CHARACTERIZATION OF A "GREEN" PROPELLANT FOR A 12 N THRUSTER

SPACE PROPULSION 2022

ESTORIL, PORTUGAL | 09 – 13 MAY 2022

Kalvin Brandão (1), Bruno Porto (2), Luís Natário (3), Renato Salles (4), Horácio Moreira (5), Tiago Moreira (6), Filipa Lourenço (7), Tiago Pardal (8), Pedro Lima (9), Xavier Geneste (10)

(1) Omnidea Lda, Lisbon, Portugal, Email: kalvin.brandao@omnidea.net
(2)...(9) Omnidea Lda, Lisbon, Portugal
(10) ESA-ESTEC, Noordwijk, Pays-Bas

KEYWORDS: additive manufacturing, thruster, chemical propulsion, green propellant

ABSTRACT:

A breadboard thruster was developed to start the characterization of an innovative "green" propellant (GP). Firing tests were performed at different chamber pressures and mixture ratios to assess the propellant decomposition at different operating conditions. The present objective is the development of a 12 N thruster for a small propulsion system fitting the standard size of an 8U CubeSat-frame.

1. INTRODUCTION

The development of a propulsion system to fill in the gap within the small satellites (SmallSats) market for high thrust values and for rapid manoeuvres is underway. For this purpose, Omnidea is developing a less toxic "green" bipropellant propulsion system with high thrust-to-power ratio to comply with SmallSats volume, power, and mass constraints.

To fit in standard CubeSat frames, the proposed system requires miniaturized components, which increases the challenge for COTS procurement and its integration. However, the main driver of this propulsion system is the thruster development with the selected GP.

In this context, a test bench was developed to support and manage thruster breadboard hot fire tests and ignitions of the GP with gaseous O_2 and H_2 torches. The obtained data such as pressures, temperatures, mass flow rates, plume characteristics, and specific impulse (calculated) were satisfactory evidence that supports GP selection.

Breadboard test results showed that the thruster design with the selected GP is feasible for propulsion system application. The main problem identified during the tests was the ignition reliability, but it can be solved with improvements in the ignition method.

2. FEATURES OF "GREEN" PROPELLANT

The GP is an ammonia-based solution, where constituent atoms are the same of current state-of-the-art "green" monopropellants, such as hydroxylammonium nitrate (HAN) and ammonium dinitramide (ADN). This energetic ionic liquid is produced in-house, considering the capability of the company's facilities and procurement. The solution concentration is tuned to achieve a low combustion temperature, an advantage for low-cost thrusters since it is not required complex cooling methods and high-temperature resistant materials. The solution assumes a similar theoretical performance and physical parameters of HNP225 [1], a demonstrated HAN-based propellant with low temperature combustion. This supports the R&D of this innovative propellant for space propulsion applications. Nevertheless, the use of the proposed solution as a propellant is unknown in the literature, and there is a lack of sources regarding its characterization and application.

The solution properties obtained from literature were extrapolated in function of temperature (as shown in *Figure 1*) for propulsion system design purposes. This data allowed the determination of saturated solution, the solution mass (by its density and tank volume), and vapour pressure for a specific operating temperature range and solution concentration.

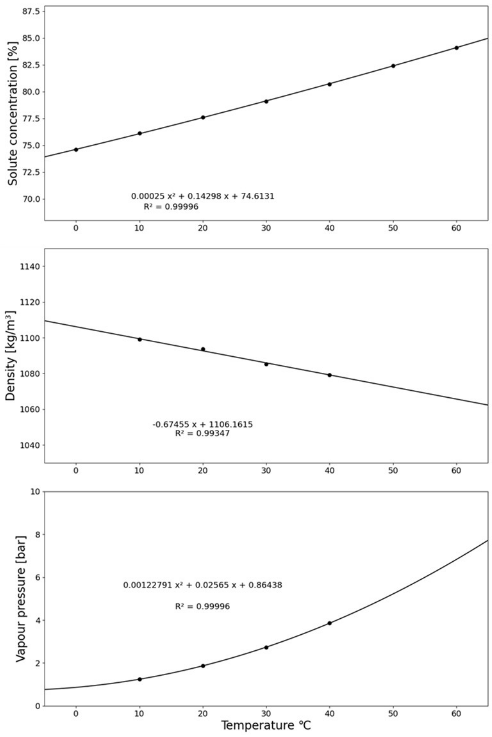

Figure 1: Solution properties vs temperature

3. PROPULSION SYSTEM CONCEPT

The project in progress aims to develop a bipropellant propulsion system that provides a thrust of 12 N. The propulsion system consists of an 8U CubeSat-frame containing all the tanks and components required to manage the propellants. The thruster is placed outside of the 8U envelope to protect the spacecraft's components from high thermal radiation during thruster operation. The goal is to optimize the design with the available volume and provide a high delta-V performance for small satellite application in LEO.

