Proceedings Paper:

Popescu, J.A., Vilag, V.A., Porumbel, I. et al. (2 more authors) (2018) Experimental approach regarding the ignition of H2/O2 mixtures in vacuum environment. In: Gherman, B. and Porumbel, I., (eds.) Transportation Research Procedia. Aerospace Europe CEAS 2017 Conference, 16-20 Oct 2017, Bucharest, Romania. Elsevier , pp. 330-338.

https://doi.org/10.1016/j.trpro.2018.02.030

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 29 (2018) 330–338

Transportation Research Procedia

www.elsevier.com/locate/procedia

Yo6th CEAS AIR & SPACE CONFERENCE AEROSPACE EUROPE 2017, CEAS 2017, 16-20 October 2017, Bucharest, Romania

Experimental approach regarding the ignition of H_2/O_2 mixtures in vacuum environment

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Abstract

The paper, elaborated in the framework of the ESA activity "Green thruster for attitude control and orbital manoeuvres of small satellites (GREENTH)", focuses on the preliminary stages of an experimental program aiming to evaluate the feasibility and to increase the maturity level of a H_2/O_2 pulsed technology for small scale space propulsion applications. For demonstrating the capability of the H_2/O_2 mixture to be pulsed and ignited in a vacuum environment, the paper presents the main technical requirements, some addressing the thruster itself, related to system dimensioning, such as the nature of manoeuvres, the thrust level, the minimum impulse bit, the operating conditions, and some addressing the experimental campaign to be performed. The design of the experimental installation has taken into account the demands coming for the challenges and limitations raised by the small-scale satellites (telecommunications satellites or even CubeSats) applications, including vacuum system dimensioning, injection and ignition systems dimensioning and equipment and instrumentation specifications. The testing program covers the selected ranges of operational parameters and the operating sequences, for pulse mode and steady state tests, in order to determine the performance level and to evaluate the pulse repeatability, respectively to demonstrate the process stability.

Peer-review under responsibility of the scientific committee of the 6th CEAS Air & Space Conference Aerospace Europe 2017.

*Keywords:*clean propulsion; experimental setup; vacuum

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1. Introduction

On-board propulsion systems must satisfy a series of functions, including orbit insertion, attitude control, station keeping, repositioning, and primary propulsion for planetary spacecraft. The success of a space mission depends, in

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2352-1465 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 6th CEAS Air & Space Conference Aerospace Europe 2017.
10.1016/j.trpro.2018.02.030

a high degree, on the performance and reliability of these systems, which can include either reaction control thrusters, reaction wheels or magnetic actuators, Kristiansen (2009). Thrusters produce the force by expelling propellant in the opposite direction, as a result of a chemical reaction or thermodynamic expansion, Wertz (1978). They are classified as hot gas when the energy is derived from a chemical reaction or cold gas when it is derived from the latent heat of a phase change, or from the work of compression. The conventional thrusters use convergent - divergent nozzles to accelerate gases to high Mach numbers at nozzle exit, generating thrust. In low atmospheric pressure or in vacuum, the Laval nozzle is not capable to completely expand the exhausted gasses, this effect leading to losses and a reduced overall efficiency.

A synthesis of existent thrusters used on satellites and spacecrafts is presented in the table below.

Table 1. Current thrusters.

Thruster	Specific impulse (s)	Electric power (kW)	Efficiency (%)	Fuel/propellant
Cold gas	50 - 75	-	-	various
Chemical reactions(one propellant)	150 - 250	-	-	N_2H_4; H_2O_2
Chemical reactions(two propellants)	300 - 450	-	-	Various combinations
Rezistojet	300	0.5 - 1	65 - 90	N_2H_4
Arcjet	500 - 600	1 - 2	25 - 45	N_2H_4
Ion thruster	2,500 - 3,500	0.5 - 4.5	40 - 80	Xe
Hall thruster	1,500 - 2,000	1.5 - 4.5	35 - 60	Xe
Pulsed-plasma thruster	900 - 1,200	0.3	7 - 15	Teflon

2. Small-scale propulsion systems

Micro-thrusters are a necessity for manoeuvring vehicles on low orbits, 100-300 km, for correction of trajectory and maintaining the orbital position, requirements derived from the necessity to compensate the significant dynamic drag produced by the rarefied air on low orbits around Earth which leads, in time, to loss of initial impulse and orbit decay. The Global Positioning Systems and other communication satellites are good examples of satellites that require constant corrections in order to maintain the high accuracy required for their correct operation.

