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MOUETTE

EXECUTIVE SUMMARY OF THE THESIS

Design and Commissioning of a Hybrid Rocket Engine with Optical Access

TESI MAGISTRALE IN AERONAUTICAL ENGINEERING – INGEGNERIA AERONAUTICA

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ACADEMIC YEAR: **2020-2021**

1. Introduction

A Hybrid Rocket Engine (HRE) is a propulsion system where fuel and oxidizer are stored separately and in different phases. Thanks to the propellant configuration, hybrids have almost no explosion hazard and are therefore safer than solid rocket motors, while featuring controllable thrust as well as shut-off and restart capabilities. Compared to liquid rocket engines, HREs have a simplified feed system resulting in reduced weight, improved reliability and, consequently, reduced costs.

Despite the several advantages and the recent discovery of fast-burning liquefying solid fuels, such as paraffin-based, HREs are still not widespread in today's space industry and the *Technology Readiness Level* associated to hybrid rocket propulsion is low. The main reason lies in the high complexity of the combustion process, as it involves several coupled physical phenomena, whose interdependencies have yet to be completely clarified.

Within this scenario, ***MOUETTE*** (Moteur OptiqUe pour ÉTudier et Tester Ergols hybrides) a lab-scale hybrid rocket engine with optical access was designed, developed and commissioned during the Master of Science thesis work carried out in collaboration with the Aéro-Thermo-Mécanique Department of *Université Libre de Bruxelles*. The burner was conceived to use gaseous oxygen as oxidizer, with a mass flow rate up to 100 g/s, and to operate with combustion chamber pressure ranging from atmospheric level to 15 bar. The test chamber features two quartz glass windows to allow high-speed imaging of the fuel grain combustion and a graphite nozzle to control the operating pressure. The feed system and the test bench have been designed and integrated into the test facility at the Belgian Air Component Air Base of Beauvechain. Leak and proof tests have been performed together with an initial test campaign aimed at assessing the overall system functionality, prior to the initiation of subsequent research steps.

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2. Hybrid Rocket Combustion

The reference model for the combustion of classical fuels in hybrid rocket engines, i.e. polymeric rubbers such as hydroxyl-terminated polybutadiene (HTPB), was developed by Marxman and Gilbert in the 60’s [1]. After the ignition of the grain, combustion occurs in the turbulent reacting boundary layer that develops over the fuel surface, and the flame is located where the oxidizer and the vaporized fuel exist in a combustible mixture. The heat generated by the flame is transferred to the fuel surface by convection and radiation (with convection being dominant), causing the solid fuel to undergo pyrolysis phenomenon. Pyrolyzed fuel vapours diffuse to the flame zone, where they mix with the gaseous oxidizer flow, providing an ignitable mixture to the diffusion flame.

Because of the physics of the diffusive combustion process, conventional hybrid fuels, such as HTPB exhibit low regression rate values [2]. In fact, as shown in Fig. 1, the diffusion of fuel mass from the solid surface to the gaseous stream, caused by fuel pyrolysis and vaporization, blocks some of the convective heat transfer to the grain, which consequently reduces the regression rate. This phenomenon, known as blocking effect, currently represents the physical limitation of conventional hybrid rocket propulsion. Low thrust levels, consequence of low regression rates, have indeed hindered the use of HREs in the past years, favoring the competing liquid and solid rocket propulsion technologies.

Only recently, in the early 2000s, the discovery of new classes of high regression rate hybrid rocket fuels has renewed the interest in hybrid propulsion systems. Following the work of Carrick and Larson, who demonstrated cryogenic solid hydrocarbons, such as solid pentane, to burn up to 10 times faster than HTPB at the same conditions [3], Karabeyoglu et al. proposed a mathematical theory justifying that both cryogenic fuels and non-cryogenic normal-alkane hydrocarbons show considerably higher regression rates than conventional fuels [4]. The reason behind the fast burning of these fuels is a different combustion process, experienced due to their low viscosity and surface tension characteristics. Referring to Fig. 2, a thin liquid layer, composed of melted fuel, is formed on the grain surface during combustion and becomes unstable under the interaction with the incoming oxidizer flow. Fuel droplets are then detached and entrained into the gas stream, originating the entrainment mechanism. As result, the entrainment of fuel droplets acts like a spray injection along the length of the combustion chamber, increasing the effective burning area and reducing the blocking effect. The mass transfer of liquid fuel droplets from the grain surface to the flame region sums to the classical fuel vaporization, resulting in a substantial increase of the regression rate.