The system was decomposed into products according to Figure 2, and its functions are as follows:

- P-1.1 Thruster: produce thrust for the propulsion system and withstand a high-temperature and pressurized combustion processes.
- P-1.2 Propellant feed system: deliver propellants from the storage to the thruster in a controlled way:
- P-1.2.1 Liquid fuel feed system: deliver liquid fuel (ammonia-based solution) from the liquid fuel storage to the thruster in a controlled way.
- P-1.2.2 Oxidizer gas feed system: deliver oxidizer gas (O_2) from the oxidizer gas storage to the thruster in a controlled way.
- P-1.2.3 Pressurant gas feed system: deliver pressurant gas (He) from the pressurant gas storage to the liquid fuel storage in a controlled way.
- P-1.3 Propellant storage: carry and store pressurized propellants:
- P-1.3.1 Liquid fuel storage: carry the liquid fuel (ammonia-based solution) and withstand its internal pressure storage of 20 bar (pressurized by He as pressurant gas).
- P-1.3.2 Oxidizer gas storage: carry the oxidizer gas (O_2) and withstand its internal pressure storage of 200 bar.
- P-1.3.3 Pressurant gas storage: carry the pressurant gas (He) and withstand its internal pressure storage of 200 bar.
- P-1.4 Power supply unit: provide electric power to the control unit for further issuing to the propulsion system electronic components.
- P-1.5 Control unit: manage electric power distribution (provided by the power supply unit), commands, and propulsion system data handling.
- P-1.6 System structure: house all propulsion system components, withstand external mechanical loads, and provide interfaces to ground support equipment and spacecraft mounting.

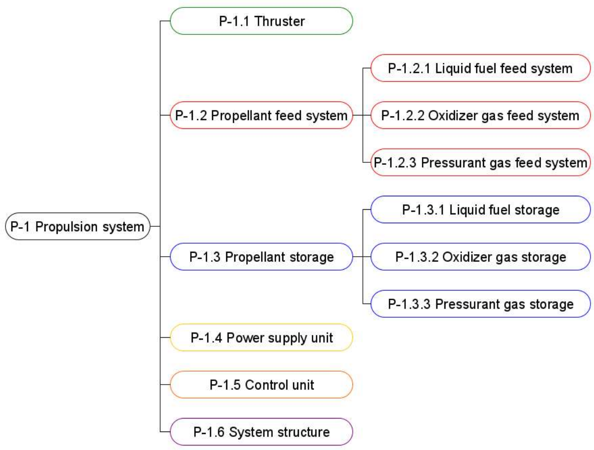

Figure 2: Propulsion system product breakdown

Thrust is produced by chemical reaction between the GP and gaseous O_2. The oxygen improves the delivered propulsion performance. Helium is used as pressurant gas to pressurize the GP and drive it through its fluid feed system. Propellant tanks and thruster are in-house developments, whereas the other components are COTS products, such as the fill/vent valves, pressure transducers, isolation valves, throttleable valves, filters, pressure regulators, power supply unit, and control unit. Figure 3 illustrates the propulsion system schematic diagram.

