed to reduce the pressure peak at start up, as seen also in the following plots.

The pressure curves of tests performed at the same mass flow and chamber pressure conditions, such as tests from 6 to 9, are similar, confirming the repeatability of the tests performed.

While the burning time is kept the same as the first tests, it can be observed that the shutdown transient is longer in pressurized tests than in the ambient pressure ones. This is due to the higher time required for the chamber to reach the ambient conditions.

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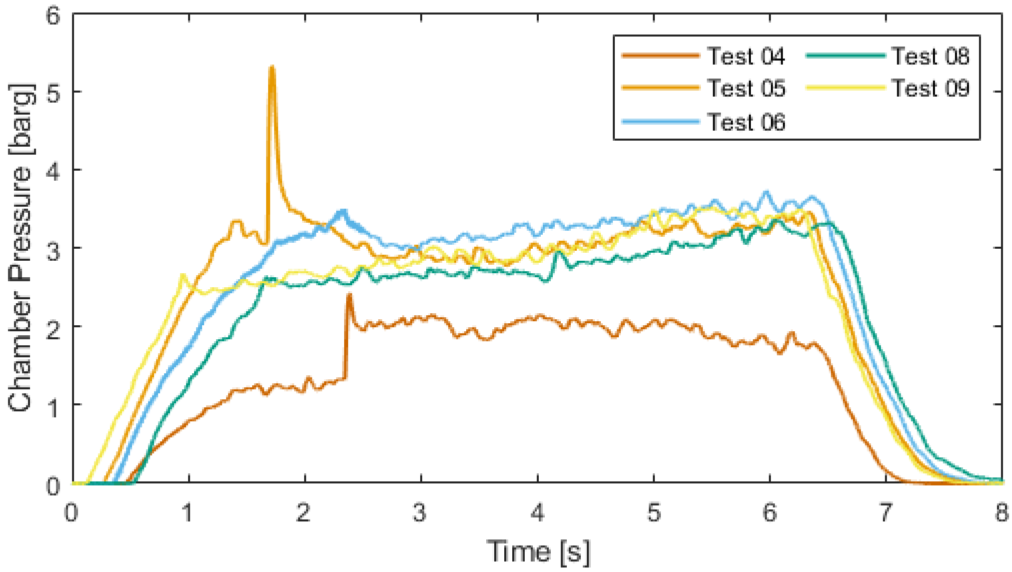

Figure 9: Chamber Pressure of tests with 50 g/s oxygen mass flow rate, with choked nozzle throat.

Tests 10 to 12 have been executed with a different chocking orifice to have a higher oxidizer mass flow rate, nominally around 80 g/s of gaseous oxygen. Figure 10 shows the pressure trend of Tests 11 and 12, while the data for Test 10 have been lost. They have been executed with the nozzle diameter of 10 mm. The average pressure is of 2.2 bar gauge. Being performed with the same pressure conditions in the feed system and in the chamber, the two plots are almost equal, confirming again the repeatability of the acquired measurements and the reliability of the burner. The pressure peak at ignition is not present anymore, due to the new igniter manufacturing procedure adopted.