The CubeSat community have been interested in small-scale propulsion systems since the inception of the CubeSat standard, in 2000, Mueller (2010), Heidt (2000). The current deployment methods used for CubeSats, as secondary payloads or deployment from the International Space Station, impose limitations to candidate propulsion systems at this small scale, Cal Poly (2009), not only in terms of reducing the size of known systems enough to fit in a small-scale satellite, but also in terms of safety, Air Force Space Command (2004). Most large-scale propulsion systems use reactive chemicals, materials stored in special conditions, or toxic propellants requiring special handling.

The CubeSats have become, from educational projects, tools for research and technology demonstration missions, the main two benefits, Toorian (2008), consisting in their adaptability to integrate into the launch vehicle by specifying agreed-to dimensions and mass properties, Hevner (2011), and in the availability of off-the-shelf components, due to the standardized sizes. So far, none of the deployed CubeSats have incorporated propulsion capable of substantial ΔV. In order to extend the operational envelope of CubeSats beyond Low Earth Orbit (LEO), or to provide CubeSats with a means of significantly changing their orbits, a propulsion system beyond the current state of the art is required. Such a propulsion system needs to be consistent with the general philosophy of CubeSats, providing performance at a low cost and under strict power, mass and volume limitations.

Experimental studies of micro propulsion systems have been considered time consuming, difficult to perform with sufficient accuracy and requiring complex experimental setups.

3. Electrolysis in space propulsion

As alternative solution to mono- and bi-propellant thrusters, the electrolysis propulsion has been considered a viable option to meet many satellite and spacecraft propulsion requirements. This technology, however, has been never used for space missions. In the same time frame, water based fuel cells have flown in a number of missions. These systems have many components similar to electrolysis propulsion systems.

Large-scale electrolysis propulsion systems have been first proposed as a means of providing primary propulsion and attitude control for large satellites, Stechman (1973), Stedman (1976), by introducing a regenerative fuel cell to be used as a battery providing either chemical energy, Mitlitsky (1999), or electric power, Mitlitsky (1996), depending on needs. Such a system could also be used to provide drinking water and oxygen to the crew, albeit at the expense of the storage and propulsive capabilities of the system, Davenport (1991). The proposed system had the disadvantage of large size, due to the necessity of storage of the obtained hydrogen and oxygen, McElroy (1989). These large-scale concepts have been since revisited, the option of their integration in small-scale spacecraft being also taken into consideration, de Groot (1997).

Different than cold gas and electric propulsion devices, water electrolysis propulsion can provide higher performance. At equal thrust levels, power requirements of water electrolysis propulsion (~0.17 N/kW) are greatly below those of electric propulsion systems (~0.08 N/kW for 2.2 kW arcjets, and 0.03 N/kW for 2.6 kW ion thrusters). These advantages become more pronounced at low power levels, where the efficiency of electric propulsion is significantly reduced. In a water electrolysis propulsion system, water stored in a lightweight, low pressure tank is fed to an electrolyser. The electrolyser consumes electrical energy to decompose the water into pressurized hydrogen and oxygen. If solar energy is available, these devices can also serve as a load levelling function, storing the energy as hydrogen and oxygen gases. The propellant is clean and inexpensive. Water can be stored in compact, lightweight tanks. The gaseous hydrogen/gaseous oxygen (GH_2/GO_2) propellants have performance measured at a specific impulse of over 350 s (at thrust levels of 0.5 to 15 N), superior to earth storable chemical alternatives. The products of combustion are clean and free of carbon, however, mission dependent contamination issues with water vapour condensation being under investigation, de Groot (1997)

Recent advances in component technology include: lightweight tankage, water vapour feed electrolysis, fuel cell technology, and thrust chamber materials for propulsion. Taken together, these developments make propulsion and power using electrolysis/fuel cell technology very attractive as separate or integrated systems.