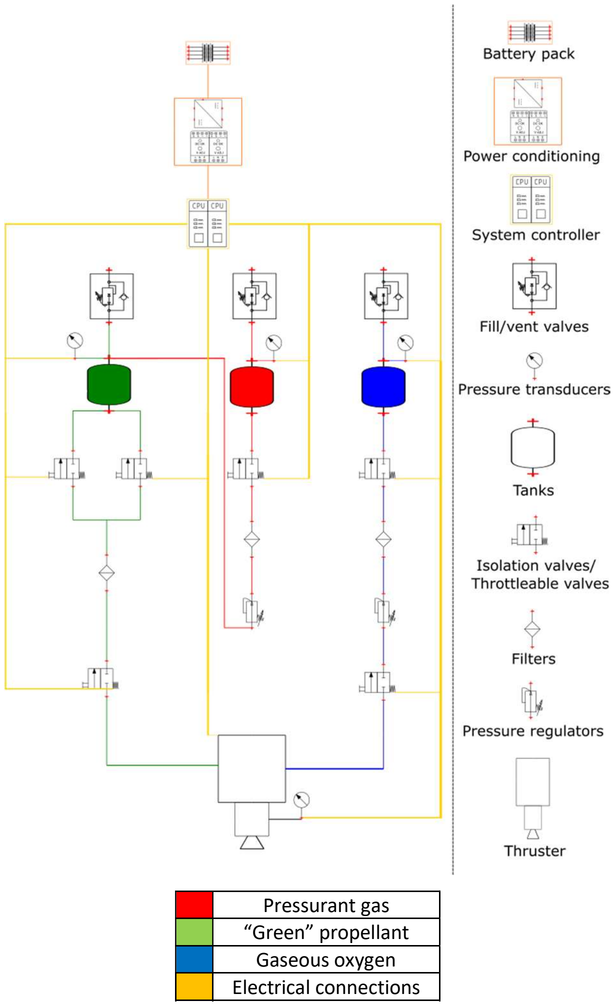

Figure 3: Propulsion system schematic diagram

Propulsion system characteristics are presented in *Table 1*. The specific impulse (I_{sp}) of 276.8 s was obtained by CEA [2] program (Chemical Equilibrium with Applications) considering an OF = 2.56. The total impulse (I_t) of 4813 was calculated multiplying the specific impulse by the gravity acceleration (g) and by the total propellant mass (wet mass minus dry mass).

Table 1: Propulsion system characteristics

Thrust [N]	12
Specific impulse in vacuum [s]	276.8
Total impulse in vacuum [N-s]	4813
Wet mass (m_{wet}) [kg]	13.83
Dry mass (m_{dry}) [kg]	12.06
Liquid fuel	“green” propellant
Oxidizer gas	Gaseous O_2
Pressurant gas	Helium (He)

This propulsion system is expected to fit a spacecraft with at least a 12U envelope (i.e., 226.3 mm x 226.3 mm x 340.5 mm). Figure 4 illustrates the expected ΔV delivered, $\Delta V = I_{SP} \cdot g \cdot \ln(m_{wet}/m_{dry})$, for different spacecraft masses (up to 180 kg).

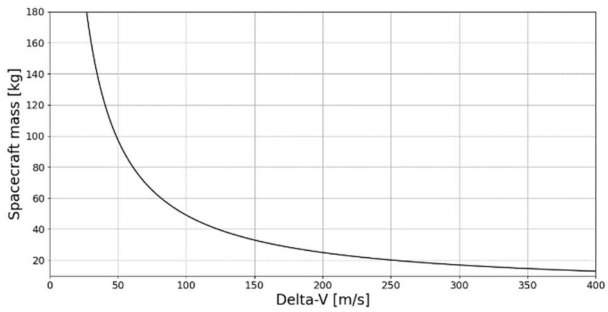

Figure 4: Delta-V for different spacecraft masses

4. BREADBOARD THRUSTER DESIGN

The breadboard thruster design assumed the nominal operating conditions of propulsion system’s thruster, such as chamber pressure of 5 bar and OF = 2.6. However, the main goal was to characterize the GP at different chamber pressures and mixture ratios to find out the minimum conditions required to decompose the GP and achieve a steady-state reaction. Considering that, the low mass flow rate of the baseline thruster would restrict these tests if using standard valves.

For this purpose, the breadboard nozzle throat has a higher diameter to operate with higher mass flow rates and a gas generator (working as an igniter extension) using H_2 as a third propellant to deliver enough energy to decompose the higher GP flow. Moreover, the breadboard nozzle expansion ratio is practically 2:1 so that outlet pressure meets the atmospheric (1 bar), yielding an expected specific impulse of 188 s. This value is lower than that of the baseline thruster of 276.8 s because the hot gas is being expanded to the atmospheric pressure instead of vacuum.

The breadboard is basically composed by an injection head, a thrust chamber, and fittings/fasteners. Figure 5 presents the breadboard product tree.

The injection body houses all injection head components and it is attached to thrust chamber and test stand by fasteners; stainless steel tubes are brazed at the injection head ports to provide the fluid interfaces for the propellants and pressure transducer lines.

