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Atmospheric Test Campaign of a Hydrogen Peroxide Propulsion System for CubeSats

Angelo Pasini†, Elia Puccinelli*, Stefano Calatafimi*, Tommaso Gerbi**
** Department of Civil and Industrial Engineering, University of Pisa*
Via Girolamo Caruso 8, 56121 Pisa, Italy
angelo.pasini@unipi.it - elia.puccinelli@phd.unipi.it - stefano.calatafimi@ing.unipi.it - t.gerbi@studenti.unipi.it
† Corresponding Author

Abstract
A ground experimental test campaign has been carried out on an HTP monopropellant propulsion system for CubeSats application for assessing its propulsive performance. One of the purposes of the test campaign was also the assessment of the diagnostic equipment suitably designed for this activity in view of its future integration inside a vacuum chamber for testing in relevant environment. The thrust balance, capable of hosting in its cradle an entire 3U CubeSat, proved to effectively measure the low level of thrust produced by the propulsion system (i.e. 500 mN in vacuum nominal condition) thus allowing the experimental measurement of the specific impulse together with the output of the flowmeter also integrated in the moving equipment of the thrust balance. The propulsion system has been operated in pulse and continuous mode matching most of its critical requirements.

Nomenclature

A_{th}= nozzle throat area
BOL= Beginning of Life
c*= characteristics velocity
COTS= Commercial-Off-The-Shelf
C_F= Thrust Coefficient
EM= Engineering Model
EOL= End of Life
FM= Flight Model
FS= Full Scale
FSO= Full Scale Output
g= gravity acceleration constant
HTP=High Test Peroxide
IB= Impulse Bit
I_{sp}= Specific Impulse
I.V.= Initial Value
MEOP= Maximum Expected Operating Pressure
p_c= combustion chamber pressure
p_{in}= tank initial pressure
t_{on}= firing valve aperture time
s.l.= sea level
TRL= Technology Readiness Level
U= CubeSat Unit
Δv= velocity change
η= efficiency
σ= Standard Deviation

1. Introduction

The CubeSats market is continuously growing in recent years, pushing the need to provide this class of satellites with propulsion systems for orbit maneuverability. The requirements imposed by these small satellites are very restrictive, especially in terms of mass, envelope, and power consumption. Today few nearly off-the-shelf European propulsion solutions can satisfy these requirements. In this context, the European Space Agency launched a call to identify the most promising European Propulsion Systems for CubeSats. The University of Pisa participated in this ESA call with the CHIPS project (CubeSat HTP Innovative Propulsion System) focused on designing, manufacturing, and testing an affordable chemical monopropellant propulsion system for CubeSats which uses hydrogen peroxide as the propellant. Hydrogen peroxide represents a green alternative to the carcinogenic hydrazine used in most monopropellant thrusters. In the frame of the CHIPS project, two test campaigns took place, one in atmospheric conditions and another in vacuum conditions. Both test campaigns aimed to verify if the designed propulsion system meets the imposed requirements and if its performance can compete with the one given by Off-the-Shell hydrazine thrusters. Obviously, hydrazine guarantees a higher specific impulse than hydrogen peroxide; however, the hydrazine is highly toxic, and its handling requires expensive protection and safety hardware and precautions: a complexity often incompatible with the limitations imposed by the CubeSats. Moreover, thanks to its high density the hydrogen peroxide can give a higher volume specific impulse which allow to save propellant storing volume representing a valuable benefit for the SmallSats missions. On the other side, respect to the nitrate blend propellants [1] the hydrogen peroxide has a lower

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adiabatic decomposition temperature, which avoid the use of pre-heater for the catalytic bed of the monopropellant thrusters and the use of expansive isolating materials and coatings for the decomposition chamber. A monopropellant solution has been selected thanks to its compactness that meets the stringent CubeSats' envelope requirements. The great heritage of the University of Pisa about this type of propulsion systems [2–4] guided the design of CHIPS and the previous studies about the hydrogen peroxide catalytic decomposition [5–8] indicates the type of catalyst pellets to be used inside the thruster. $P_t\, \alpha - Al_2O_3$ pellets demonstrated to be one of the best candidates for filling the CHIPS catalytic bed thanks to their high thermal resistance, propellant decomposition efficiency, and durability.
The important lesson learned from the previous experimental activities conducted on this type of propulsion system at the University of Pisa [4,9,10], especially in the frame of the recent PulCheR project [11,12], highlighted the path to follow during the atmospheric experimental campaign of CHIPS. One step closer, respect to the previous test campaign, was the development of a test apparatus capable of housing not only the thruster but the entire propulsion system for the performance characterization. The design and development of such apparatus was one of the main points of the CHIPS project and the final configuration obtained showed an incredible versatility allowing the testing of not only CHIPS but potentially of whichever propulsion system with up to 3U of envelope and demonstrating to be interfaceable with different test facilities in both atmospheric and vacuum conditions. The present work presents the atmospheric test campaign conducted in the frame of the CHIPS project in atmospheric conditions utilizing this newly design test bench. The test article was the Engineering Model of CHIPS, since at this stage of the project a TRL >3 was required to be achieved at the end of the test campaign and the test's safety procedures forces to add more valves and sensors to the tested configuration. This low TRL allowed for the waiving of the verification of some requirements more related to the Flight Model of the propulsion system during the test and for the use of COTS products not qualified for space for the development of the Engineering Model. This opportunity quickens the various steps of the project without impeding to verify most of the imposed requirements during the test campaign. Finally, the great accuracy of the designed thrust balance (0.6% FS), the implementation of a mass flow meter inside the system for a direct measure of the mass flow rate and the recording of the exhausts pressure and temperatures enabled a precise determination of the propulsive capabilities of the developed low-thrust monopropellant propulsion system.

2. Propulsion System Design

CubeSats are used in a variety of different mission scenarios and so, the propulsion system should be reliable and versatile to guarantee the success of all the operations. With this in mind, the design followed a general mission with a lifetime of minimum 3 years in which the propellant used was 98% wt. Hydrogen Peroxide. Together with basic principles of simplicity, low cost and maximization of the propulsive performances in terms of Δv, the general requirements for the propulsion system were set and are reported in Table 1.

Table 1: CHIPS Requirements

Parameter	**Requirement**
Propellant	HTP 98% wt.
Specific Impulse	>150 s
Power Consumption	≤ 5 W
Thrust	≤ 0.5 N
Minimum Impulse Bit	≤ 25 mN s
Propellant Volume	≥ 0.3 dm^3
MEOP	≥ 24 bar
Dry mass	≤ 1.2 kg
Volume Envelope	≤ 2U
Material HTP compatibility	Grade I and II
Lifetime	≥ 3 yrs
Propellant Management Operation	Blow down
TRL	≥ 3
Overall Price	≤ 50k€

2.1 Flight Model

Figure 1 shows a schematic of the flight model configuration designed in the frame of the project following the imposed requirements. The flight segment of the filling and draining system is comprised of two fill-and-drain valves, with each valve serving a specific fluid inside the tank. A feed-line connects the propellant storage side of the tank to the thrust

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chamber and this line is equipped with a filter and three solenoidal valves, which collectively ensure three barriers to prevent catastrophic events, as required in [13]. The monopropellant thruster is composed by a catalytic bed and a nozzle that generates the required thrust for moving the satellites. The system is equipped with three sensors: a temperature sensor and a pressure transducer to monitor the propellant's condition inside the tank, along with an additional temperature sensor to measure the thruster's temperature. All the components were deliberately chosen to be compatible with the 98% wt. Hydrogen Peroxide (HTP). The selection of this propellant is a notable advantage of the propulsion system because it is a non-toxic and cost-effective propellant with a well-established track record in spaceflight. While it exhibits a lower specific impulse at high levels compared to hydrazine and nitrate blends, it compensates with its higher density, offering similar performance. Additionally, its ease to handling, the absence of a pre-heater requirement for decomposition, and its relatively low decomposition temperature (900-1300 K) eliminate the need for expensive materials in the combustion chamber. These characteristics make Hydrogen Peroxide a promising, straightforward, and economical choice for CubeSats' propulsion systems.

