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Experimental Setup for H_2/O_2 Small Thruster Evaluation

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Abstract. In the context of developing a propulsion system for small-scale space platforms, particularly CubeSats, currently treated as secondary payload, several challenges are raised by designing an experimental installation dedicated to testing a H_2/O_2 thruster. Starting from the research projects imposing the operational requirements for the propulsion system and the ofunctional requirements for the testing system, the paper presents the methods for sizing and calibrating the main pieces of equipment used for accurate and stable control of mass flow and mixture ratio, as well as a vacuum chamber computation predicting the evolution of parameters during tests. The conclusions and future work section is related to necessary adjustments for planning of an extensive test campaign able to characterize the performance and behaviour of the studied thruster.

Keywords: CubeSat, experimental, space propulsion, thruster, vacuum

1 Introduction

Small-scale space platforms, particularly the CubeSats, are advantageous from the point of view of various types of missions, such as: demonstration of technology: possibility of testing new instruments and materials in spatial missions, without substantial loss; scientific: space measurements, magnetic field information gathering, earthquake detection improvement; educational projects: opportunity for students to develop a space mission; commercial missions: telecommunication provision, capture of Earth observation images.

The platforms of this type are usually launched, as secondary payload, in LEO (Low Earth Orbit) and therefore have a limited lifetime. The lower the orbit, the higher the gravitational attraction and the satellite has to rotate faster around the Earth for counterbalancing it. At 160 km, a speed of around 21,160 km/h is required, meaning that the satellite will surround the Earth in about 90 minutes [1].

As the altitude increases and the damage caused by the forward resistance decreases, the duration of the missions can be extended. At 300 km altitude, the propulsion system can extend the life of a CubeSat 3U with at least 10 months and at 400 km with at least 4.5 years. This system can provide a CubeSat forward drag compensation in LEO, allowing the position to hold for long periods compared to the current resource for a few days or weeks [2].

Currently, the small size satellites do not have any propulsion capabilities and they are more or less uncontrolled, the attitude control being, in some cases, done by changing the centre of gravity and orbital manoeuvres being excluded. A propulsion system for CubeSats is an interesting subject since the start of their manufacturing. The research activity covered by the paper is related to the development of a clean propulsion system based on water electrolysis technology, able to extend the life of the mission and maintain altitude for a longer period.

This technology, at reduced scale, has been tried in the USA, first by TUI's development, with the full support of NASA, of the HYDROS propulsion system, in two standard configurations: a 2U HYDROS-C module intended for CubeSats and NanoSats, and a HYDROS-M module intended for 50-180 kg microsatellites [3], second by Cornell University's CubeSat propulsion project focused on a water-electrolysis propulsion system [4].

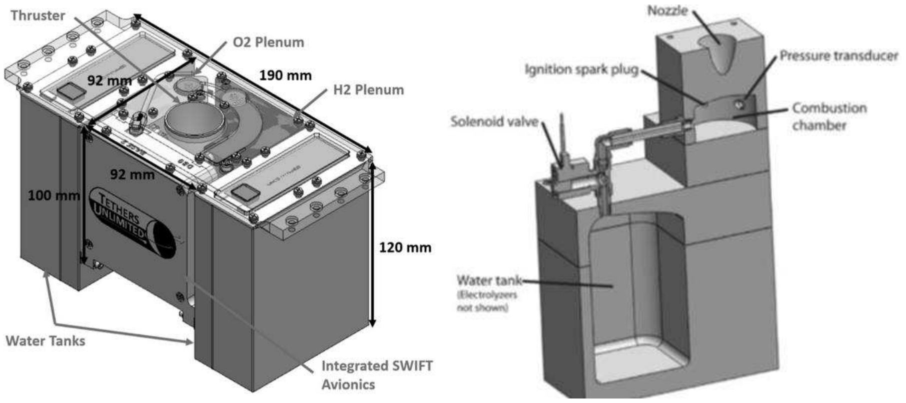

Fig. 1. Prototype electrolysis propulsion systems developed by Tethers - HYDROS-C technology [3] (left) and Cornell University [4] (right)

2 Experimental Setup Sizing

The paper focuses on sizing and calibrating the main pieces of equipment included in the experimental installation necessary for testing a H_2/O_2 small-scale thruster. The parametric tests aim to verify the impact of design parameters upon the performance and quality of the product, and they are based on input data sets such as: inlet pressure, mass flow rate, mixture ratio, valve opening time, pulse trail length. The measurement of the parameters must be continuous, at frequencies previously set for each parameter, in order to capture the phenomenon, therefore the equipment for monitoring, control and data acquisition must be customized, controlled and calibrated in order to ensure good operability and precision.