The breadboard seal between the injection body and thrust chamber is achieved by a rigorous surface quality with a tight fit tolerance. The glow plug igniter seal is made with a copper ring and the fluidic tubes connection are made using compression fittings.

The glow plug provides the required heat to ignite the O_2 and H_2 mixture inside the igniter chamber, to generate the hot gas to ignite the main reaction. The main reaction gases are fed by the injectors located at the injection head facing the combustion chamber inlet and the igniter injector (hot gases from igniter). The gas generator is composed by the igniter injector, O_2 and H_2 core injectors, and perimeter injectors. The hot gases from the igniter injector are responsible for igniting the gas generator mixture.

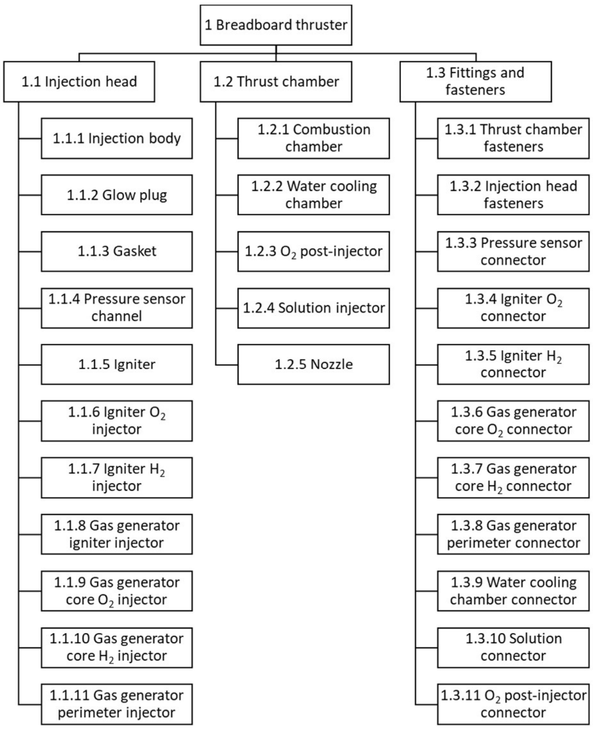

Figure 5: Breadboard thruster product tree

The solution injectors and the O_2 post-injectors are placed in the thrust chamber inner wall, downstream of the injection head face. The hot gases from the gas generator mixture are responsible to ignite the solution and the post-injected oxygen. The combustion chamber withstands the pressurized global reaction at high temperature with assistance of a water-cooled chamber. The nozzle expands the hot gases from the combustion chamber to generate thrust and the pressure sensor channel conducts the chamber pressure to the transducer. Figure 6 illustrates the external and internal design of the breadboard.

Considering the complex internal geometries, the breadboard thruster was produced by additive manufacturing process with a cobalt-chrome alloy.

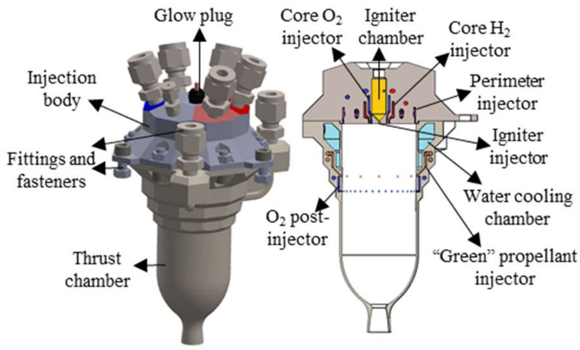

Figure 6: Breadboard thruster design

5. TEST STAND

The test stand was designed to fulfil the requirements of the breadboard tests. The main functions of the test stand are:

- feed pressurized propellants to the breadboard,
- adjust the mass flow rate for each breadboard injector,
- purge the system with nitrogen and water,
- data acquisition of total mass flow rates of each propellant, solution temperature, tank pressures, and chamber pressure as a function of time.

Figure 7 illustrates the test stand design with all components assembled, which is basically divided in nine sections with specific functions:

- Structure: houses all components of the test stand and withstands static and dynamic loads,
- Electronic devices: provides electric power supply, controlling, and data acquisition,
- Nitrogen line: connects to nitrogen cylinder to pressurize or purge the solution and water tanks,
- Oxygen feed system: feeds O_2 with adjusted mass flow rates for each breadboard O_2 injector,
- Hydrogen feed system: feeds H_2 with adjusted mass flow rates for each breadboard H_2 injector,
- Perimeter feed lines: allows the feeding exchange into perimeter injector between O_2 or H_2,
- Solution feed system: feeds GP with adjusted mass flow rates for the breadboard solution injector,

- Water purge system: purges the breadboard and solution line with water and nitrogen gas,
- Breadboard propellant feed lines: provides interfaces for feeding propellants to the breadboard.