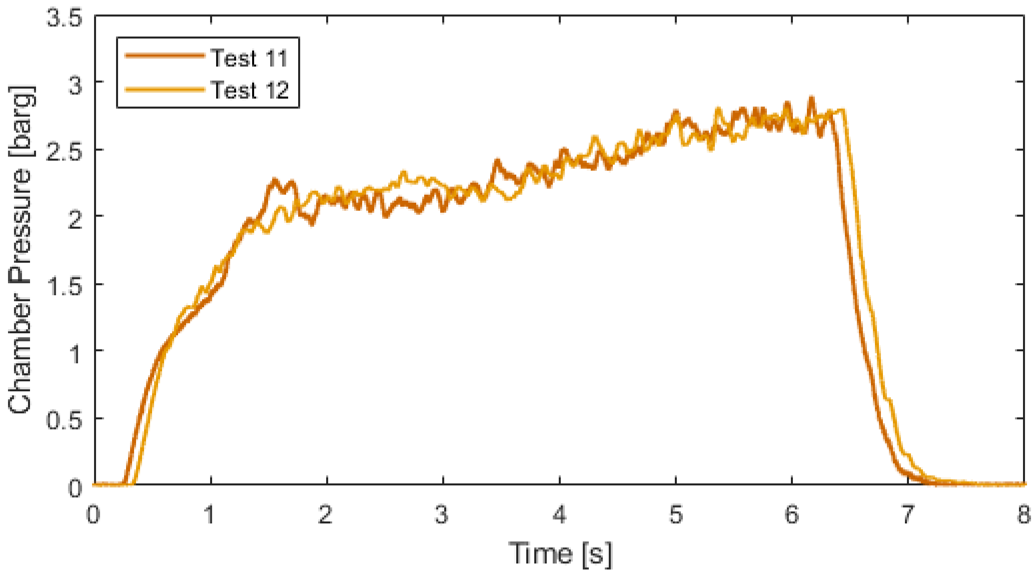

Figure 10: Chamber Pressure of tests with 80 g/s oxygen mass flow rate.

The last tranche of tests discussed in this section has been carried out with the highest mass flow rate, with the orifice set for a nominal mass flow rate of 100 g/s. The pressure trends are shown in Figure 11. The tests show a good repeatability and the pressure peak at ignition is not present anymore. Test 19 has an average pressure of 3 bar gauge, obtained with the 15 mm nozzle. Tests 20, 24 and 25 have a pressure of 5 bar gauge, given by the 10 mm nozzle, while Tests 21 and 22 go above the critical pressure of paraffin wax, with 7 bar gauge, using the 8 mm nozzle.

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To assess the performance of MOUETTE at higher pressure and temperatures over longer burning times, Tests 21 to 23 have been conducted for a 7.5 second nominal time, 2 seconds longer than the other tests. The burner withstands well the heat, as the high oxidizer to fuel ratio allows for a lower temperature of the gas in contact with the chamber walls. The most critical component for longer tests proved to be the nitrile rubber gaskets, used in the window frames to seal the optical access, as they tend to carbonize if exposed to high temperatures for a longer timeframe. Therefore, they to be inspected between tests and changed more often. If the gaskets fail, the high temperature gas flows through the optical access, damaging the quartz window, the aluminium frame and burning the nitrile gasket even more.

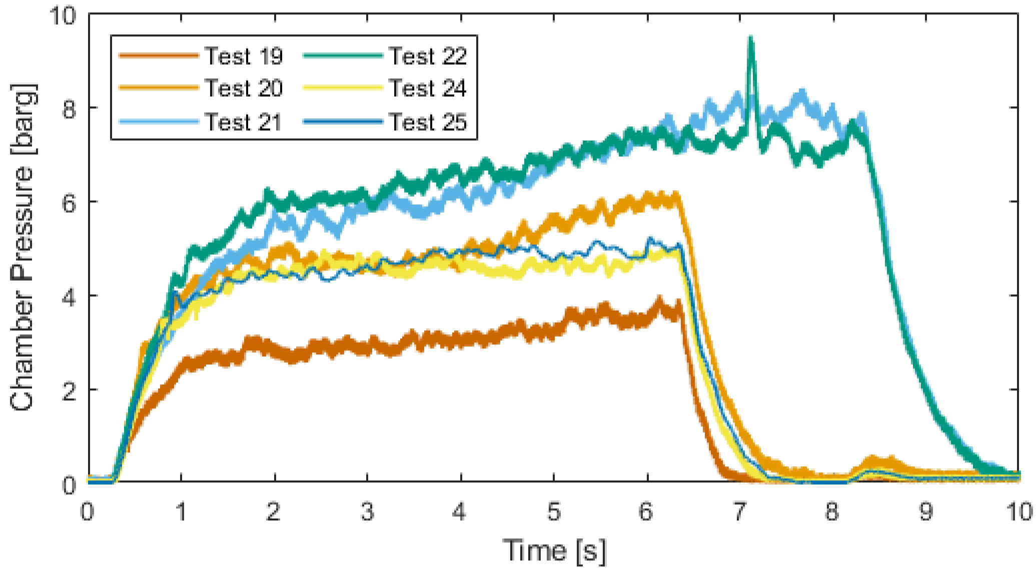

Figure 11: Chamber Pressure of tests with 100 g/s oxygen mass flow rate.

To conclude the discussion of the results, the pressure curves shown in Figure 12 are a plot of the pressure in the feed system of MOUETTE, taken for Test 6, as example. P1 is the pressure upstream of the main valve, P2 upstream of the choking orifice, P3 downstream of the orifice and P4 in the injection manifold. The choking orifice acted as required, maintaining constant the quantity of oxygen flowing into the chamber and isolating the feed systems from pressure oscillations due to the combustion process. This can be seen in the plot, as the curves of P1 and P2 are stable and are not affected by the peak in the combustion chamber, captured by P3 and P4, downstream of the orifice.

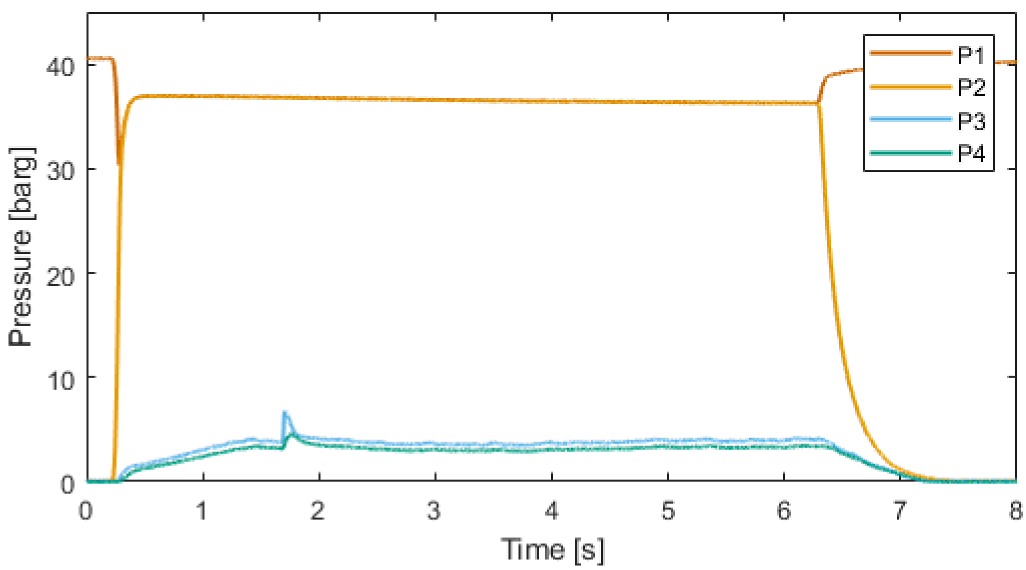

Figure 12: Pressure curves in feed system of Test 6.

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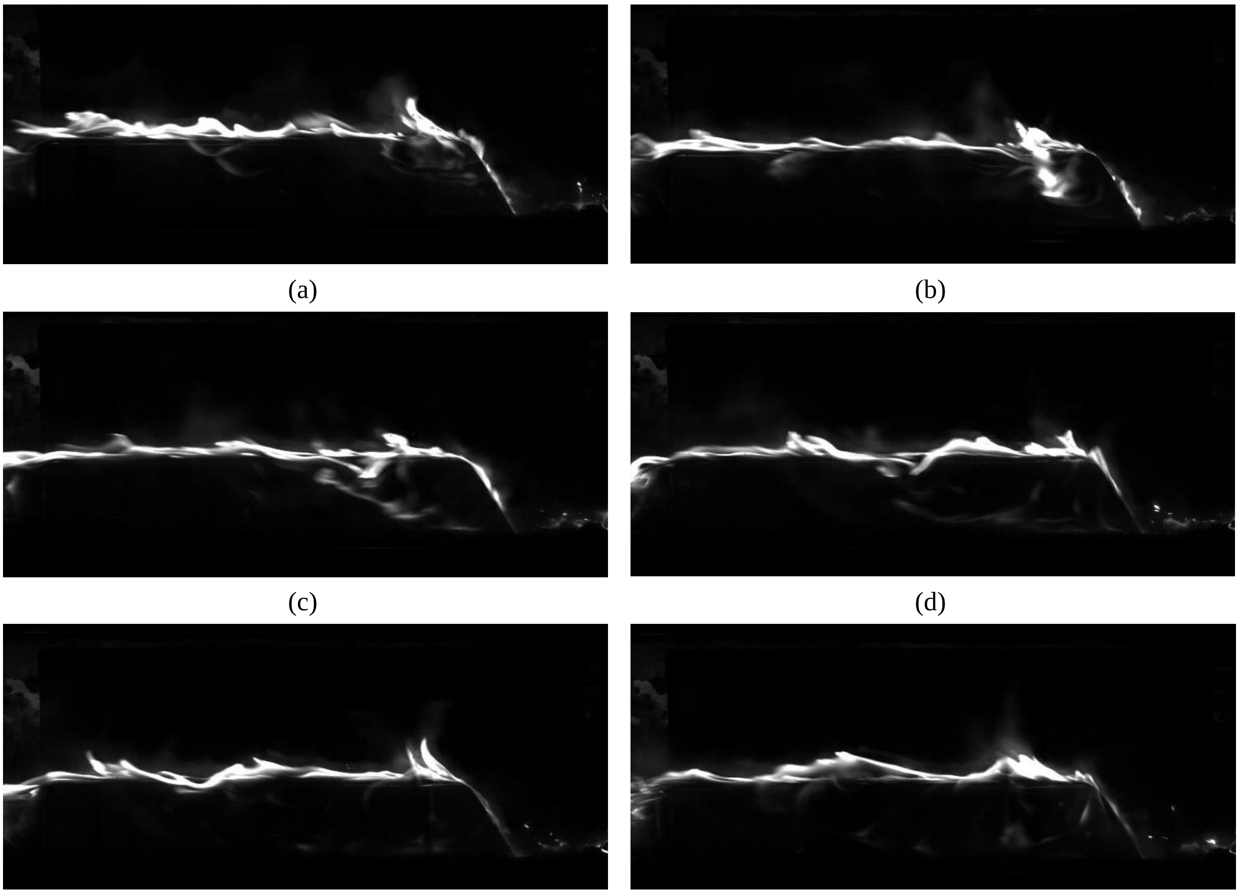
4.5. Flame visualization

While the MOUETTE slab burner satisfied the requirements of burning time, pressure, and mass flow rate, one of the initial objectives of the design was the improvement of the measurements which could be acquired through the optical access. For the commissioning campaign, high-speed videos of the combustion process have been acquired, mostly using filters to perform OH* or CH* chemiluminescence. The results allowed to better comprehend the ignition process and the burning behaviour of the fuel. The initial tests were also used to trim the camera parameters, to increase the quality of the acquired videos.

The discussion and analysis of the visualization results is out of the scope of this paper, but some selected frame sequences are presented in this section, to provide an assessment of the visualization capabilities of MOUETTE.

The first sequence of frames, shown in Figure 13, is taken from Test 11. In the pictures, oxygen flows from right to left. The original video was acquired with a filter for CH* emission and was acquired at 3000 frames per seconds, with a resolution of 512x352 pixels. The sequence of frames extracted and shown in the figure has a time interval of 3.3 ms between images, at about 2 second of burning time, when the combustion chamber pressure is at about 2 bar gauge. In this part of the test, the pressure is under the critical pressure of paraffin, the diffusive flame structures can be identified, and their evolution traced in the video. With this type of images numerical methods can be applied to investigate the liquid layer instabilities phenomena on the fuel surface [11]. The leading edge of the fuel grain presents a stronger recirculation zone, while the flame later reattaches on the surface of the grain.



(a) (b) (c) (d) (e) (f)

Figure 13: Visualization of Test 11.

The second sequence of frames selected for this paper is shown in Figure 14, taken from Test 22. As for the previous set of images, they are recorded using a filter for CH* emission with an acquisition speed of 3000 frames per seconds, with a resolution of 512x352 pixels. The sequence of frames extracted and shown in the figure has a time interval of 3.3 ms between the images and shows the behaviour of the fuel grain at 5 second of burning time. In these photographs, the pressure in the chamber is above 7 bar gauge. At this pressure the observed blowing events become more violent, frequent, fast and intermittent, providing results which adheres with the observations at similar conditions of Jens [8]

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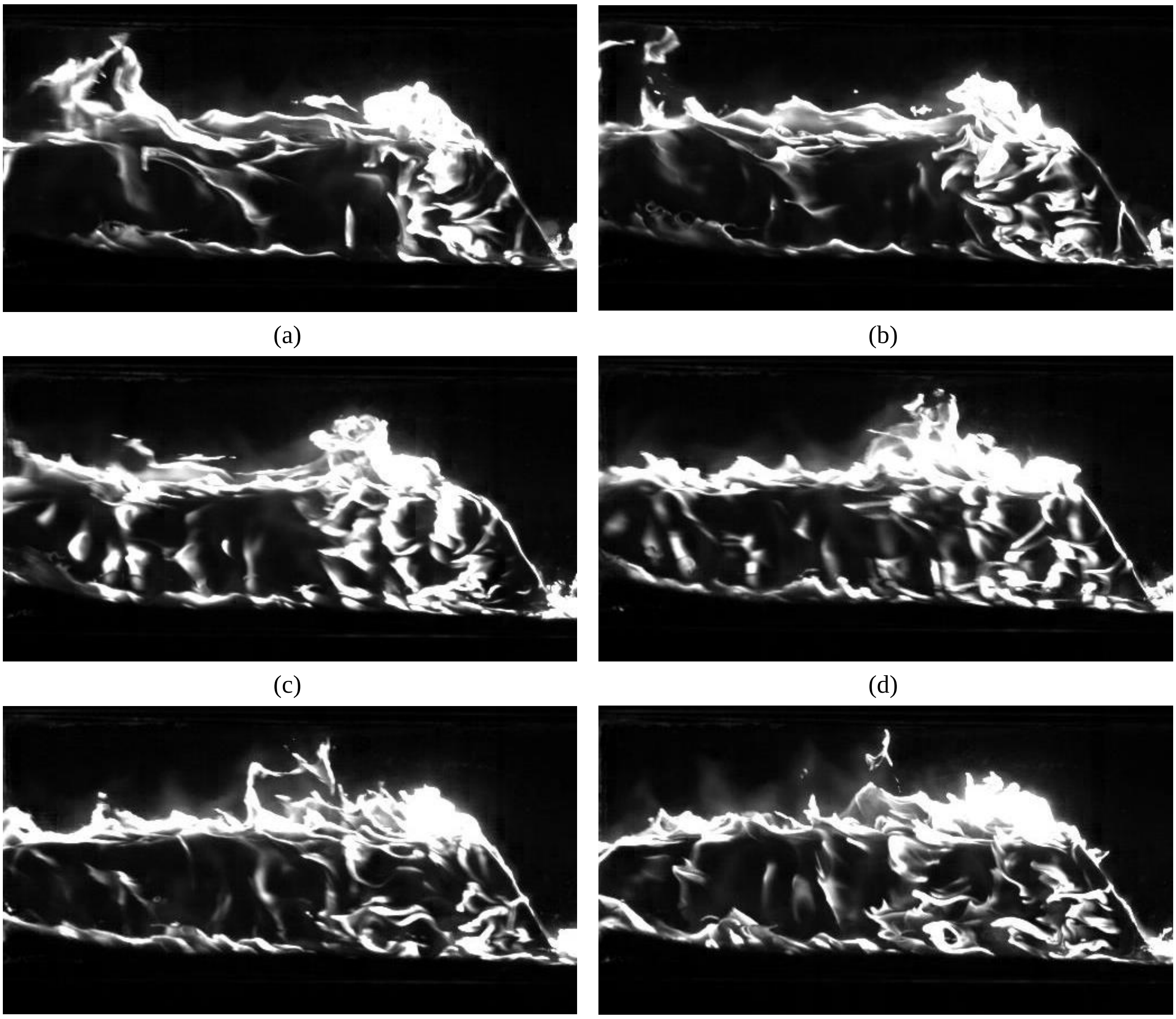
and Petrarolo [11], which suggest that this behaviour onset when the chamber pressure exceeds the critical pressure of paraffin wax. The effect on combustion of the recirculation zone at the leading edge of the fuel grain is also more pronounced, and paraffin is burning also on the lateral sides of the grain, which are exposed to the oxidizer flow. When compared with the previous sequence, also the height of the combustion zone increase