Solid alkanes, such as commercial paraffin waxes, are nowadays the most interesting and studied class of fast-burning, non-cryogenic liquefying solid fuels. Thanks to the availability, low-cost, easy manufacturing and contained environmental impact, paraffin-based fuels are the perfect candidates for HREs delivering high-thrust levels with simple grain geometries, thus exploiting the advantages of hybrid rocket propulsion technology.

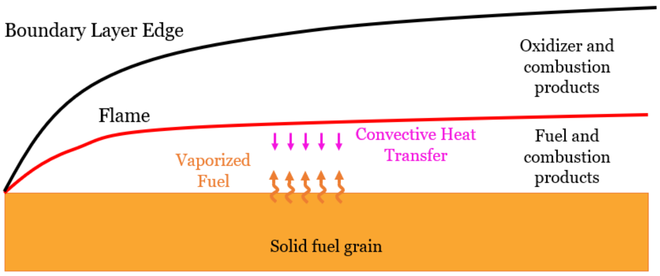

Figure 1: *Schematic of the diffusive combustion process for conventional hybrid fuel.*

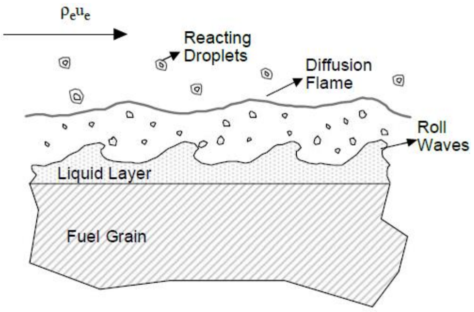

Figure 2: *Schematic of the entrainment phenomenon characterizing liquefying solid fuels [4].*

3. Hybrid Combustion Visualization and Work Motivation

As discussed in Section 2, the internal ballistics of a HRE is extremely complex, especially when liquefying solid fuels are considered. The major motivation is that it involves several deeply coupled phenomena, just to mention the main ones: turbulent reacting boundary layer, diffusive combustion, heat transfer, chemical kinetics, interaction between three phases (solid grain, liquid melt layer, gaseous oxidizer stream) and droplets entrainment. It follows that the theoretical modelling of hybrid combustion is very challenging and, as a matter of fact, current theories are not able to accurately predict the regression rate of a hybrid rocket fuel without the support of a rigorous test campaign for the desired propellant combination. For the same reasons, numerical activities to simulate the combustion of a hybrid rocket engine are quite complicated and, therefore, not very frequent, as a complete description of the transition process from an unstable free surface to dispersed droplets appears to be well beyond actual CFD solver capabilities [5].

Since a much more detailed study of hybrid propellants internal ballistics is mandatory in order to comprehend the complicated physical phenomena involved, visualization experiments provide a non-intrusive solution to investigate the burning process within the turbulent boundary layer of HREs.

Although a few hybrid combustion visualization facilities have been developed in recent years, a systematic and well accepted understanding of the hybrid combustion process, involving the solid fuels liquefaction, is limited to atmospheric pressure conditions only [5], and the technological maturity of HREs is still between a university level of research and development and an industrial business level.

Within this framework, the Master of Science thesis has involved the design, development and commissioning of a lab-scale hybrid rocket engine with optical access, with the objective of providing an experimental setup enabling an exhaustive characterization of the combustion process in hybrid motors, in a broad range of operative conditions. With reference to paraffin-based fuels, the main choice, on which the engine design was developed, was the selection of 15 bar as maximum chamber pressure. In fact, although hybrid engines operate at even higher pressures, beyond the critical pressure of paraffin, which is about 7 bar, the physics of the combustion process is expected to remain unchanged. Therefore, a maximum chamber pressure of 15 bar ensures the capability of studying the combustion process of HREs at realistic operating conditions.