Assuming the two working gases to be combusted for producing thrust, H_2 and O_2, are obtained using a PEM (proton-exchange membrane) water electrolysis system, the experimental installation uses two main fluid supplying lines, each with installed gas tank and pressure reducer, flowmeter, safety devices (one-way valve, filter, flame arrester), section control element and command element.

The thruster experimental assembly is placed inside a vacuum chamber. Once the fluids reach an imposed pressure, the control valves open, supplying a mix of hydrogen and oxygen ready to ignite [5]. A small spark/glow plug causes the gas mixture to combust. The gas then expands through a convergent-divergent nozzle, producing the necessary thrust.

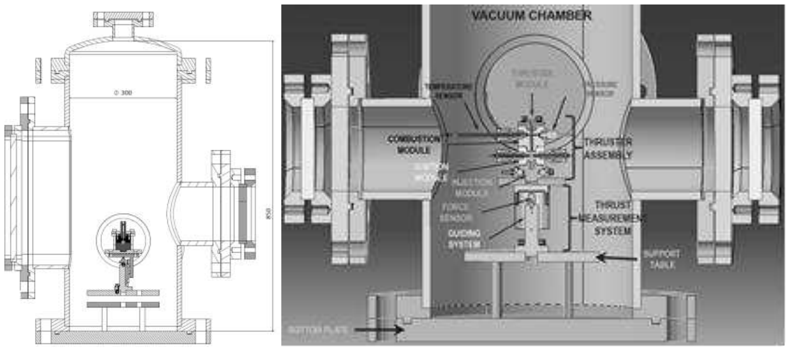

Fig. 2. Thruster experimental assembly inside the vacuum chamber

2.1 Mass Flow Calculation

The design point of the H_2/O_2 thruster imposes the performance in terms of thrust level and specific impulse.

The imposed thrust level, of 1 N, is a compromise between the state-of-the-art, the miniaturization capabilities and the specific impulse. The specific impulse, defined for a steady-state operation, is imposed within the 350 ÷ 390 s range, considered achievable for a mixture ratio close to stoichiometric, which, in theory, provides optimum combustion parameters. The proposed mixture ratio initially required is (0.8 ÷ 1.2) from stoichiometric, with the nominal mixture ratio to be defined based on experimental observations related to thermal/heat transfer/cooling issues, in order to avoid hardware degradation [5].

$$M_{mix} = F / (I_{sp} \cdot g) \ , \qquad (1)$$

where $g = 9.8\ m/s^2$. The mass flow rate of the mixture is, therefore, in the range of 0.23 ÷ 0.3 g/s

Considering the range of the mass flow rate for each gas in the combustion reaction, as well as additional operational requirements, the flowmeters customized for the application cover the 0.0008 ÷ 0.04 g/s range for H_2 and, respectively, the 0.006 ÷ 0.3 g/s range for O_2, with a 0.5% precision and allowing a 22 bar internal pressure drop.

2.2 Injection Section Control

The mass flow rate of the two gases, in the ranges mentioned above, are controlled with the help of needle valves, one installed on each injection line. They are designed to provide accurate and stable control of flow rate.

The diagram in Fig. 3 illustrates the fineness of the valves control at the nominal pressure of 15 bara and three constant O_2 sections, for the variation of the H_2 section. The diagram is limited to the range of mixture ratios close to stoichiometric.

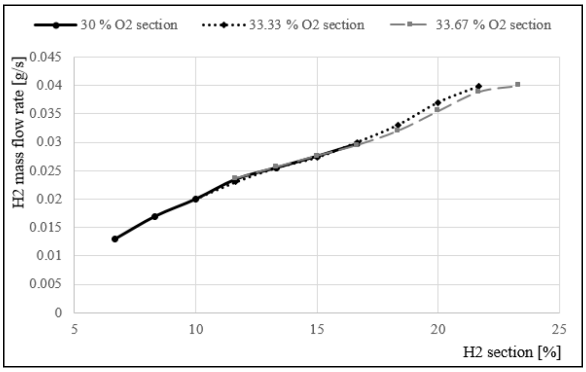

Fig. 3. H_2 mass flow rate variation with the modification of the injection section

2.3 Vacuum Chamber Computation

The vacuum chamber has a fixed volume, known in value. Before the experiment start, it is presumed that a vacuum is created within the available volume. Initially, the vacuum chamber has a small quantity of air inside, at an absolute pressure below 300 Pa, as thruster operational requirement, and ambient temperature considered 300 K.