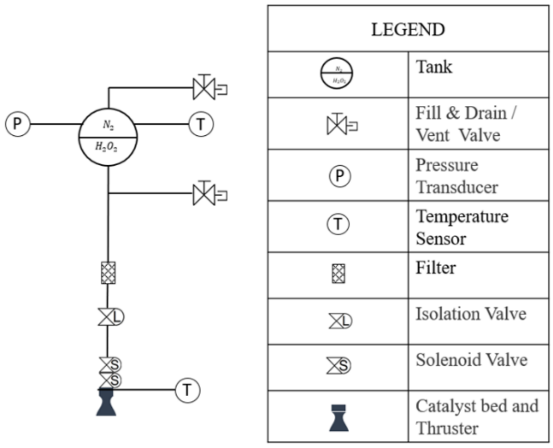

Figure 1: CHIPS Flight Model Configuration

The storage subsystem is one of the main critical elements of the propulsion system and for this reason and because of the lack of suitable COTS product in the market, compatible with 98% HTP, a new tank was studied and designed [14]. The driving principles adopted are similar to the ones of the propulsion system: maximization of the storable propellant volume, minimization of the dry mass, low cost, simplicity.

2.2 Engineering Model

In order to test the propulsion system, from the schematic of the flight model, described above, an engineering model has been developed and its schematic can be found in Figure 2. The main components, namely the two fill and drain valves, the filter, the isolation valve, the two solenoid firing valves, the thruster, the pressure transducer for the tank and the temperature sensors for both the tank and the combustion chamber remained the same with respect to the flight model. The two models present also the same operating principle being both of them blowdown systems with the pressure decreasing from BOL to EOL. Extra pressure transducers and temperature sensors, together with a mass flowmeter to acquire the mass flowrate in real time have been added to be able to assess all the properties and verify the requirements for the propulsion system. The safety requirements imposed on the EM as well, implied an increase in number of valves adopted and therefore an increase in the complexity of the overall system. One of the main points in the development of the engineering model was the replacement of the newly designed tank of the flight model. A tank present on the market but not suitable to fully satisfy the CHIPS requirements was chosen as a substitute for the proposed innovative tank, in order not to invest too much time in the realization of the latter tank. This change made it possible to carry out tests within the time limits imposed by the project with the compromise of having waived some important requirements regarding the size and mass of the propulsion system; however, this is a natural effect of the process of increasing the TRL of a product starting from very low TRLs. Finally, Figure 2 illustrates with the green line the boundaries of a possible vacuum chamber housing the system. The adaptability of the developed EM allows for its use in both vacuum and atmospheric conditions without changing the configuration.

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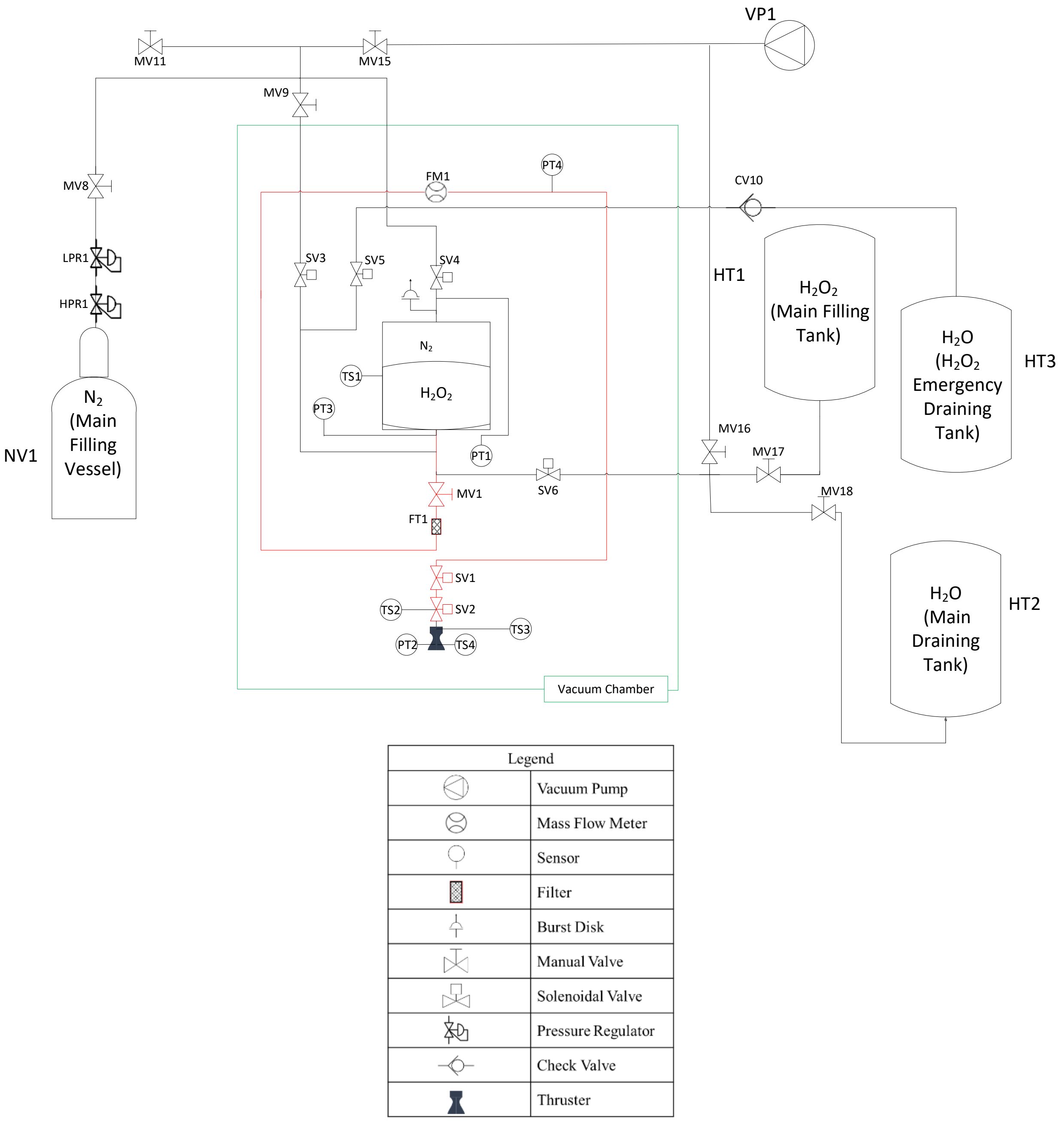