Optical investigations of paraffin-based fuels, especially at super-critical pressure, will empower an extensive comprehension of the internal ballistics, with the ultimate mission of contributing to make hybrid propulsion a competitive candidate for the next generation of launch systems and in-space missions, taking full advantage of its enhanced safety and low-cost benefits.

4. Design of a Hybrid Rocket Engine with Optical Access

The purpose of this Section is to provide a brief overview of the design process that led to the completion of *MOUETTE* project. A more detailed explaination and motivation of each design choice is contained in the complete thesis report.

4.1 Requirements and Oxidizer Selection

The first step of the design involved the identification of the engine's requirements, that were defined as: a) optical accessibility, i.e. the capability of visualizing the combustion process from the exterior; b) combustion chamber pressure ranging from atmospheric levels up to 15 bar; and c) compatible dimensions with an old *Université Libre de Bruxelles* (ULB) – *Royal Military Academy* (RMA) slab burner.

Gaseous oxygen was selected as the oxidizer agent, so that a much clearer and "cleaner" visualization of the combustion process could be obtained compared to the use of liquid oxidizers. As consequence, the materials used for the construction of the engine components were chosen taking into account the essential requirement of oxygen compatibility.

4.2 Engine Structure

A modular structure was adopted for the engine's design: *MOUETTE* is composed by multiple parts (modules) that can be assembled, disassembled and replaced to grant an easy and fast manual access to the engine interior. In the following, each component is associated with a number referring to Fig. 3.

The Main-Chamber (**3**), the Pre-Chamber (**2**) and the Post-Chamber (**6**) constitute the fundamental modules of *MOUETTE* structure of and are built in AISI 304L stainless steel. They feature a circular cross section, in order to withstand the stresses generated by elevated chamber pressures, and have been manufactured starting from commercial stainless steel hollow bars. The connection at the extremities between the chambers and the other components is made by means of Flanges, machined from AISI 304L stainless steel plates and then welded to the chambers ends. The welding of Flanges was treated and designed with special care to ensure structural resistance and tightness even at high pressures. This led for welding connections to adopt the so-called *Socket Flange Welding*, a peculiar welding procedure for high-pressure piping in accordance with ASME B31.1 1998 127.3 standard.

The Main-Chamber is *MOUETTE*'s most peculiar component as well as the engine's core, i.e. where combustion takes place. It features two side windows so that the combustion process of the hybrid fuel sample can be visualized from the outside. The Main-Chamber has a 280 mm length, 74 mm inner diameter and a 120 mm outer diameter; a high thickness has been adopted to directly machine the window slots inside it.

The Pre-Chamber is the component located between the Injector Head (**1**) and the Main-Chamber and its function is to provide the Main-Chamber with the most uniform and laminar oxidizer flow possible. A CFD simulation of gaseous oxygen injection at the worst conditions for flow separation was performed using *Ansys Fluent*, in order to estimate the required length to ensure a full oxidizer flow reattachment. Based on the numerical simulation result, it was chosen to have a 300 mm long Pre-Chamber.

The Post-Chamber was designed with the main function of separating the Main-chamber and the Nozzle (**13**), so that the internal ballistics is not affected by nozzle fluid dynamics. In addition, it accommodates a graphite insert, namely the Convergent Insert (**12**).

The Injector Head and the Injector Plate (**8**) are the two parts that compose *MOUETTE*'s injection system. Oxygen enters the Injector Head and it is then injected into the Pre-chamber through the Injector Plate. The Injector Head was built in AISI 304L stainless steel and was designed to be connected to the Pre-chamber. On one side it has a truncated cone geometry with a 1/2" NPT female threaded hole for the connection of the feed line. On the face in contact with the Pre-chamber, the Injector Head features instead a slot to accommodate the Injection Plate. The Injector Plate, built in brass, has the function to uniform, distribute and inject into the Pre-chamber the oxygen flow delivered by the feedline, playing the role of a distribution grid. The flow is injected through 5 mm diameter holes, whose number, and the related flow passage area, was chosen in order to obtain the desired pressure jump across the plate. Two Injector Plates were designed with *7* and *19* holes, respectively.