Table 1. Input data

Parameter	Symbol	Units	Value
Vacuum chamber volume	V	m^3	0.0547
Vacuum chamber initial pressure	p_{air}	Pa	300
Vacuum chamber initial temperature	T_{air}	K	300
Air specific constant	R_{air}	J/kg/K	287
Air specific heat capacity at constant pressure	cp_{air}	J/kg/K	1080
Water mass flow rate	M_w	kg/s	0.00028
Water injection temperature	T_w	K	3446
Water specific constant	R_w	J/kg/K	461.5
Water specific heat capacity at constant pressure	cp_w	J/kg/K	13383.8

To compute the pressure rise in the vacuum chamber, due to the injection of H_2 and O_2 and the consequent combustion, we assume that we directly inject water, the computation being conducted on the stoichiometric mixture values. The injected water mass flow rate corresponds to the sum of H_2 and O_2 mass flow rates and at the temperature computed with NASA CEA program [6] for their combustion.

To compute the vacuum chamber pressure variation in time, a small time step is considered, "dt", the mixture properties being computed at a given "i" moment. First, we compute the air mass initially existing in the volume of the vacuum chamber, which corresponds to step 0, then, the accumulated mass, after step i, for which an i·dt time corresponds, since the stating of the experiment:

$$m_0 = (p_{air} \cdot V) / (R_{air} \cdot T_{air}) . \tag{2}$$

$$m_i = m_{i-1} + M_w \cdot dt = m_0 + M_w \cdot i \cdot dt. \tag{3}$$

Taking into account that the specific gas constant, the specific heat capacity at constant pressure and the specific enthalpy are intensive properties, they will be computed as:

$$cp_i = (m_{i-1} \cdot cp_{i-1} + M_w \cdot dt \cdot cp_w) / m_i , \tag{4}$$

$$R_i = (m_{i-1} \cdot cp_{i-1} + M_w \cdot dt \cdot R_w) / m_i , \tag{5}$$

$$h_i = (m_{i-1} \cdot cp_{i-1} + M_w \cdot dt \cdot h_w) / m_i = (m_{i-1} \cdot cp_{i-1 \cdot T_{i-1}} + M_w \cdot dt \cdot cp_w \cdot T_w) / m_i , \tag{6}$$

where cp_0, R_0 and T_0 are the properties corresponding to the initial air in the vacuum chamber. The mixture temperature, density and pressure at step "i" can be computed:

$$T_i = h_i / cp_i , \tag{7}$$

$$\rho_i = m_i / V , \tag{8}$$

$$p_i = m_i \cdot R_i \cdot T_i / V . \tag{9}$$

Applying these formulas to the input data given in Table 1, and considering a time step, dt, of 0.1 seconds, the vacuum chamber pressure variation in time can be visualized in Fig. 4.

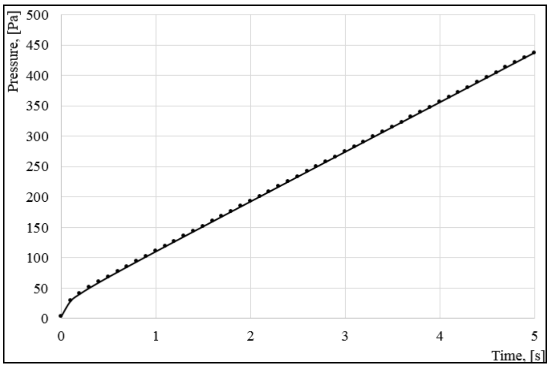

Fig. 4. Pressure variation during thruster tests

4 Conclusions and Future Work

The testing of a small-scale H_2/O_2 thruster, in vacuum conditions, imposes several categories of requirements, operational and experimental, in order to offer the input data for a testing matrix. The paper presents the methods of determining a series of initial conditions by calculating the ranges of fluids' mass flow rates, calibrating the injection sections and observing the increase in pressure in the vacuum chamber.

The vacuum computation is of particular importance for the experimental program due to the fact that the repeatability of the combustion process and, therefore, the capacity of the hardware to create thrust, must be demonstrated in longer sequences of firings, conducted in relevant environment conditions. Based on the computed results, the necessity of supplementing the available vacuum volume becomes a necessary next step in sizing the experimental installation.

An experimental campaign able to characterize the performance and behaviour of the studied thruster implies future work including the optimization of testing time, as a compromise between the initial pressure and the time for obtaining it, as well as the optimization of processes for ensuring stable combustion and nozzle flow.

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