Figure 2: CHIPS Engineering Model Configuration

2.3 Thruster

The thruster represents the main component of the propulsion system, and it was entirely designed by the team of the University of Pisa based on the scaling down of the thruster developed during the PulCheR project [3,12]. various factors drove the thruster design and Table 2 shows the most important among them. In particular, the compact size and the modularity were two main aspects of the proposed design; these aspects were met by adopting a configuration composed of three distinct parts easy assembleable one with each other to compose a thruster with a reduced envelope. The three main thruster's elements are the nozzle, the catalytic bed, and the distribution plate. The configuration adopted for the thruster is monopropellant, as discernable by the presence of a catalytic bed; this choice allows for a more compact and simpler layout. The catalytic bed houses high-temperature resistant catalyst pellets of Pt-α-Al_2O_3 developed internally by the University of Pisa and tested in the frame of the CHIPS project, which decomposes the HTP propellant in few milliseconds in and exothermic reaction producing hot gases. These gases cross the distribution plate and arrive in the thrust chamber from which they expand and accelerate through the nozzle for generating the desired thrust. The catalytic bed volume is about 158 mm^3 and the amount of generated hot gases can provide a thrust

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of 0.5 N at BOL when the feeding pressure is about 18 bar and thrust of 0.125 N at EOL with a feeding pressure close to 5 bar.
Originally, the project envisaged the development of two different thrusters: one for atmospheric tests and the other for vacuum tests. The main difference between these two prototypes was in the different expansion ratio of the nozzles, as visible in Figure 3. The nozzle designed for the atmospheric test campaign has an expansion ratio of 2 to match the gas exiting pressure with the atmospheric conditions and minimizing the thrust losses due to the flow separation. On the other side, the nozzle for the vacuum experimental campaign presents an expansion ratio of 70. A delay in the manufacturing of the atmospheric nozzle forced to use the one foreseen for the vacuum test campaign also in the atmospheric test campaign, in order to preserve the project timeline. For this reason, the thrust level obtained during the atmospheric test campaign was not the nominal one, since flow separation losses affect the measured thrust.
Finally, four rods with a tapered shape separate the thruster from the tank and the other components of the propulsion system for reducing the amount of heat lost by thruster towards the rest of the propulsion system. These rods carry out an important function since the firing valves can correctly operate only in a limited range of temperatures (up to 60°C) and reducing the heat absorbed by them is essential to avoid any failure of the system. The same is true for the feed line and the tank since the hydrogen peroxide inside these components decomposes in a self-sustained way if reaches the 100°C and this phenomenon would obviously lead to a loss of the propulsion system and a catastrophic failure. Figure 4 illustrates the pellets catalyst used and the thruster assembly.

Table 2: CHIPS Thruster Requirements

Parameter	**Requirement**
Operational Temperatures	≤ 1000 °C
MEOP	≥ 18 bar
Thrust	≤ 0.5 N
c* efficiency	≥ 0.90
Operational Mode	Continuous firing
Operational Mode	Pulse mode
Total throughput	≥ 0.4 kg
Volume Envelope	≤ 1U

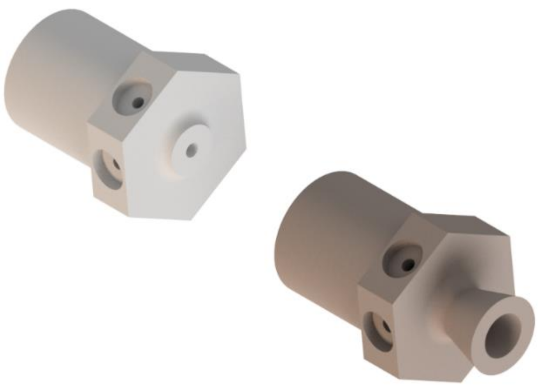

Figure 3: CHIPS Atmospheric (left) and Vacuum (right) Nozzles

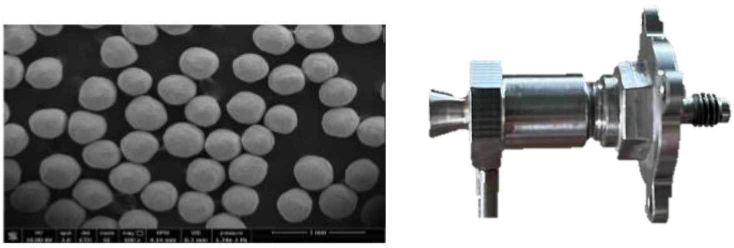

Figure 4: CHIPS Catalyst Pellets and Thruster

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3. Test Apparatus

The atmospheric tests were conducted entirely at the University of Pisa laboratory facility. The main features driving the test apparatus realization were the possibility to include all the sensors necessary for a full characterization of the system performance, the easiness of access to the test article, the possibility to quick mount and demount the propulsion system, and the safety of the operations. Looking at the schematic of Figure 2, the drain tank, the pressurant vessel, the main filling tank, and the emergency tank were included in the test facility and placed at a safety distance from the system and the personnel to avoid any accident derived from HTP spilling or pressurant gas losses. Four flexible tubes compatible with the HTP connected these four tanks to the propulsion system. Two valves placed on each of these lines constituted safety barriers against HTP losses in accidental scenarios. A proper emergency procedure was also developed verting on the complete emptying of the system through the propellant expulsion in the emergency line and tank. Figure 5 shows the structure built to house the system and all the sensors during the tests. A one-degree-of-freedom thrust balance forms the main body of the structure. This thrust balance features an innovative design made to be able to test not only CHIPS, but any chemical propulsion system inserted in a 3U CubeSat. This design comprises a central body consisting of an H-beam from which two C-beams extend; one of them has two flexures attached to which an entire 3U structure containing the propulsion system to be tested is hooked up, while the other gathered the system hoses making them come out perpendicular to the thrust plane, so that they do not absorb any component of the force vector. A D-sub bar located on the back of the thrust balance collects all the cables coming from the various sensors and allows the exchange of signals with the acquisition system. The developed configuration allows to house all the sensors directly on the thrust balance, even the flowmeter. Generally, this sensor is placed in a peripheral line and outside the thrust balance, however, exploiting the positioning versatility of the Coriolis flowmeter, this sensor has been inserted in the propulsion system feeding line and positioned directly on the thrust balance, thus becoming an integral part of the test apparatus. The thrust balance can measure the generated thrust thank to the system of flexure and to a load cell. The flexures are extremely flexible in the axial direction in order to absorb a negligible amount of the axial thrust while sustaining the weight of the hanged system. The load cell aligned with the thrust vector and inserted in an adapter between the CubeSat structure and the thrust balance H-beam measures the axial thrust.
Finally, the static calibration of the thrust balance showed that it was able to measure the axial thrust with an accuracy of 0.6% FS with a calibrated Full Scale of 4.453 N and a Standard Deviation of 0.014 N.