The Nozzle Plate (**7**), manufactured in AISI 304L, represents the engine's closure and it is located downstream of the Post-Chamber. Its peculiarity is to present an internal housing to accommodate the Nozzle.

The Grain Holder (**10**) and the Pre-Chamber Insert (**9**) are the two components located at the bottom of the Main-Chamber and Pre-Chamber, respectively, and are both made of brass. The Grain Holder has the function of holding in place the solid Fuel Grain (**11**) and, since its sole presence would imply the existence of a step in its fore end, a Pre-Chamber Insert was added to preserve a uniform internal section and avoid the formation of turbulent structures in the flow field.

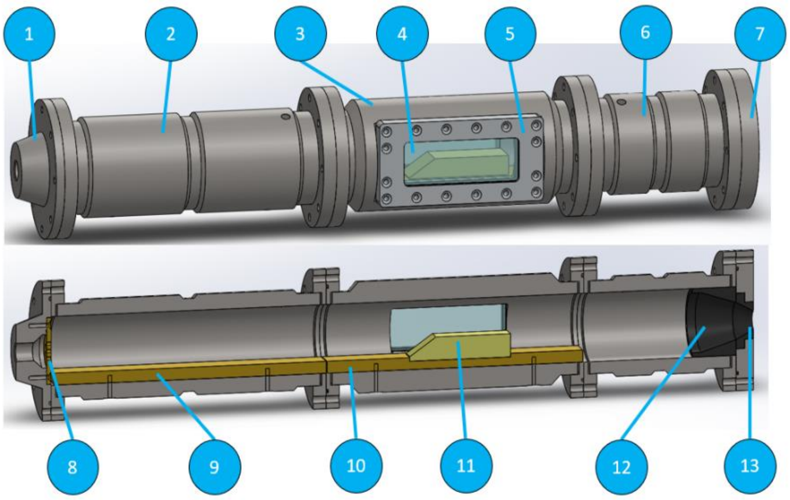

Figure 3: *Overview of MOUETTE's components.*

The fundamental optical accessibility requirement is satisfied thanks to two side windows in correspondence of the Main-Chamber, each one featuring a quartz Glass (**4**), held in place by a Window Frame (**5**) built in aluminum. Due to Glass brittleness, it was necessary to select the material and design the component, as well as its coupling to the Main-Chamber and the Window Frame, with particular care. Since the Glass operates under high temperature conditions, quartz was chosen due to its high maximum continuous operating temperature and low coefficient of thermal expansion. The quartz Glasses have a 16 mm thickness, sized to withstand the maximum chamber pressure of 15 bar and considering a safety factor of 2.5.

The exhaust system of *MOUETTE* consists of a Convergent Insert and a Nozzle, both manufactured in graphite. The Convergent Insert is designed to be inserted inside the Post-Chamber and has the function of directing combustion products to the Nozzle. The latter resides in the housing inside the Nozzle Plate and has the crucial function of adjusting the combustion chamber pressure. Since, in *MOUETTE* applications, the specific impulse is not a parameter of interest, it was chosen to have just a convergent Nozzle with the function of accelerating the flow of combustion products up to *Mach* 1 at its efflux section. To meet the requirement of operating at different values of chamber pressure, different Nozzles with different throat areas were designed. The calculation of the required Nozzle throat area to have a certain desired chamber pressure was performed exploiting the well-known characteristic velocity definition: $c^* = p_c\ A_t /\ \dot{m}$, where p_c is the chamber pressure, A_t the throat area and $\dot{m}$ the sum of the oxidizer and fuel mass flow rates. Since, during the design phase, the paraffin burning rate specific for *MOUETTE* was not known, the fuel mass flow rate was estimated on the basis of a regression rate correlation selected from literature, in particular from Reference [6].

4.3 Feed System

MOUETTE's feed system (Fig 4) consists of a gaseous oxygen line to supply the oxidizer to the engine and a gaseous nitrogen line for extinguishing the combustion process. Each line features a pressure regulator located on the tank and a series of valves, pressure sensors and thermocouples to control the flow and measure its thermophysical properties. The main engine run valve is the electro-pneumatic valve installed on the oxygen line, equipped with a pneumatic actuator operated by nitrogen. The oxygen line features an adjustable choked orifice to set the desired oxidizer mass flow rate.