4. "GREENTH" project overview

Green thruster for attitude control and orbital manoeuvres of small satellites is a project consisting in evaluating the feasibility and increasing the maturity of a H_2/O_2pulsed technology for its application as an attitude control thruster. It aims to demonstrate, by experimental means, the capability of the H_2/O_2 mixture to be pulsed and ignited in a vacuum environment. The activity includes defining an ignition system, an experimental injection system, for obtaining a series of mixtures and proving the working concept, designing and manufacturing an experimental setup and testing the system in order to verify the H_2/O_2 pulsing technology, characterizing the H_2/O_2 ignition in vacuum environment, analysing the test results and recommending steps for further development.

Such a technology has not yet been tried in European context, the only tentatives taking place in USA, first by TUI's development, with the full support of NASA, of the HYDROS propulsion system, theoretically able to provide 100 Ns per 100 ml of water, Tethers Unlimited, Inc., second by Cornell University's CubeSat propulsion project focused on a water-electrolysis propulsion system, Zeledon (2012).

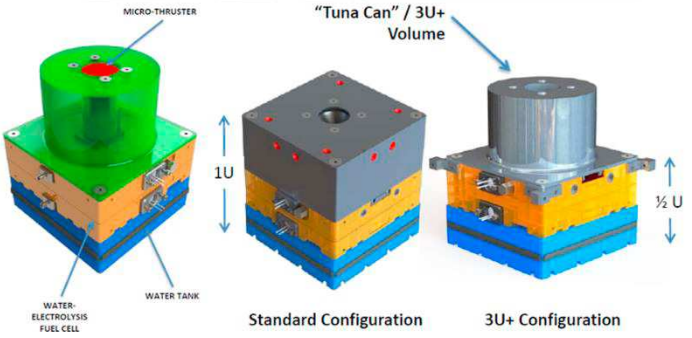

Fig. 1. HYDROS technology

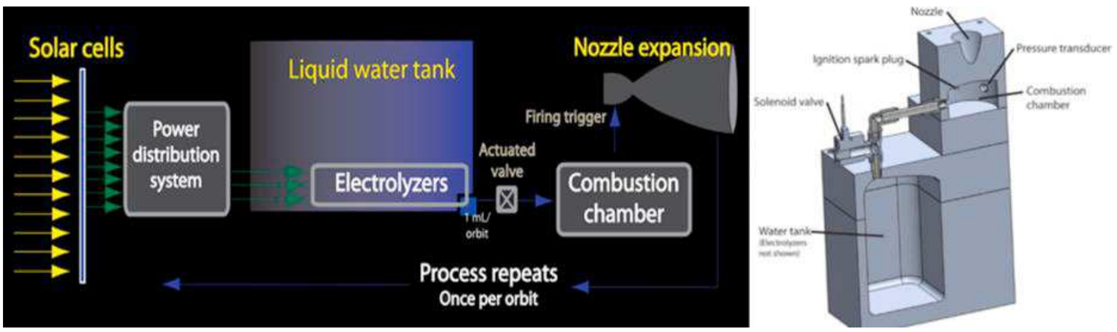

Fig. 2. Schematic of the operation of a CubeSat prototype electrolysis propulsion system

Since GREENTH project is focused on increasing the maturity level of H_2/O_2miniaturized propulsion system, a series of technical requirements have been released, some addressing the thrusters itself and some addressing the experimental campaign to be performed. The discussions on the requirements definition took into account the general expertise of the specialists involved into the project and, as much as possible, the demands coming for possible future applications like small satellites (telecommunications satellites or CubeSats).