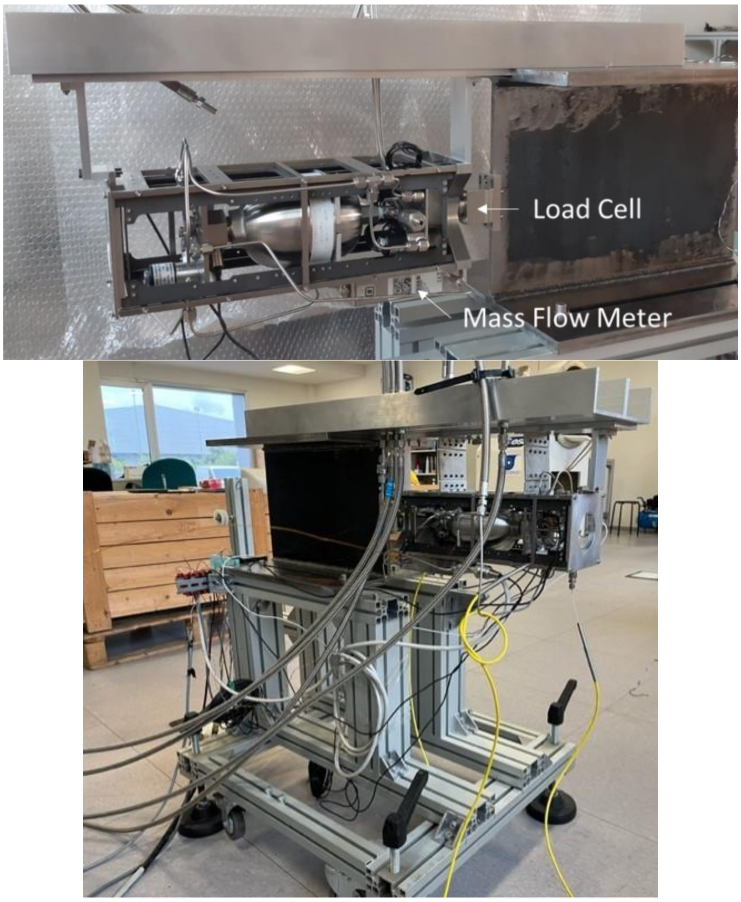

Figure 5: CHIPS Atmospheric Test Set-up

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3.1 Diagnostic and Instrumentation

Table 3 reports CHIPS sensors composing the EM for the atmospheric experimental campaign with their range and accuracy values and a reference to the position occupied inside the test segment. The accuracy of the sensors is referring to a confidence level of 95.4% associated to plus or minus two standard deviations (±2 σ).

Table 3: CHIPS Instrumentation Accuracy

Sensor	Range	Accuracy	Place
Kulite ETL/T-500-375M-A (PT1)	0-50 bar	± 0.25% FSO	Tank gas side
Kulite ETL/T-500-375M-A (PT1000)	-50-300 °C	± 0.15 °C	Tank gas side
Kulite ETM-500-375M-SG (PT3)	0-70 bar	± 0.25% FSO	Tank liquid side
Kulite ETM-500-375M-SG (PT4)	0-70 bar	± 0.25% FSO	Feeding line
Kulite XTM-190M-A (PT2)	0-35 bar	±1% FSO	Thrust chamber
TCF-A-J-3000 Tersid (TS1)	-200-1200 °C	± 2 °C	Tank surface
MTS-40053-K-150-3000 Tersid (TS2)	-200-1350 °C	± 1.5 °C	Firing valve surface
MTS-40053-K-150-3000 Tersid (TS3)	-200-1350 °C	± 1.5 °C	Thruster surface
MTS-40103-K-150-3000 Tersid (TS4)	-200-1350 °C	± 1.5 °C	Thrust chamber
Bronkhorst M13 Coriolis (FM1)	30-1500 g/h	± 0.2% I.V.	Feeding line
Honeywell Model 13 1000 gr (LD1)	0-1000 gr	± 0.7 % FSO	Thrust balance

Figure 6 reports a CAD rendering of the developed EM with highlighted all the sensors inserted in the system. The main purpose of the pressure transducers connected to the tank gas and liquid side and to the feeding line is to monitor the status of the HTP to be sure that no propellant decomposition is happening during the test. The same is true for the inserted thermocouples. In case at least one of these sensors records a temperature or pressure value above the fixed safety threshold an emergency procedure will trigger completely emptying the tank. A passive method is also implemented by the insertion of a burst disk on the gas side of the tank; the disk will break if the pressure in the tank surpasses the designed value and the pressurant gas will flow out form the system reducing the risk of explosion. A J-type surface thermocouple recorded the liquid-side tank surface temperature to verify the margin respect to the self-sustained decomposition temperature. Other two surface temperature sensors of type K monitored the firing valve and the catalytic bed surface status. The thermocouple and the pressure tap connected to the nozzle record the temperature and pressure of the exhaust gases exiting the thruster. These measures together with the ones provided by the mass flow meter and the load cell allows to fully characterize the system’s propulsive performance by estimating the quantities reported in Table 4. The method adopted for determining the accuracies shown in the table is explained in a companion paper [15].

Table 4: CHIPS Measured Quantities and Corresponding Sensors

Quantity Formula	Related EM Sensor	Accuracy at Nominal Conditions
F	Honeywell Model 13 1000 gr (LD1) Bronkhorst M13 Coriolis (FM1) Kulite XTM-190M-A (PT2)	$\begin{cases} F = 500 \pm 28 \text{ mN} \\ \dot{m} = 0.3115 \pm 0.0062 \text{ g/s} \\ p_c = 14.00 \pm 0.35 \text{ bar} \\ I_{sp} = 163.6 \pm 9.7 \text{ s} \\ c^* = 900 \pm 46 \text{ m/s} \\ C_F = 1.78 \pm 0.13 \\ \eta_{c^*} = 0.900 \pm 0.046 \\ \eta_{C_F} = 0.980 \pm 0.072 \end{cases}$
$IB = \int_0^{T_{pulse}} F(t)\,dt \Rightarrow MIB = \min(IB)$		
$I_{sp} = \dfrac{F}{\dot{m}g}$		
$C_F = \dfrac{F}{p_c A_{th}} \Rightarrow \eta_{C_F} = \dfrac{C_F}{C_F^{(theo)}}$		
$c^* = \dfrac{p_c A_{th}}{\dot{m}} \Rightarrow \eta_{c^*} = \dfrac{c^*}{c^{*(theo)}}$		

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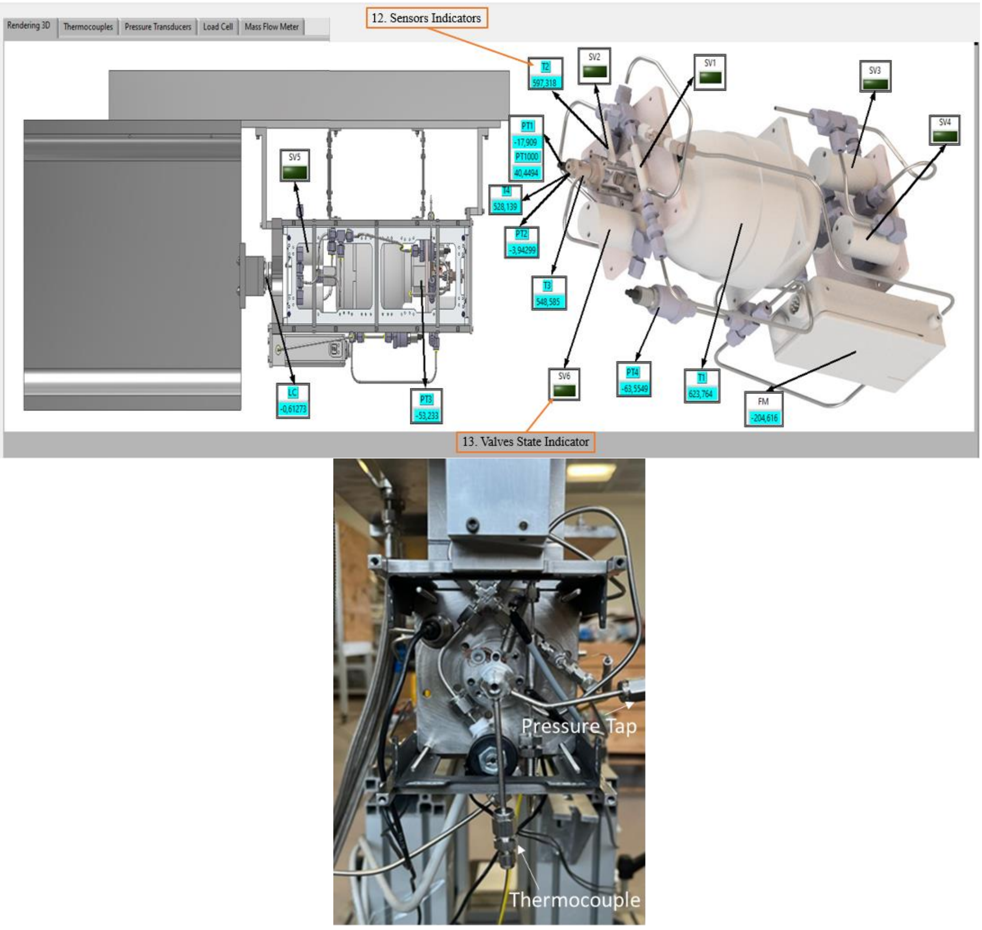

Figure 6: CAD (upper) and Physical (lower) Realization of CHIPS Engineering Model

A LabVIEW® data acquisition and control program developed internally by the CHIPS team records and shows in real-time the outputs of all the sensors gathered by a National Instrument acquisition system. Figure 7 shows the schematic adopted for the LabVIEW® program. A power supply unit differentiate four voltages with which feeding the valves and the sensors; a 12 V line feeds the valves with the possibility to decrease the feeding potential down to 5V for the firing valves to self-heating and maintain their temperatures below the operating limit. The pressure transducers are all fed by 10 V line, while the mass flow meter at 24 V. The PT1000 thermoresistance and the decomposition chamber pressure transducer are connected to a converter and amplifier, respectively, to make more readable their outputs; these additional components are fed at 5 V. The program allows to operate the valves in both manual and automatic mode to accelerate the test procedure and to consent a direct intervention of the personnel also during the test. Finally, the need to record the signals also during the pulse mode operations pushes for setting the acquisition frequency at 2500 Hz.

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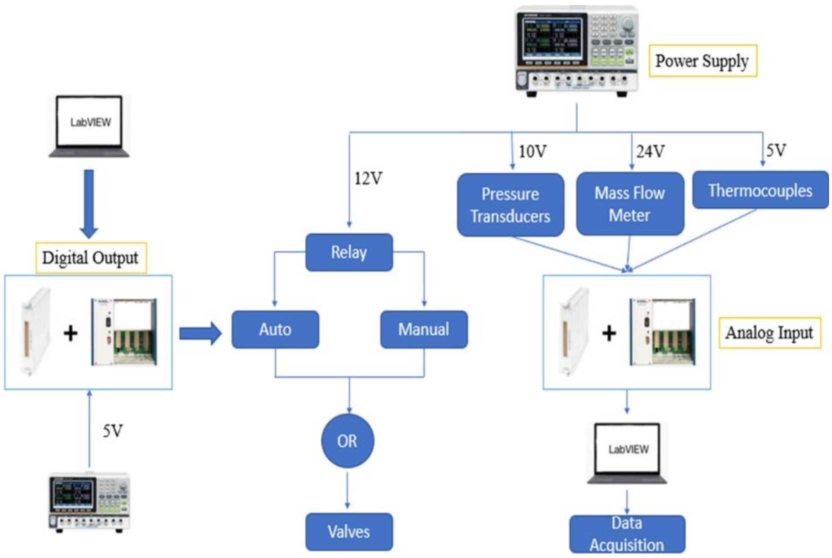

Figure 7: LabVIEW® Program Schematic

4. Experimental Results and Discussion

The CHIPS atmospheric test campaign includes testing in both continuous and pulse mode to verify the potential of the designed propulsion system in accomplishing the CubeSats' different mission scenarios. The following figures illustrates the results obtained in this experimental campaign starting with the continuous firing testing and concluding with the pulse mode achievements.

As explained above, the nozzle utilized during the atmospheric test campaign was not the optimal designed one, but the one with an expansion ratio equal to 70 suitable for the vacuum test. For this reason, the thrust obtained during this test campaign was lower than the nominal one, due to the flow separation occurring inside the nozzle. This effect is detectable in Figure 8 showing the thrust coefficient efficiency obtained during the continuous firing which is lower than 0.6, well below the nominal expected value in vacuum (i.e. higher than 0.9).

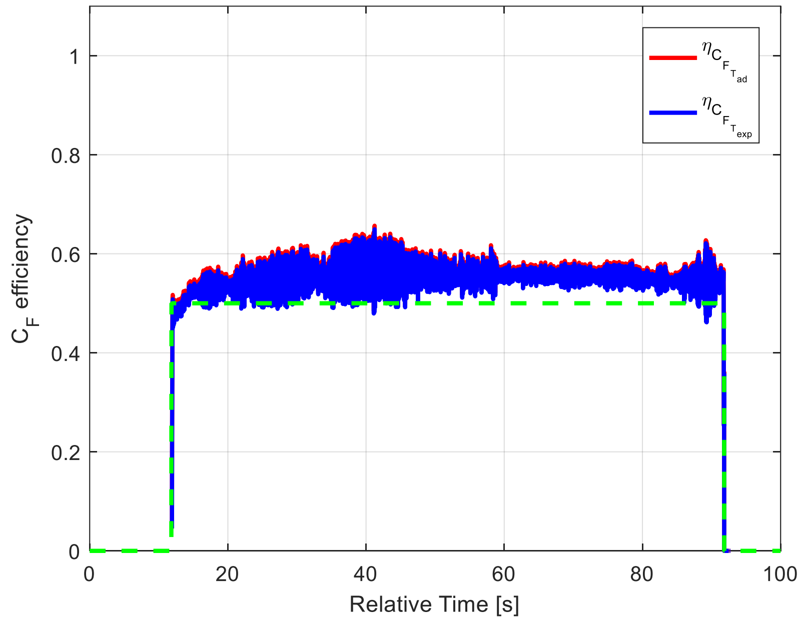

Figure 8: Thrust Coefficient Evolution during Continuous Atmospheric Firing

Figure 10 shows the time evolution during the continuative firings of the recorded quantities; these quantities are the pressure inside both sides of the tank, the catalytic bed inlet pressure, the thrust chamber pressure, the thrust, and the mass flow rate. The right-hand side of the figure illustrates the results for the first firing lasting 80 s, while the left-

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hand side the results of the second firing lasting 10 s. As visible from the results of the first firing, a physical instability occurred at the beginning of the experiment. The oscillations were detected from both the load cell and the exhaust gases pressure transducers with the same frequency (Figure 10), sign that this instability is related to the gasdynamic inside the catalytic bed and not to an incorrect mechanical behavior of the thrust balance. However, after about 50 s the instability dumped by itself, probably thanks to a catalyst pellets rearrangement inside the catalytic bed, and during the second continuative firing there were no traces of the instability and the propulsion system showed its actual performance, reported in Table *5*; with the exception of specific impulse and thrust for the causes mentioned above, all required propulsive parameters were satisfied by the system during this test campaign.

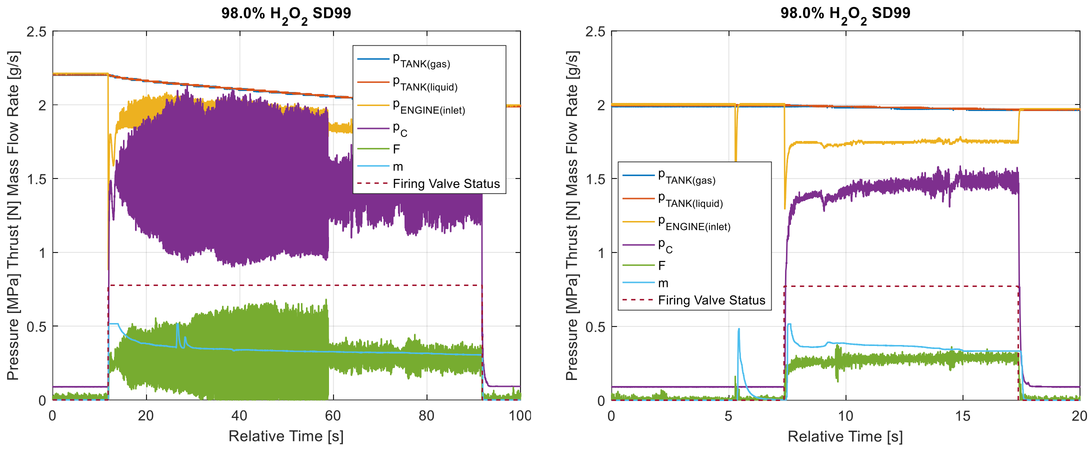

Figure 9: CHIPS Continuative Firings Results

Table 5: CHIPS Continuative Firing Performance

Parameter	Value	Threshold Value
F (N)	0.3 (s.l.)	≤ 0.5
Isp (s)	80 (s.l.)	160
Rise-time (ms)	<100	150
Thrust Roughness	<3%	±5% at 2σ
η_{c*} (c*-efficiency)	0.9	0.9

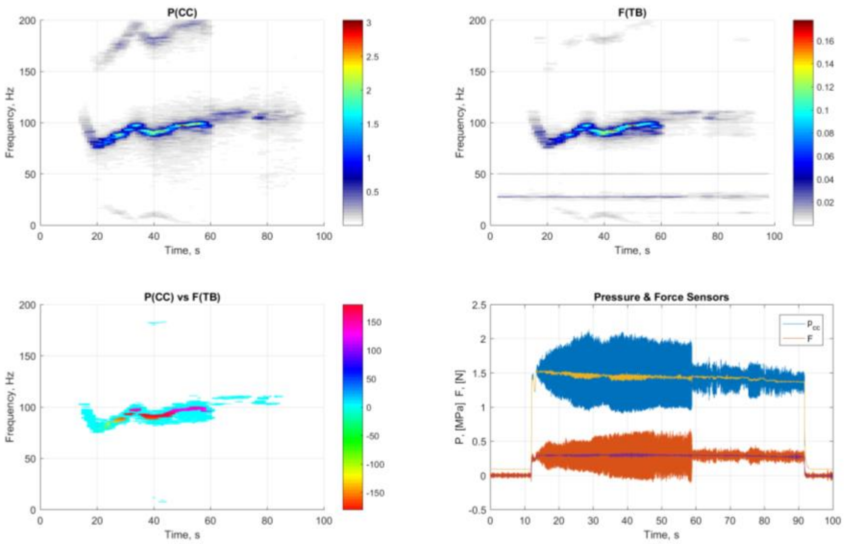

Figure 10: CHIPS First Continuative Firing Spectral Analysis of the Chamber Pressure and Thrust Signals

The oscillations present in the second firing where due to the background noise of the thrust balance, which is highlighted in the thrust roughness graph showed in Figure 12. These oscillations had a small amplitude, especially if

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compared to the one obtained in the vacuum test campaign reported in a companion paper [15]. The small amplitude of the oscillations is excellent feedback for the performance of the newly designed thrust balance since these mean that the apparatus is capable to furnish a good isolation of the system from the surrounding environment. Figure 11 and Figure 12 better explains the estimation of the thrust roughness. Figure 11 shows the signal of the recorded decomposition chamber pressure, and its composition in the steady value and the 2σ deviance as function of time. In the case of the first continuative firing the instability made the oscillatory component of the signal well recognizable, even during the second part of the firing where the instability was supposed to be suppressed. Therefore, the obtained relative roughness for the pressure assumed high values, and the same is valid for the absolute thrust roughness, as visible from Figure 12 (about 7% in after 50 s). On the other hand, the absence of instability during the second firing made the oscillatory component of the pressure signal equal to zero, reducing in this way also the relative roughness to a negligible value. As stated above the stiffness of the system and the isolation provided by the thrust balance allowed for obtaining a thrust roughness close to 0 N in the absence of instability during the second continuative firing.

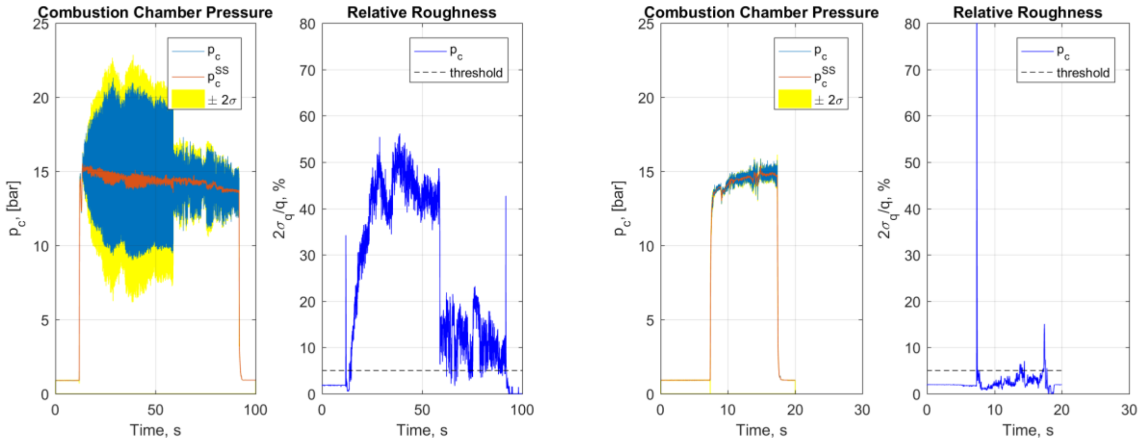

Figure 11: CHIPS First (left) and Second (right) Continuative Firings Chamber Pressure Signal Composition and Roughness