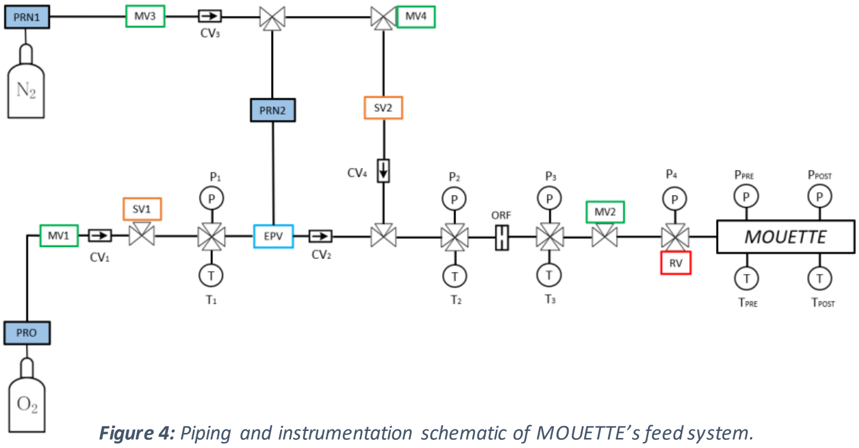

Figure 4: Piping and instrumentation schematic of MOUETTE's feed system.

4.4 Test Bench

The *MOUETTE* test bench has been designed with the purpose of securing the engine and facilitating the assembly and disassembly procedures. To properly fasten the engine, the generated thrust was estimated with a maximum value of around 100 N. The test bench consists of a frame Table on which a steel component with rails is fixed. On the latter, two double-t elements are placed in the desired position. The engine then lays on two Supports, each one welded to the respective double-t component, and is secured with two Clamps.

The feed line was installed on a grid panel, which was then fixed on a lateral side of the Table. A picture of the test bench is reported in Fig. 5.

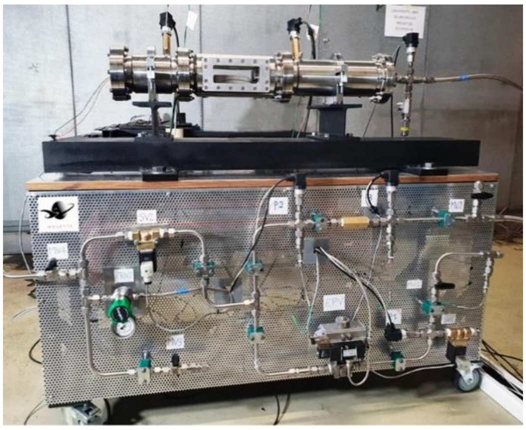

Figure 5: *MOUETTE test bench.*

5. Engine Commissioning and Experimental Activity

Engine pressurization tests and a preliminary test campaign to verify system functionality have been conducted at the Belgian Air Component Air Base of Beauvechain. The test facility consists of a safe room with an exhaust gas duct enabling to perform firing tests, and an adjacent control room featuring a bulletproof glass to allow a view of the test room interior.

A LabVIEW program was developed to manage a National Instruments (NI) DAQmx USB 6218 data acquisition, processing and distribution system, which function is to acquire sensor data and control solenoid valves and ignition to perform tests. To control each test, the NI module commands the opening/closing of solenoid valves and the ignition by operating relays located in a control box, along with a power supply.

The solid fuel grain ignition is performed through a so-called *rocket candy*, used as a pyrotechnic igniter. *Rocket candy* is basically a type of rocket propellant featuring sugar as fuel, and containing an oxidizer, such as potassium nitrate (KNO_3). Before each test, a *rocket candy* is placed next to the fore end of the paraffin grain, and it is wrapped by a nichrome wire. When a voltage is applied across the wire, the latter heats up due to Joule effect and causes the rocket candy to burn. The hot gases generated by the ignitor raise the temperature inside the chamber and gasify a small portion of the fuel grain, leading, once the oxygen flow is initiated, to ignition.