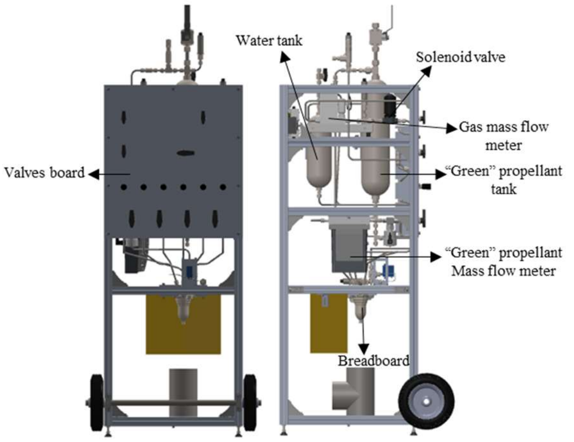

Figure 7: Test stand design

There are established procedures to operate the test stand considering the required breadboard tests and test stand installation. Test stand operation is basically performed by a Human-Machine Interface (HMI) to control the mass flow meters, solenoids and programmed routines, as well as by handling the selector valves, cut-off valves, and metering valves of the board to establish the test setup. Figure 8 presents the complete test stand flow path diagram.

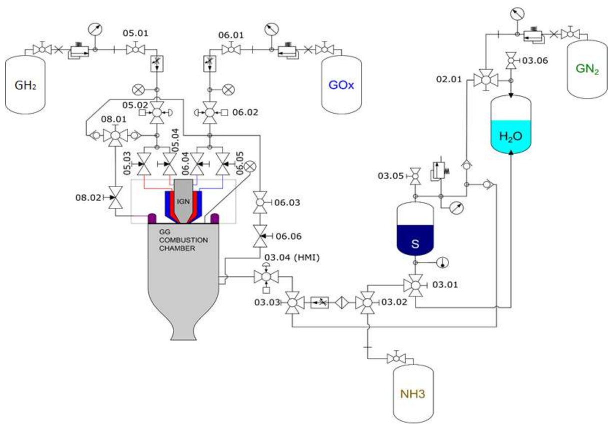

Figure 8: Test stand schematic diagram

6. BREADBOARD FIRING TEST RESULTS

Breadboard tests were performed for specific OF conditions at different pressures. The goal was to find out the necessary conditions to decompose the GP, obtain the firing tests performance, and carry out breadboard operations monitoring. For all tests, the gases (O_2 and H_2) burned for 5 seconds and the GP for 4 seconds, injected 0.5 seconds after torch gas injection started. The acceptance criteria established in breadboard test plan was at least 2 seconds of steady-state combustion for each value of OF and mass flow rate condition. Tests were validated by plume visualization and by chamber pressure measurement.

6.1. "Green" propellant decomposition

The GP decomposition results are presented in Figure 9. When the plume oscillated, ejecting non-reacted GP, it was considered as uncompleted decomposition, represented by the label "Unstable/Incomplete decomposition".

The results show that GP decomposition effectiveness is proportional to the chamber pressure increase for OF ≤ 3 or GP percentage ≥ 65%. For chamber pressure higher than 3 bar the decomposition occurs for all proposed OF values and up to 90% of GP fraction (10% of gases). This is an important result to demonstrate the feasibility of the envisioned propulsion system, that is being designed with an OF < 3 and operating chamber pressures of up to 5 bar.