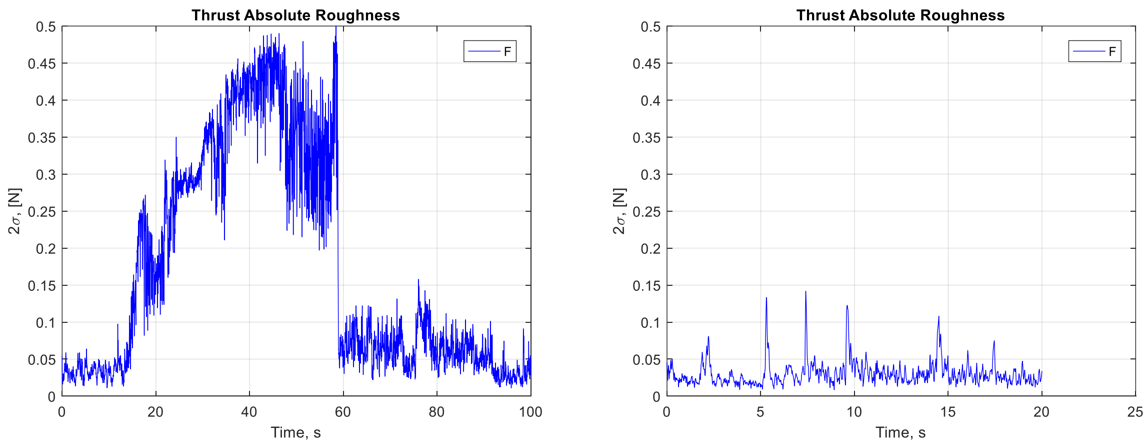

Figure 12: CHIPS First (left) and Second (right) Continuative Firing Thrust Roughness

Figure 13 shows the recorded signals for the pulsed firing with an aperture time of the firing valve of 900 ms. This opening time was the largest time tested in pulse mode, and as visible from the figure, the system reached a steady thrust level during the aperture of the valve. Always looking at the figure a tail in the recorded mass flow rate signal is visible in correspondence of the valve closing instant; this is a hysteresis of the Coriolis mass flow meter which distort the actual mass flow rate recorded value and all the quantities derived by it. Techniques to avoid this measurement problem are still under study at the University of Pisa. Figure 14 illustrates the impulse bit obtained by the corresponding train pulses reported in Figure 13. Obviously, the large opening time of the valve make these values higher than the target MIB (0.025 Ns), however, the figure highlights how the system can generate a repeatable thrust at each pulse obtaining in this away an almost steady value of impulse bit. Figure 15 reports the performance obtained

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in the pulses with a firing valve opening time of 50 ms. This t_{on} was the smallest value for which the system was capable of developing the 90% of the nominal expected thrust. The repeatability of the thrust is visible also in this case with all the peaks present in the figure aligned, and the obtained impulse bit, shown in Figure 16 assume the same value among all the pulses and is below the fixed threshold. The obtained results highlight how CHIPS can operate also in pulsed mode providing competitive performance. Table *6* indicates the propulsive performance characterizing the various pulsed firing realized during the test campaign together with the correspondent firing valve aperture time. These values confirm that CHIPS met most of the imposed requirements about the pulsed propulsive mode.

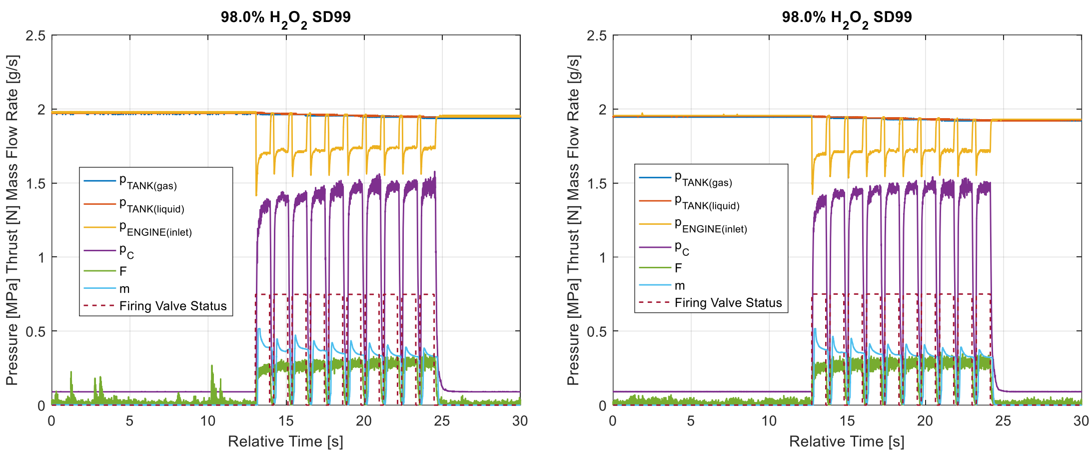

Figure 13: First ten 900 ms t_{on} pulses (left) and last ten 900 ms t_{on} pulses (right).

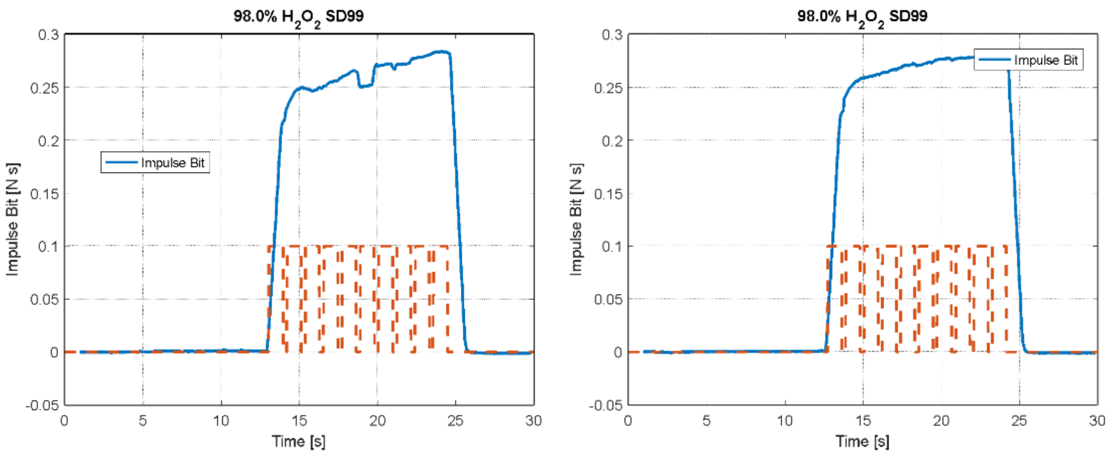

Figure 14: Impulse bit of first ten 900 ms t_{on} pulses (left) and last ten 900 ms t_{on} pulses (right).

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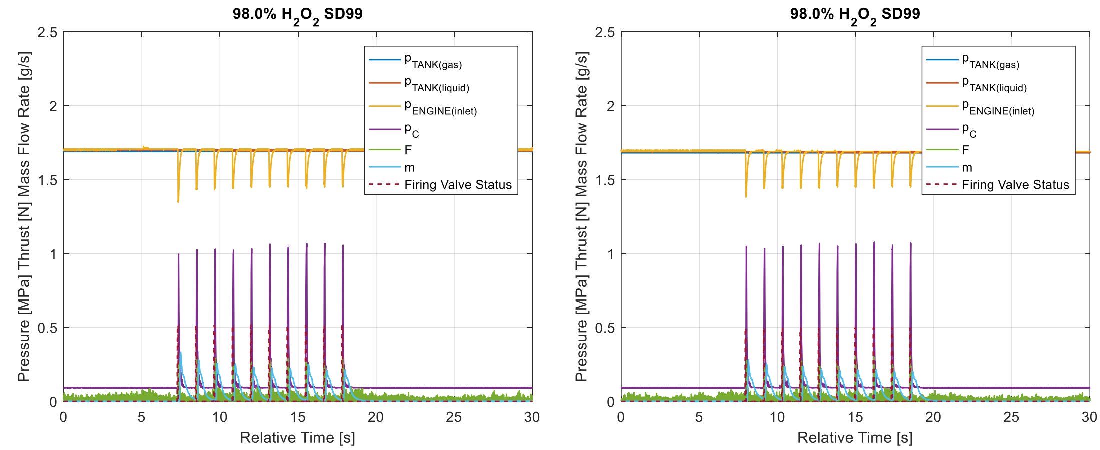

Figure 15: First ten 50 ms t_{on} pulses (left) and last ten 50 ms t_{on} pulses (right).

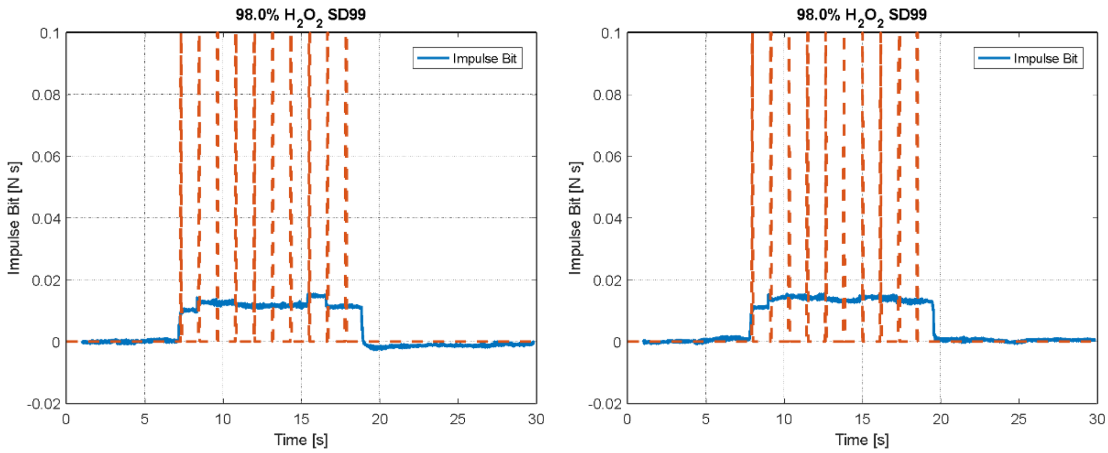

Figure 16: Impulse bit of first ten 50 ms t_{on} pulses (left) and last ten 50 ms t_{on} pulses (right).

Table 6: CHIPS Pulses Train Nominal Performance

t_{on} (ms)	N° Pulses	p_{in} (bar)	F(N)	Impulse Bit (Ns)
900 (first series)	20	20	0.300 (s.l.)	0.260 (s.l.)
900 (second series)	20	16	0.190 (s.l.)	0.220 (s.l.)
800 (first series)	20	19	0.300 (s.l.)	0.230 (s.l.)
700 (first series)	20	19	0.270 (s.l.)	0.190 (s.l.)
600 (first series)	20	18	0.270 (s.l.)	0.150 (s.l.)
500 (first series)	20	18	0.250 (s.l.)	0.120 (s.l.)
400 (first series)	20	18	0.250 (s.l.)	0.110 (s.l.)
300 (first series)	80	17	0.230 (s.l.)	0.077 (s.l.)
200 (first series)	80	17	0.230 (s.l.)	0.050 (s.l.)
100 (first series)	80	17	0.220 (s.l.)	0.025 (s.l.)
50 (first series)	80	16	0.200 (s.l.)	0.016 (s.l.)
25 (first series)	80	16	0.150 (s.l.)	0.010 (s.l.)
25 (second series)	80	16	0.130 (s.l.)	0.015 (s.l.)

Finally, the catalyst pellets were not changed during the overall atmospheric test campaign to check the total throughput of the propulsion system. However, due to a catalyst pellets degradation the test was concluded earlier, and the total mass elaborated by these pellets was 0.1 kg at the end of the experiment.

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6. Conclusions

The Engineering Model of the propulsion system described in this work was successfully tested in atmospheric conditions and met most of the imposed requirements. A thrust balance designed by the University of Pisa housed the entire 3U in which the system was inserted during the experimental campaign. The thrust balance showed good performance in terms of both following the thrust generated by the system and isolating the system from external vibration. The compact and versatile design of this thrust balance makes it a suitable solution for the test campaign of various SmallSats propulsion system solutions. A LabVIEW® program developed internally by the CHIPS team recorded the signals coming from all the eleven sensors included in the propulsion system and the simultaneous control of the six valves. The use of a nozzle designed for the vacuum conditions in the atmospheric test campaign clouded the actual performance of CHIPS. However, the recorded performance shows the promising potential of the developed propulsion system; it reached a specific impulse at sea level of 80 s, with thrust at sea level lower than 0.3 N and a minimum impulse bit of 0.025 mNs, and it has very quick response time lower than 50 ms. The c* efficiency obtained was equal to or greater than 90%, the thrust roughness lower than the 3% at 2σ, and the propellant total throughput was 0.1 kg before the degradation of the catalyst pellets, probably due to the mechanical stresses produced by the initial recorded instability. The causes of this instability are still unknown, probably are related to an incorrect packing of the catalytic bed; however, this instability disappeared after about 50 s of test allowing for obtaining the nominal performance during the other firings. This test campaign also highlights the versatility of CHIPS to operate in continuous and pulsed mode being a suitable solution as both main and attitude control engine. The pulsed firings showed the capability of the system to generate a steady thrust with valve opening times ranging from 900 down to 50 ms, while maintaining an optimum repeatability and reaching competitive value of minimum impulse bit. Finally, even in the Engineering Model configuration the system was able to satisfy stringent encumbrance, mass and power consumption requirements maintaining its envelope inside the 3U, its mass below the 10 kg and its power consumption below 5 W. All these achievements represent a solid and promising basis on which to plan subsequent CHIPS test campaigns to reach a TRL=9 with its Flight Model.

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