4.1. Thruster system performance requirements

The thruster system requirements are related to:

- Thrust level, a requirement that is a compromise between the state-of-the-art, miniaturization capabilities and specific impulse and the mass flow rate. The expected thrust level is below 3 [N], with a targeted value of 1 [N].
- The roughness is defined peak to peak, relative to the overall mean line. It is expected that the thrust will vary with a certain frequency and the required deviation from peak-to-peak must be within some limits. The target range of ± 5% is considered reasonable due to the gaseous state of propellants and miniaturization. Should the roughness be larger, waivers can be considered on a case-by-case basis.
- Thrust stability of 99 %. In other words, after successful ignition and after a maximum of thrust have been reached, for steady state, the mean thrust shall remain stable within 1% at constant inlet conditions. This is not considered a hard requirement, as long as the thrust level is repeatable, since any decrease in thrust stability may be compensated at platform level (small satellites) if the exact behaviour of the thruster is known.
- The specific impulse is a performance parameter of the propulsion system and in the present context its value for a so called steady-state operation is imposed within 350 ÷ 390 [s], considered achievable for the proposed mixture ratios, which in theory provides optimum combustion parameters. The interval values are lower than similar classical chemical propulsion system (rocket engines with liquid propellants) since a decrease of performances is expected due to miniaturization of the thruster. Steady-state operation refers to continuous operation of the thruster during a time frame of the order of about 10 [s].
- Minimum impulse bit below 0.75 [Ns]. For this requirement, from platform point of view "the lower, the better" is required in order to provide high accuracy especially for attitude control. The minimum impulse bit value is related to valve opening/closing time, and can be assessed based on the thrust rise time. A value below 0.05 [Ns] is targeted. For an imposed thrust level, the lowest achievable value is strongly related to the feeding valves opening and closing time, and by the combustion process which must take place during this short time interval.

4.2. Testing system requirements

The system developed for experimental demonstration needs to respect series of requirements, as well:

- Vacuum level below 3 mbar. Vacuum level is related to the environment of platform operation. A value of less than 3 [mbar] absolute pressure (< 3 [mbar]) is considered relevant in the frame of GREENTH project as a good compromise between the objectives and associated costs, with consequences in vacuum pump selection and test chamber design.

- Mixture ratio between 0.8 and 1.2, with the nominal mixture ratio to be defined during the experimental campaign. Defined as the ratio of hydrogen flow rate to oxygen flow rate in comparison to a so-called nominal mixture ratio, it is considered in a range narrowed down from an initial extended one. Initially, the nominal mixture ratio was considered to be the stoichiometric mixture ratio but a margin was agreed due to temperature/heat transfer/cooling issues. The nominal mixture ratio will be defined as the mixture ratio allowing a 10 [s] firing in the combustion chamber without hardware degradation.
- The mixture ratio for ignition will be defined after the experimental campaign, targeting the lowest combustion temperature given by the lowest amount of fuel capable of ignition, since this amount will provide the lowest combustion temperature and issues related to heat transfer/cooling can be avoided or at least minimized. The implication of this requirement gives on one hand the necessity to perform some preliminary experiments to determine the mixture ratio for ignition and on the other hand provides larger safety margin with respect to the high temperature expected into the thruster.
- The inlet pressure will be set at the pressure regulators of the H_2 and O_2 tanks, in a larger range, of 10 ÷ 20 [bar], targeting a nominal pressure of 15 [bar]. This requirement refers to the pressure at the inlet of the thruster of both hydrogen and oxygen. During the experimental campaign, the inlet pressure is to be set at the pressure regulators, upstream the flow rate control devices. Implication of this requirement and its respective range of values relates directly to the preliminary design of the hydrogen and oxygen feeding systems and to the design of the thruster itself.
- Pulse train length between 10 and 50 pulses. Preliminary estimations of steady state time indicate a value of 10 s. This requirement refers to the pulse mode of operation, provides better control at platform level. The values are to be confirmed during the preliminary testing based on the observation of the thermal behaviour of the thruster in steady-state operation (if the temperature exceed certain safety limits, the number of batches will be decreased and/or cooling devices will be included) and the possibility of maintaining a relevant pressure level. A significant factor determining the pulse train length is related to valve opening/closing time.
- Thrust and pulse repeatability are very similar, referring to the repeatability of thruster operation. A margin of ± 10% is imposed in order to be able to predict in a reasonable way the control at platform level. The manner of calculating it involves the evaluation of the time integral of thrust for 50 firings at the same inlet conditions. The 50 firings will be analysed considering a normal (Gaussian) distribution of the calculated area.
- Opening time of the inlet valve below 0.2 [s]. The opening time is defined as the time from the moment the command is sent up to full valve opening (i.e. electrical signal). A value of 0.05 [s] is targeted. This requirement refers directly to the performances of the inlet valves (hydrogen and oxygen) in terms of necessary time for full opening. Since the two devices are ON/OFF valves, the values seem to be realistic but the evaluation must take into consideration also the mass flow rates calculated as the quantity of fluid delivered during one pulse.
- Thrust rise time of 500 [ms], with a targeted value of 100 [ms], will be determined through testing. The thrust rise time is measured from the moment the command is sent, and up to 90% thrust.
- Materials resistance and compatibility. The materials used for the thruster must be able to withstand high temperatures, or cooling must be considered. Also, materials compatibility will have to be taken into account. This requirement refers to all the materials used into the project (i.e. thruster, feeding lines, vacuum chamber etc.). As indication, the 300S stainless steel class of materials has been imposed since it is accepted in terms of suitability and safety of the overall operation. This requirement also covers the materials to be use for thruster manufacturing, taking into consideration high temperature superalloys like Ni-based and Pt-based since they provide a good compromise between performances and associated costs. The implication of this requirement relates to thruster design and manufacturing due to small dimensions and special machining tool.
- Acquisition rates / Instrumentation/ control. The measurement of the parameters is continuous, at frequencies previously set for each parameter, in order to capture the phenomenon.

5. Experimental approach

In order to achieve the thruster operation in a relevant environment, in the desired ranges, the experimental installation had to respect all the previously presented requirements, based on which the test bench had to be designed and the command, control and monitoring equipment had to be selected. Moreover, appropriate protective measures had to be taken for a safe operation.

5.1. Experimental set-up details

The experimental installation includes two main injection lines, including gas tanks, pressure regulators, flow measurement equipment, safety devices and command elements, supplying gaseous hydrogen and gaseous oxygen, one additional line for introducing a neutral gas between test sequences, an ignition control system and the automatics system. The thruster assembly is placed inside a vacuum chamber. Once the hydrogen and oxygen mixture reaches an imposed pressure, on each line, a solenoid valve opens between the propellant tank and the combustion chamber, supplying a mix of hydrogen and oxygen ready to ignite. A small spark plug driven by a capacitive ignition circuit causes the gas mixture to combust. The gas then expands through a convergent-divergent nozzle, which produces the thrust necessary to impart a ΔV on the satellite.

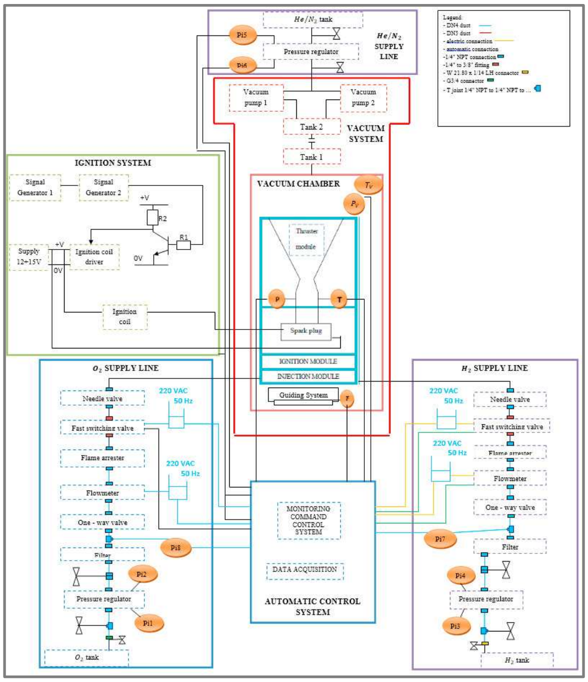

Fig. 3. Experimental installation – Main systems

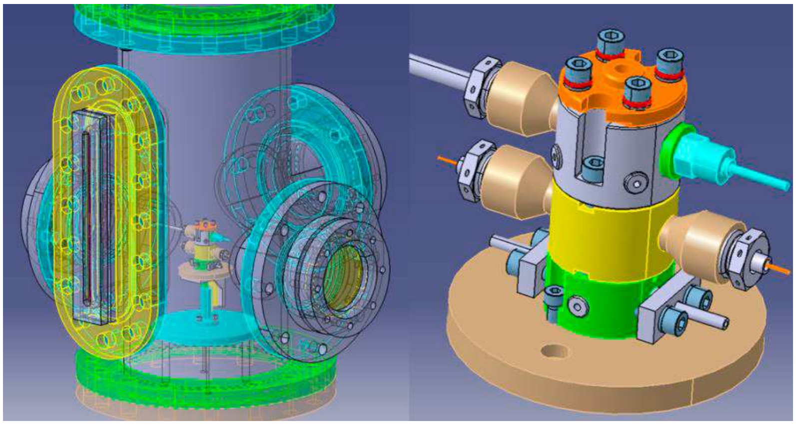

Fig. 4. Thruster experimental assembly inside the vacuum chamber

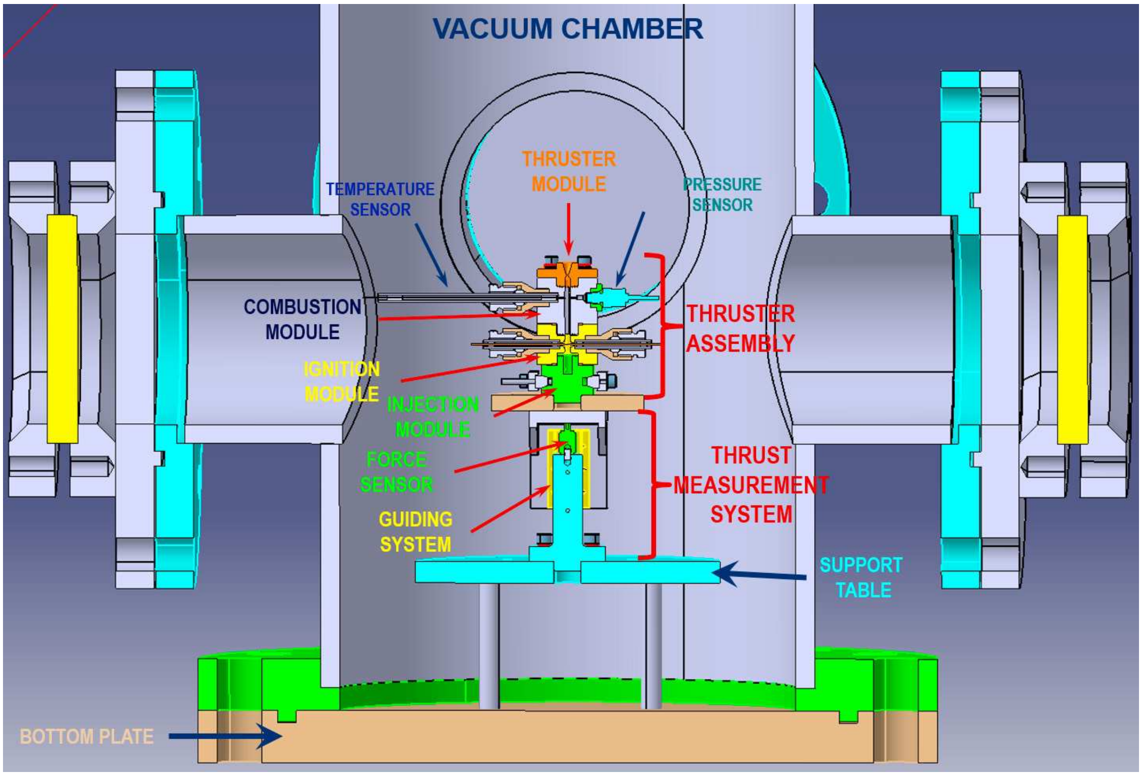

Fig. 5. Thruster experimental assembly – section view details

5.2. Testing plan

The test program is an essential part of the overall design procedure to assess the expected performance of the test item as well as the conditions under which it operates. For an innovative new product, as is the case here, the parametric tests are to be carried out, in order to verify the impact of design parameters upon the performances and quality of the product. Test planning, test requirements, and test criteria shall be derived from the design requirements. A testing plan for the thruster integrates the test procedures, defines all the test stages and the success criteria, as well as the ground set-up requirements, as presented in the previous sections of the paper.