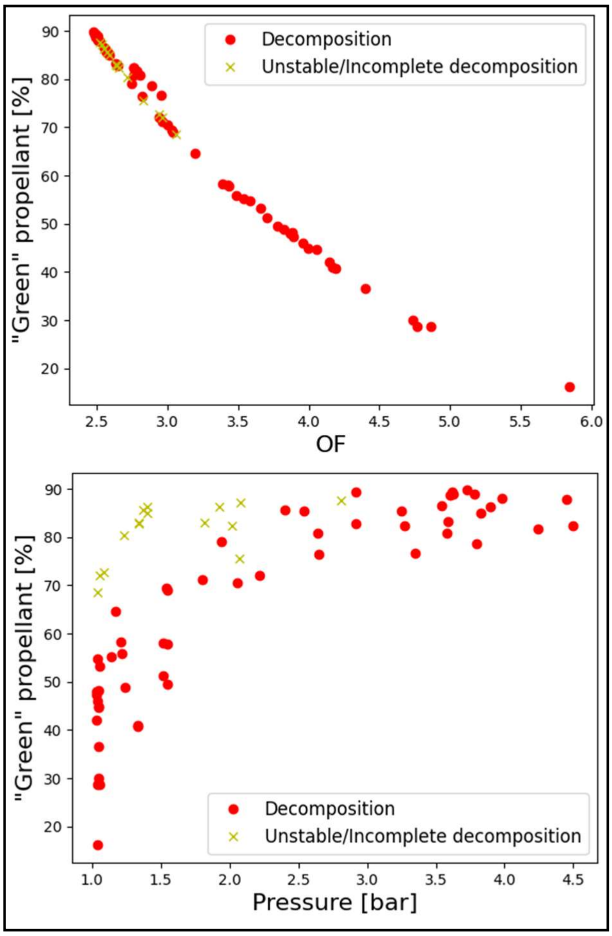

Figure 9: "Green" propellant decomposition

6.2. Firing test performance

Breadboard tests provided choked flow conditions. For tests with chamber pressures higher than 2 bar it was observed that the sonic condition at the throat is verified, producing a characteristic plume with shock diamonds typical of supersonic flow. Figure *10* shows a breadboard test at subsonic (< 2 bar) condition on the left and supersonic (> 2 bar) condition on the right.

Figure 10: Firing tests' exhaust plume

The chamber pressure data obtained from each breadboard test was plotted in function of time to obtain the pressure profile, as shown in Figure 11. The thrust profile was calculated by multiplying the filtered pressure data, the theoretical thrust coefficient, and the breadboard nozzle throat area. The highest chamber pressure and thrust obtained were 4.5 bar and 19.7 N, respectively.

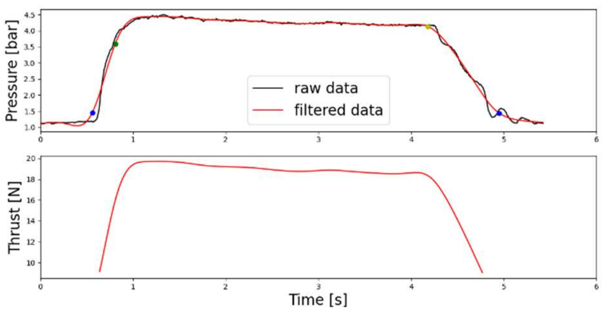

Figure 11: Chamber pressure profile

The other propulsion parameters such as total impulse, average thrust, and burning time were also calculated [3] from the filtered pressure data. The curve profile from Figure 11 resulted in a total impulse of 69.5 N-s and average thrust of 19.2 N for a steady state burning time of 3.6 s, confirming the GP decomposition for more than 2 s. Considering these results and despite the nozzle geometry differences, it is expected to reach a 12 N thrust with the proposed GP for the envisioned propulsion system.

The specific impulses were obtained dividing the average thrust by the total "weight" flow rate of each test. For tests where the total O_2 mass flow rate was injected by the core injectors the specific impulse average was 172 s, whereas distributing the O_2 injection by both core and perimeter injectors it was 145 s. These values correspond to 92% and 77% of theoretical (188 s). The lower performance for perimeter injection case is likely because of low mixture of O_2 near the chamber inner wall with the GP, not contributing for the global reaction. Nevertheless, for a characterization phase, the actual specific impulse of 92% reveals a satisfactory efficiency of the GP for propulsion application.

6.3. Breadboard operations monitoring

The thrust chamber's temperature was monitored during all firing tests by an infrared camera to prevent it from exceeding the cobalt-chrome alloy temperature limit of 1150 ºC [4]. The maximum measured thrust chamber's temperature was 850 ºC, as shown in Figure 12.