The hybrid combustion in the engine is visualized via high-speed imaging together with OH* and CH* chemiluminescence filters. High-speed videos are recorded using a Photron FASTCAM SA4, courtesy of the Royal Military Academy of Belgium.

After successful cold flow pressure tests, a preliminary test campaign was carried out in early April 2022. Ignition tests were performed to verify the operation of the igniter over the desired range of oxidizer mass flow rates and combustion chamber pressures. Combustion tests (Fig. 6) confirmed all the mechanical equipment, feed system, test bench, data acquisition and control system, and the engine itself to perform as expected. The high-speed camera apparatus was installed in the test facility, and the initially collected high-speed OH* (Fig. 7) and CH* chemiluminescence have confirmed the effective possibility to study the internal ballistics of hybrid rocket combustion with *MOUETTE* engine.

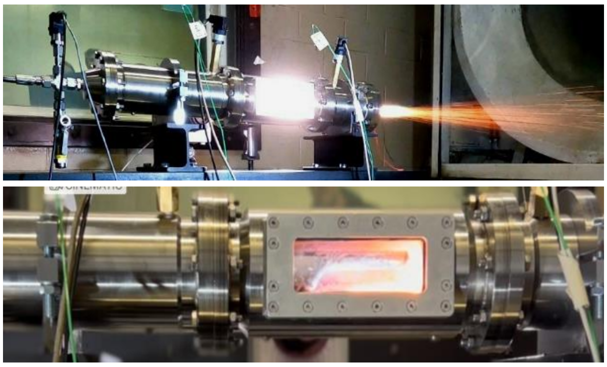

Figure 6: *MOUETTE firing tests.*

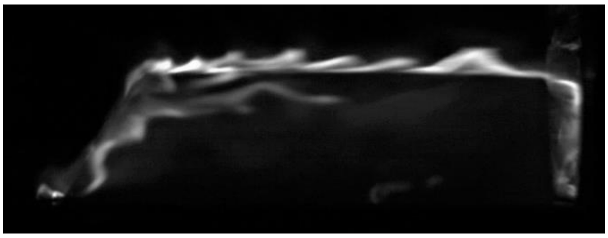

Figure 7: *High-speed OH* chemiluminescence image of paraffin combustion at 2.5 bar. The development of roll waves on the grain surface is detected and is in accordance to the typical combustion process of liquefying solid fuels leading to droplet entrainment, as predicted by state-of-the-art theory and experimental results. (Oxygen flows from left to right)*

6. Conclusions

MOUETTE, a hybrid rocket engine with optical access, was developed during this thesis work. To have designed a rocket engine from scratch, commissioned it, and had it operational in just 6 months was a quite significant accomplishment.

The combustion visualization facility was conceived to enable a deep comprehension of the challenging internal ballistics of hybrid rocket engines via visual analysis, even at paraffin-based fuels supercritical pressure conditions. Real-time data of the combustion process will not only allow an extensive characterization of the phenomenon, but also support an improvement of numerical models for CFD simulations, which are currently not accurate enough, especially for liquefying solid fuels. The project was developed with the mission of increasing the *Technology Readiness Level* of hybrid propulsion, in order to make it a competitive candidate for the next generation of launch systems and in-space missions.

7. Acknowledgements

This thesis work for the Master of Science in Aeronautical Engineering lay within the framework of the ASCenSIon program. The project received funding from the European Union's Horizon 2020 research and innovation program, under Marie Skłodowska-Curie grant agreement no. 860956.

I would like to thank my supervisor, prof. Roberto Andriani of Politecnico di Milano, and prof. Antonella Ingenito, of the University La Sapienza of Rome, for the support and advice received during the whole thesis work, and also for enabling the collaboration with the Université Libre de Bruxelles.

To the whole Aéro-Thermo-Mécanique Department of Université Libre de Bruxelles, and especially to the Head of the Department Prof. Patrick Hendrick, go my sincere thanks for having warmly welcomed and hosted me throughout the period of my stay in Brussels, continuously helped me in the performance of my work, and made me feel at all times as part of the Department itself.

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