(a) (b) (c) (d) (e) (f)

Figure 14: Visualization of Test 22.

The last sequence has been taken from Test 4, shown in Figure 15. The images are taken around the pressure peak described in the previous section. The original video is acquired using a filter for OH* emission, at 1000 frames per seconds, with a resolution of 896x640 pixels. The frames depicted have a time interval of 20 ms between each other. These photographs are shown because they depict an explosive event that took place during the test.

As the procedure to attach the fuel grain to the chamber was not yet accurately defined, the oxygen could flow underneath the bottom part of the leading edge, burning the paraffin wax grain from beneath. The fast accumulation of gas provoked the detachment of the fuel grain from the holder, and the event is shown in Image (b) of the figure. After a few milliseconds the grain goes back on the holder and is shown in Image (h) of the figure.

From the designer point of view, the event identified a flaw in the fuel grain attachment procedure, which was then improved, but Images from (c) to (g) are also interesting for paraffin wax fuels research, as they allow to see a large quantity of liquid paraffin droplets, which are being blown away from the fuel surface and entrain in the flow, burning away. This is another visual confirmation of the liquefying properties of paraffin wax, and the outcome of the event is again similar to the observations of Jens [8] and Petrarolo [11].

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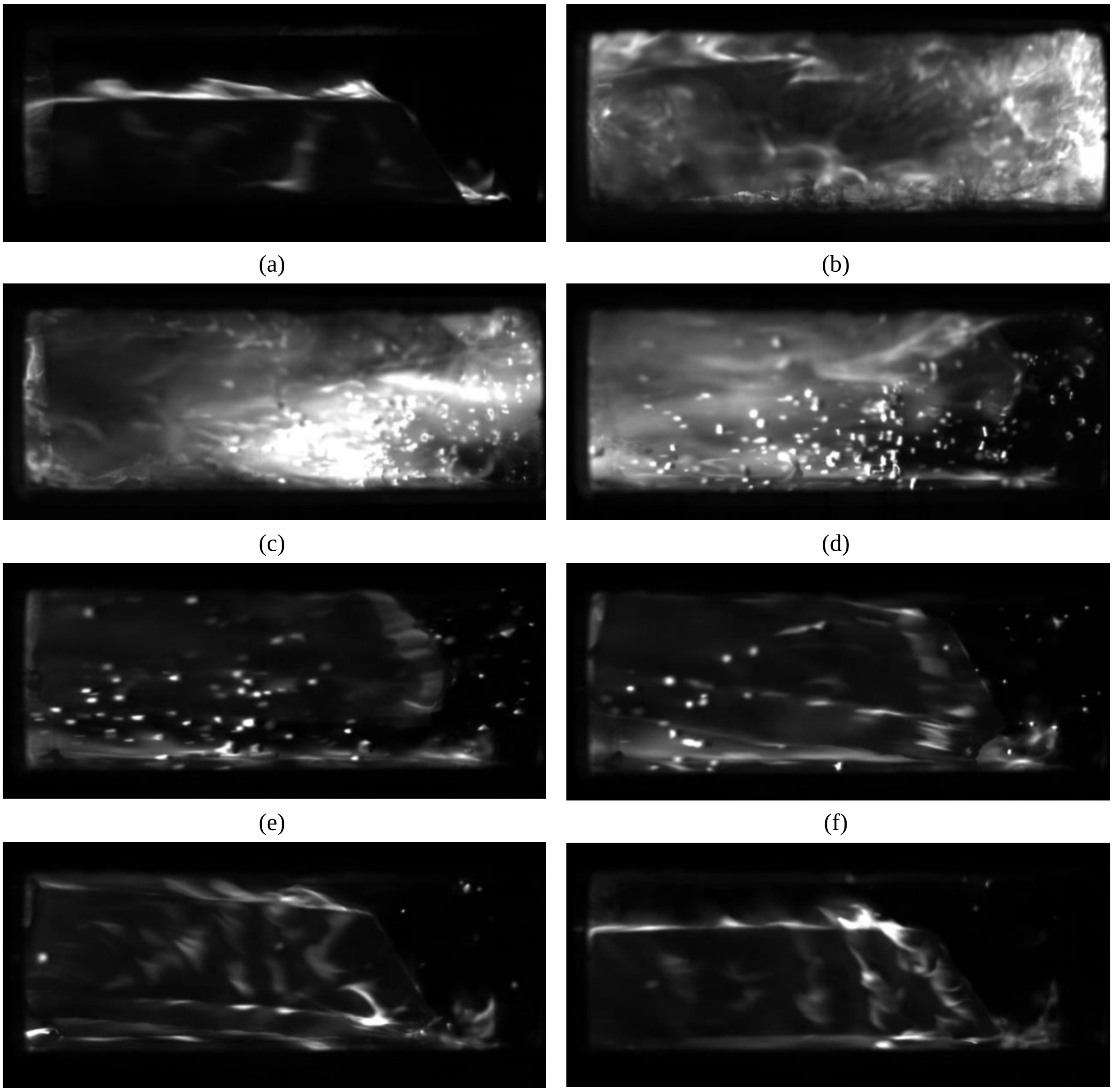

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 15: Visualization of Test 4.

5. Conclusions

This paper describes the efforts carried out by the Aero-Thermo-Mechanics Department of the Université libre de Bruxelles to develop a new slab burner for hybrid rocket solid fuel investigation. The new system, called MOUETTE, has been conceived as an improvement of an already existing slab burner used by the department and developed in cooperation with Royal Military Academy. Once designed and manufactured, the MOUETTE has been used for an initial test campaign of 25 tests, where the burner reliability and adherence to the design requirements have been evaluated.

The campaign assessed the performance of the burner, and pressure data have been recorded, as well as regression rate measurements of the fuel grain, and OH* and CH* chemiluminescence high-speed videos of the combustion process, which will be discussed in further works. The oxygen mass flow rate has been varied from 50 to 100 g/s, and the pressure in the chamber from atmospheric values to more than 7 bar gauge. Tests have been conducted for burning times of 5.5 and 7.5 seconds, to assess the resistance of MOUETTE to higher heat loads for longer periods of time.

The preliminary analysis of the high-speed videos allowed to visualize the different burning regimes at low pressure and high pressure, and the presence of liquid droplets has been confirmed during blowing events of the flame.

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Figure 16: MOUETTE and ASCenSIon logo.

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