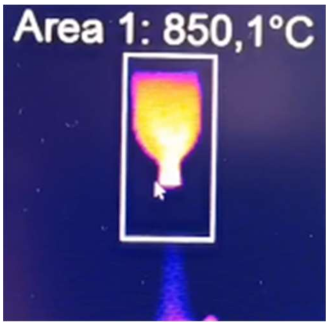

Figure 12: Temperature by infrared camera

The problems observed during breadboard tests were the deposition of GP on the injection head, frequently clogging the igniter injector and the pressure sensor channel, as shown in Figure 13. The phenomenon caused some ignition failures and high-pressure measurement delays, not registering the steady state chamber pressure in some tests. The heating coil of the glow plug igniter oxidized after every few tests with the GP, requiring frequent replacement.

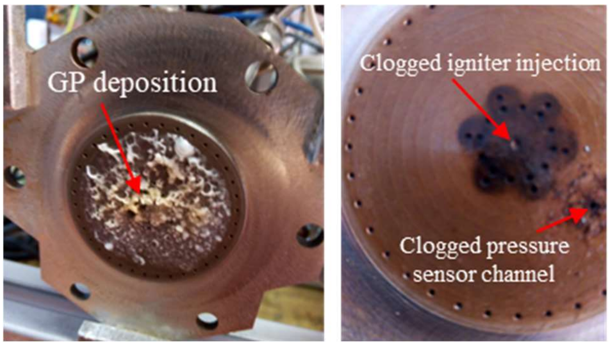

Figure 13: GP deposition

7. CURRENT DESIGN STATUS

Breadboard tests showed the need to improve the ignition process, which presented unreliable ignitions with the glow plug because of its filament oxidation. Acknowledging the observed issues, a heater resistor method with a ceramic glow plug protected by a sheath was chosen as an alternative to the glow plug igniter with the thin filament exposed.

This heater resistor consists of a heated element that provides higher energy and temperature to directly decompose a small quantity of GP. Then, O_2 is injected to react and increase the energy in the gas, which is transmitted to the additional GP and oxygen injection. This power augmentation can decompose a higher amount of GP and with the injection of additional O_2 it boosts even more the power delivery.

This method requires a longer and heavier thruster but eliminates the need for H_2 as gaseous fuel for ignition, simplifying the propulsion system design and reducing the system risk. The thruster development with a heater resistor assumes the propulsion system constraints as well as evaluate its feasibility and impacts on the system. The thruster subsystem product tree with this ignition method is shown in Figure 14, which presents the main components in red boxes. The general functions of each component are:

- P-1.1.1 Propellant inlet control: admit propellant from the propellant feed system and deliver to the injection head in a controlled way:
- P-1.1.1.1 Liquid fuel throttleable valve: admit liquid fuel (ammonia-based solution) from the liquid fuel feed system and deliver to the injection head in a controlled way.
- P-1.1.1.2 Oxidizer gas throttleable valve: admit oxidizer gas (O_2) from the oxidizer gas feed system and deliver to the injection head in a controlled way.
- P-1.1.2 Injection head: receive propellants from the propellant inlet control and manage them by flow paths for injecting them into the combustion chamber, as well as provide flow path from combustion chamber to the pressure transducer.
- P-1.1.3 Heater resistor igniter: provide heat energy to the liquid fuel for its decomposition.
- P-1.1.4 Pressure transducer: measure the combustion chamber pressure during combustion process.
- P-1.1.5 Combustion chamber: contain and withstand the high-temperature and pressurized global reaction (O_2 and ammonia-based solution).
- P-1.1.6 Nozzle: expand the hot gases from combustion chamber to produce thrust.
- P-1.1.7 Thruster mount: mount the thruster components to the propulsion system and withstand mechanical loads produced during thruster operation and by other external sources