The parametric tests, aiming to verify the impact of design parameters upon the performance and quality of the product, are divided, based on the input data sets, into several stages:

Preliminary tests

- Objectives:tightness tests; verification of the fast switching valves and the flowmeters operation; determination of the experimental equivalent ratio; determination of the dependence: mass flow rate dependence on H_2/O_2 minimum feed line section; determination of the dependence: effective valve time ON on inlet pressure.
- Fixed parameters: atmospheric pressure; minimum combustor length; full nozzle thruster; working fluids: compressed air/ compressed He/N_2.
- Variable parameters: inlet pressure; valve time ON; H_2/O_2 line section.

Ignition tests

- Objective:verification of the ignition system operability.
- Fixed parameters: H_2/O_2 line section; atmospheric pressure; full nozzle thruster; working fluids: H_2/O_2.
- Variable parameters: inlet pressure; combustor length; electrodes location; ignition location; spark frequency; electric power.

Preliminary steady state tests

- Objectives: thrust measurement; pressure and temperature measurement in the combustor.
- Fixed parameters: environmental pressure – vacuum; full nozzle thruster; valve – open; working fluids: H_2/O_2; H_2/O_2 feed line section.
- Variable parameters: inlet pressure; mixture ratio; combustor length; electrodes location; ignition location; spark frequency; electric power.

Final steady state tests

- Objectives: thrust measurement; pressure and temperature measurement in the combustor.
- Fixed parameters: environmental pressure – vacuum; full nozzle thruster; valve – open; working fluids: H_2/O_2; H_2/O_2 feed line section; electrodes location; ignition location; spark frequency; electric power.
- Variable parameters: inlet pressure; mixture ratio; combustor length.

Preliminary pulse mode tests

- Objectives: thrust measurement; pressure and temperature measurement in the combustor.
- Fixed parameters: environmental pressure – vacuum; full nozzle thruster; working fluids: H_2/O_2; H_2/O_2 feed line section.
- Variable parameters: inlet pressure; mixture ratio; Valve time ON; combustor length; electrodes location; ignition location; spark frequency; electric power.

Finalpulse mode tests

- Objectives: thrust measurement; pressure and temperature measurement in the combustor.
- Fixed parameters: environmental pressure – vacuum; full nozzle thruster; valve – open; working fluids: H_2/O_2; H_2/O_2 feed line section; electrodes location; ignition location; spark frequency; electric power.
- Variable parameters: inlet pressure; mixture ratio; combustor length.

6. Conclusions and future work

In the context of an increase in importance and usage of small-scale spacecrafts/CubeSats for demonstration missions, the project GREENTH proposes a water electrolysis propulsion system of reduced dimensions, cleaner and safer for both launch vehicle and deployed satellite.

The paper presents a series of requirements for the thruster system, in terms of desired performance, as well as the requirements of an experimental installation capable to demonstrate the feasibility of a H_2/O_2 pulsed technology applicable to an attitude control thruster. The experimental set-up and the operation principle are briefly presented, along with the proposed stages of the testing program.

A testing campaign will be carried out in the next stage of the project, with experimental results to be presented in future papers and used as input data in complementary research projects. It is expected that the analysis of the experimental results will contribute to further development of small-scale propulsion systems able to satisfy the technical requirements imposed by the space missions.

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