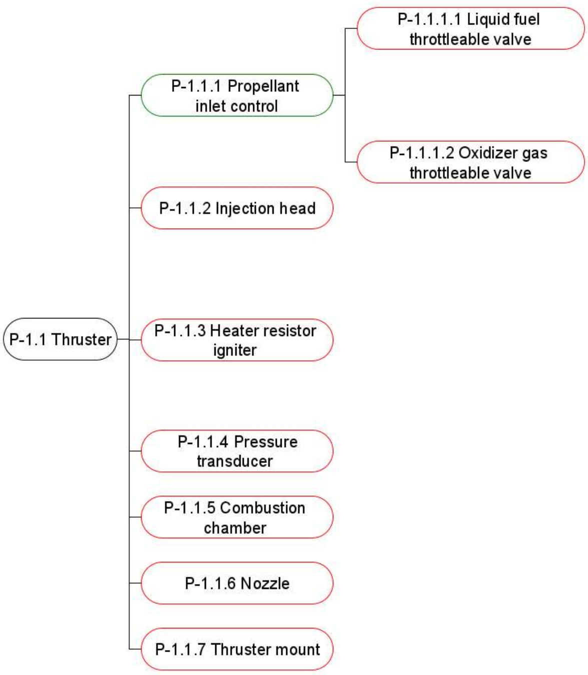

Figure 14: Thruster product tree

The O_2 tank is a Composite Overwrapped Pressure Vessel (COPV) developed in previous projects by Omnidea [5], whereas the tanks for the GP and He were designed as “integrated” tanks, as shown in Figure 15.

The current tank configuration adopting the integrated GP and He tanks around the COPV tank aimed to optimize the volume available around the COPV tank. There is a He path through the rear side wall of GP tank connecting the He tanks. The integrated tanks will be produced by additive manufacturing process.

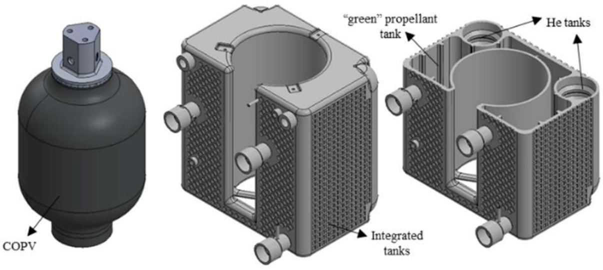

Figure 15: Propellant tanks configuration

The current propulsion system configuration for future assembly, integration, and test for ambient condition tests (left) and for vacuum application (right) are presented in Figure 16. The difference is the thruster nozzle size, where for vacuum application it has an expansion area ratio of 200:1, and for ambient condition tests it is approximately 2:1.

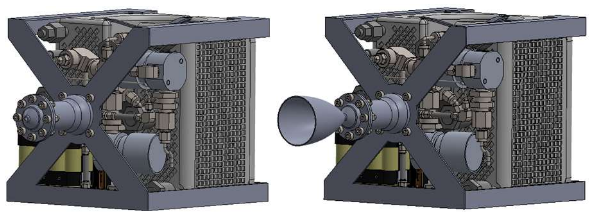

Figure 16: Propulsion system configuration

8. CONCLUSIONS AND FUTURE WORK

8.1. Conclusions and lessons learned

Breadboard test results provided significant information to proceed with the thruster design, confirming that the selected GP is feasible for space propulsion application. The main issue observed during the tests has been the ignition reliability, but the results provided enough data for ignition design improvement.

The GP operates efficiently for chamber pressures higher than 3 bar with an estimated actual /theoretical specific impulse performance higher than 90%. The breadboard withstands firing tests during at least 4 seconds with the cobalt-chrome alloy, showing that additive manufacturing process with this material is suitable for thrusters with complex design. These outcomes with the maximum obtained chamber pressure of 4.5 bar and thrust of 19.7 N demonstrate the feasibility of the 12 N propulsion system currently under development.

8.2. Future work

The thruster design with the ceramic glow plug is being manufactured and will be tested with the same test stand. The results of future firing tests will examine the feasibility of the proposed design. If confirmed the thruster concept, the next phase is the assembly, integration, and test of the complete propulsion system.

9. REFERENCES

[1] Ahmed E. S. Nosseir, Angelo Cervone, and Angelo Pasini; Review of State-of-the-Art Green Monopropellants: For Propulsion Systems Analysts and Designers; MDPI; 2021.

[2] B. J. McBride and S. Gordon; Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications: II-User Manual and Program Description; 1996

[3] George P. Sutton and Oscar Biblarz; Rocket Propulsion Elements; chapter 12.2; 9th edition; Wiley; 2017.

[4] Material datasheet: EOS CobaltChrome MP1.

[5] T. Pardal, F. Lourenço, P. Lima, T. Moreira, R. Marques, P. N. Fernades, G. Pereira; Development of a Xenon Storage COPV with a Seamless Aluminium Liner; SP2018_231; 2018.

ACKNOWLEDGEMENTS

Part of the work described in this paper was carried out under a programme of and funded by the European Space Agency. The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

All researchers acknowledge Project "SADLE", CENTRO-01-0247-FEDER-045110, supported by Fundo Europeu de Desenvolvimento Regional (FEDER).

Cofinanciado por: