REGULUS: Know-How Acquired on Iodine Propellant

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Abstract: The electric propulsion subsystems currently used for commercial missions are designed to operate with xenon as propellant thanks to its good performance and storability. With the arrival on the market of large satellite constellations, the cost of propulsion subsystems is going down, while the amount of required propellant is considerably growing. In this context, the price of xenon (~1.5-2 k€/kg) is becoming a major concern, and in the latest years, alternative propellants have attracted lots of attention. Iodine has been identified as one of the most promising solutions thanks to its low cost (90% lower than the price of xenon) and good propulsive performances. For this reason, the REGULUS platform has been upgraded to be fully iodine-compatible. REGULUS is a complete propulsion system for SmallSats which integrates the Magnetically Enhanced Plasma Thruster with its subsystems, namely thermo-structural, electronics, and fluidic. This work is intended to give an overview on the different aspects related to iodine performances and handling, which have been addressed during the development of REGULUS. First, the response of the Magnetically Enhanced Plasma Thruster to different propellants (i.e. xenon and iodine) has been studied both numerically and experimentally. Second, the fluidic line devoted to the management of iodine has been characterized with dedicated functional tests.

I.Introduction

The satellite industry is undergoing a major breakthrough today, alsoknown as "New Space Economy". The arrival on the market of large satellite constellations[1] will provide several new services that will induce dramatic improvements in many sectors, from natural disaster monitoring and recovery to the development of the "internet of the things". However, to realize this new scenario to the full, space systems are characterized by extremely high demands on compactness, cost reduction, performance and flexibility[2]. These constrains are particularly strict for propulsion units[3], which are essential to perform orbital manoeuvers among other applications, and which allow to increase the constellation lifetime and the quality of the service, as well as to provide new ones. Despite the most promising candidates to propel large constellations of SmallSats (including CubeSats) are Electric Propulsion (EP) systems[3], there are still many technical issues to overcome. At the state of the art, SmallSats are typically launched into their prescribed low Earth orbits with no or limited propulsion onboard[4]. The latter is in fact too expensive and difficult to integrate, mainly because of the adoption of xenon as propellant. In spite of its good propulsive

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performances, xenon has some drawbacks: it is very expensive (~1.5-2 k€/kg) and it is stored in pressurized tanks at supercritical state (pressure ~180 bar)[5]. Therefore, bulky tanks and strict safety measurements are required to handle systems fed with xenon propellant.

The adoption of iodine as alternative propellant seems the most promising near-term solution to provide low-cost and low-volume systems, with high-delta-velocity performance, unpressurized tanks and safe transportation and handling. In fact, regarding storage and handling requirements, iodine shows many advantages in respect to xenon.

- Iodine can be stored in solid state and, in turn, it is three times denser than supercritical xenon (even the liquid lithium in solid state has lower density than iodine)[5]. Consequently, the total impulse in the same volume is higher, enabling high delta-v maneuvers for EP (maintenance, deorbiting, interplanetary mission). Moreover, the tank can be in any shape to fill the spacecraft requirements (no need of domes, typical of spherical tanks)
- Iodine can be stored at moderate temperature (e.g., ambient temperature) and pressure (e.g., atmospheric pressure), so no cryogenic or strict thermal control is required[6]
- Iodine has low procurement cost: 90% less than xenon[7]
- Iodine is safe, therefore cheaper pre-launch handling operations are required for on-site filling. Moreover, iodine suffers no transportation issues as the tank is not under pressure, therefore the entire subsystem can be shipped ready for use. This aspect is of paramount importance for the constellations currently under study, for which satellites are expected to be delivered at a rate of >1 per day. This in comparison to the current production rate of few propulsion subsystems per year, which is the current electric propulsion market standard.

Moreover, it is worth noting that the use of iodine will also remove another of the main limitations to the realization of many constellations, that is the world production of xenon (i.e. even if few of the constellations currently planned would actually take place, the world production of xenon is and will not be enough to cover all the needs). Another advantage of the adoption of iodine as a propellant for EP systems is that the plasma properties of a xenon and an iodine discharge are similar[7]:

- xenon atomic mass $M_{Xe} = 131.3$ u, iodine $M_I = 126.9$ u
- xenon first ionization potential $\varepsilon_{Xe} = 12.1$ eV, iodine $\varepsilon_I = 10.5$ eV
- xenon peak ionization cross section $\sigma_{Xe} = 4.8 \times 10^{-16}$ m^2, iodine $\sigma_I = 6.0 \times 10^{-16}$ m^2

Moreover, from a propulsive standpoint, it has been shown[8] that (i) xenon and iodine performances are similar for ion and hall-effect thrusters, and (ii) most of the iodine propellant in the exhaust exits as single-charged atoms (I^+). The other species (e.g., I^- and I_2^+) are not so relevant for the propulsive performance but may affect the chemical compatibility. The main drawback of iodine, which limits its widespread as alternative propellant, is its aggressive chemical nature[9]. This imposes a deep review of the material used to ensure compatibility with the long lifetime normally requested by space missions. In addition, the management of a solid propellant, with the mass flow rate controlled via evaporation rate, requires a non-trivial thermal control design, which is not only limited to the tank, but also covers the piping and various fluidic components[9].

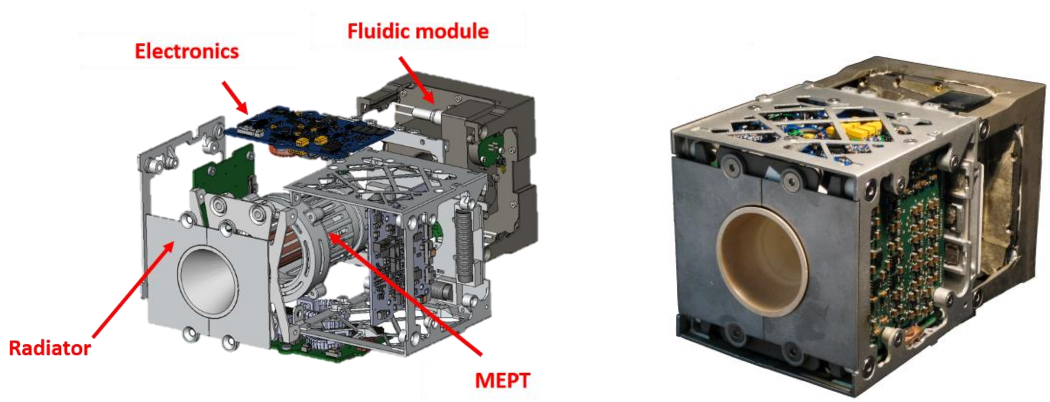

Figure 1: Rendering and picture of the REGULUS propulsion unit.

The use of iodine as an alternative to xenon has been considered for more than a decade. It was first proposed by Dressler, *et al.*, in 2000[10] and was later reinforced as viable by multiple studies and tests. One of the most noticeable achievement is the NASA's Iodine Satellite (iSAT)[9], a small satellite demonstration mission designed and built at

NASA's Marshall Spacecraft Center. The mission was initially planned for launch in fall 2017, then later moved to mid-2018, until in May 2017 the project was temporarily suspended to allow for the propulsion system to mature. Another important project is the Lunar iceCube[11] in which a 60-W RF Ion thruster is intended to propel a 6U CubeSat in a lunar observation mission, and the launch is planned for 2021.

This paper is intended to discuss the know-how acquired on iodine management, testing and simulation during the development of the REGULUS platform[12]. Specifically, REGULUS is a propulsion system micro and small satellites which integrates the Magnetically Enhanced Plasma Thruster (MEPT)[12] with the electronics, fluidic line, and structure in a 1.5 U envelope. The principal features of REGULUS when operated with iodine propellant are: (i) achievable thrust of 0.6 mN and specific impulse of 600 s with an input power of 50 W, (ii) total impulse up to 3000 Ns, or up to 11000 Ns enlarging the total envelope to 2, (iii) use of no space-grade qualified component in order to lower the costs. The latter is the most critical aspect of the entire design because of the difficulty of finding industrial components iodine-compatible. In particular, REGULUS will be fully qualified on ground by the end of the year, and its In-Orbit-Demonstration (IOD) is planned in Q2/Q3 2020 onboard UniSat-7.

The rest of the work is organized as follows: in Section II the MEPT thruster is characterized (both experimentally and numerically) whether propelled with xenon or iodine. In Section III the fluidic line is described and the results of functional tests are presented. Finally, in Section IV conclusions are drawn.

II.Comparison between iodine and xenon propellants

A. Experimental

The experimental evaluation of iodine as a propellant for the MEPT thruster was carried out in the electric propulsion facility of T4i/CISAS[13]. The objective of the test campaign was the comparison of the performance achieved by the MEPT employing both xenon and iodine, in order to support the validity of the latter as an alternative propellant.

1. *Set-up description*

The MEPT thruster was placed on T4i/CISAS's thrust balance[14], mounted inside a vacuum chamber of length 2 m and diameter 0.6 m. The thruster was connected to a dual gas feeding system (see Figure 2), allowing operation with either iodine vapor or xenon gas without changing the set-up. Xenon flow was provided by an MKS 1179B flow controller, connected to a pressurized reservoir, while iodine was provided by means of a prototype Iodine Feed System (IFS), composed of a heated tank and a manifold containing valves and flow control orifices (see Section III). Both the xenon flow controller and the IFS were connected to a T junction mounted on a vacuum gas feedthrough, leading to a 2 m long heated gas tube; the latter had a custom-built flexible extremity, approximately 0.5 m long, connected to the MEPT. The extremity is heated by means of a Ni-Cr heater wire, and is made of silicone tube in order to minimize the impact of the feeding line on the torsional stiffness of the thrust balance. All the gas feeding system sections interested by iodine flow were heated by means of wires or pads controlled by dedicated thermostats. The resultant uncertainty on the thrust measurements is in the order of ±15-20%. RF power was provided via a Spin HFPA-300 amplifier, driven by an HP8648B signal generator and connected to the MEPT thanks to a coaxial power line. RF power was monitored through custom-built vector voltages and current probes. The latter solution allows to estimate the RF power with an accuracy in the order of ±10%.

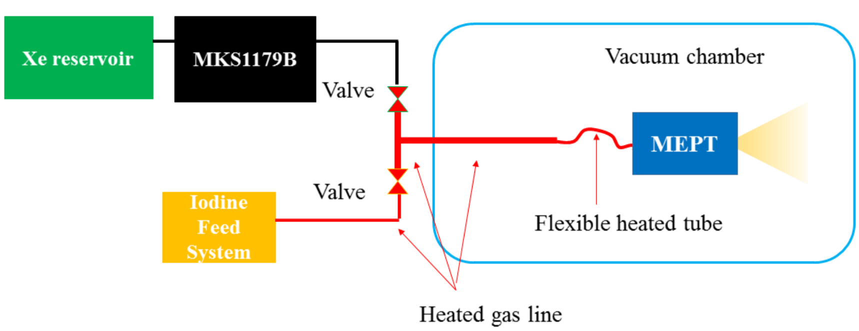

Figure 2: Schematic of the gas feeding line.

2. Iodine mass flow estimation

Iodine, especially when heated, is chemically aggressive towards many common materials, such as aluminum, stainless steels and many kinds of polymers, thus typically making impossible the use of systems and components normally employed with inert gases. This aspect prevented us to mount a mass flow measurement system downstream the iodine reservoir, to avoid damages connected to the presence of hot iodine vapors and thus distorted real time estimations of the instantaneous iodine mass flow. In order to circumvent this limitation, the following strategy has been devised:

- the mass flow of iodine is dictated by the geometry of the conduits and by the pressure and temperature of the vapor. Since the first element is fixed (at least in the time frame of interest) the latter two quantities determine the flow, hence, if we control them, we can regulate the flow. This is facilitated by the fact that, in the IFS, pressure is governed by temperature, since the mechanism of iodine vapor generation is sublimation;
- in order to calibrate such system, we have preemptively performed a series of tests with the IFS alone, in which we have measured the net mass loss of the system after a series of prolonged (1-2 hours) firings at stable pressure (and hence temperature) conditions. The tests were repeated ranging the pressure between 20-100 mbar. The mass loss was estimated by means of a high-sensitivity Kern PLS 1200-3A balance;
- we have then calculated the average iodine mass flow during each test as $\dot{m}_{avg} = \Delta m / t_f$, where t_f is the firing time and Δm is the net mass loss;
- we employed these data to construct a look-up table in which the average iodine mass flow is linked to the diameter of the control orifice and to pressure;
- during the thrust measurements, we have reproduced the set of orifice diameter and pressure/temperature granting an average mass flow rate near 0.1 mg/s. The latter was checked *a posteriori* by performing a net mass loss measurement after the firing.

This strategy allowed us to perform an estimation of the iodine mass flow employed in the tests, although at a reduced degree of accuracy (typically around ±10-15%) with respect to the MKS 1179B flow controller employed for Xenon (accuracy < 0.005 mg/s). The increased uncertainty was mainly due to the transients experienced by the IFS pressure at the beginning of the thruster firing, when there was a drop from the initial value in static conditions (no flow) to the lower value experienced in dynamic conditions.

3. Results

The results of the test campaign are summarized in Figure 4: the performance produced by iodine is only slightly inferior (10-20%) to the one achieved using xenon both in terms of thrust and specific impulse, although the latter, in the case of iodine, is characterized by a wider margin of error with respect to xenon, due to the increased uncertainty associated with the flow control method we adopted for iodine. Some test points are also characterized by a relatively high uncertainty levels on power measurements, connected to RF disturbances arisen during the tests. The validity of the iodine flow control system was testified by the relatively stable plasma discharge achieved during each firing, which exhibited substantially constant electrical parameters, as explained in detail in Section II.A.2

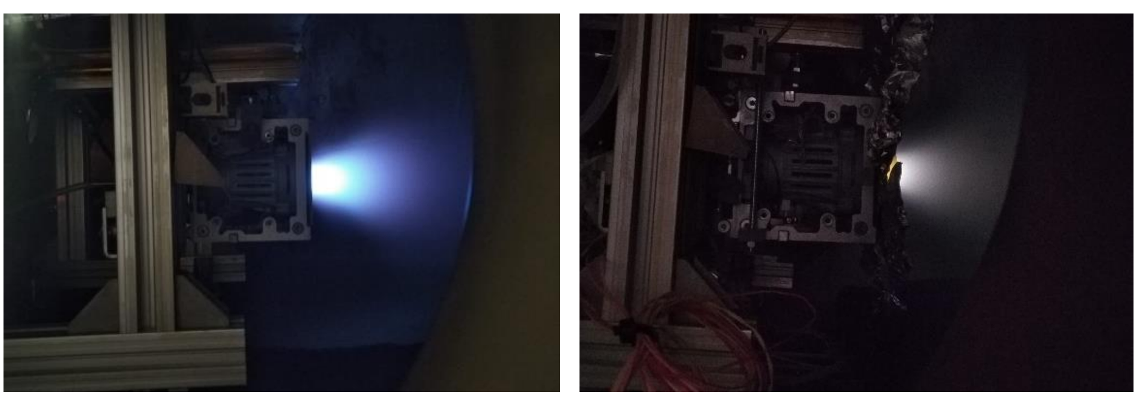

Figure 3: Picture of the MEPT thruster firing with xenon (left) and iodine (right) propellants.

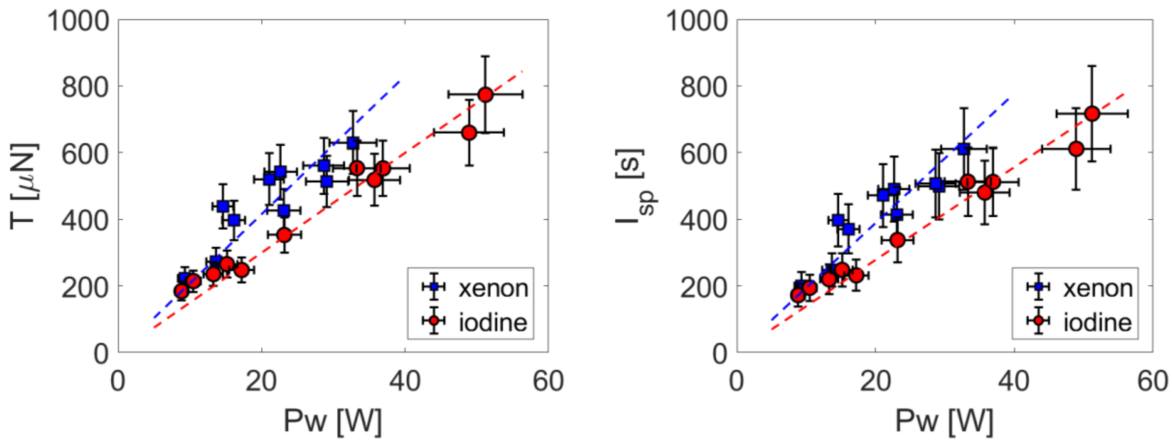

Figure 4. Thrust T and specific impulse I_{sp} produced by the MEPT as a function of the net power to thruster Pw. Two propellants analyzed, namely iodine and xenon.

B. Numerical

A numerical analysis has been performed in order to confirm that similar propulsive performances are achieved by MEPT whether operated with xenon or iodine propellant.

Specifically, the plume generated by MEPT has been simulated in the computation domain depicted in Figure 5. The REGULUS platform is assumed to be installed in a 6U CubeSat operating in LEO orbit. The calculation is performed with Spacecraft Plasma Interaction System (SPIS)[15] adopting a Particle-In-Cell (PIC) methodology[16]. The species simulated are electrons and ions (i) of the ambient plasma (e^- and O^+), along with (ii) those produced by the thruster operation (e^- and Xe^+ or I^+ depending on the case at hand). The ambient plasma is assumed non-collisional and characterized by the following properties[17]

- Electron temperature $T_e^A = 0.2$ eV, electron density $n_e^A = 10^{10}$ m^{-3}
- Ion temperature $T_O^A = 0.2$ eV, ion density $n_O^A = 10^{10}$ m^{-3}

At the same time, the plasma produced by the thruster is non-collisional too, and is injected into the domain through the surface labelled as "REGULUS outlet" in Figure 5. The following properties are assumed

- Ion temperature $T_i = 0.03$ eV, electron temperature $T_e = 3$ eV
- Ions and electrons injection flux $\Gamma = 5 \times 10^{20}$ m^{-2}
- Ions and electrons speed $V = 1500$ m/s

In particular, such a value of Γ derives from the assumption that all the 0.1 mg/s mass flow rate is ionized; moreover, for iodine propellant, no extra compounds (e.g., I^- and I_2^+) have been considered[8]. V has the value of the Bohm speed and, to be consistent with the Bohm criterion, we have assumed that the "REGULUS outlet" surface has a bias of +20 V in respect to the other surfaces of the satellite. The latter are considered metallic and connected at the satellite ground; an equivalent capacitance of 10^{-9} F has been assumed for the system. The principal simplification done in the present simulation is that the magneto-static field is null $B_0 = 0$ G in the computation domain. The latter has a spherical envelope of radius 0.5 m and is meshed in 175000 tetrahedra. Finally, in order to reduce the simulation time, the computational domain is rescaled of a factor $f = 50$ in respect to the physical system in accordance with the similarity laws reported in Taccogna, *et al.*[18] Nevertheless, in the following the results are depicted in the physical domain (i.e., not-rescaled), and not in the computational (i.e., rescaled).

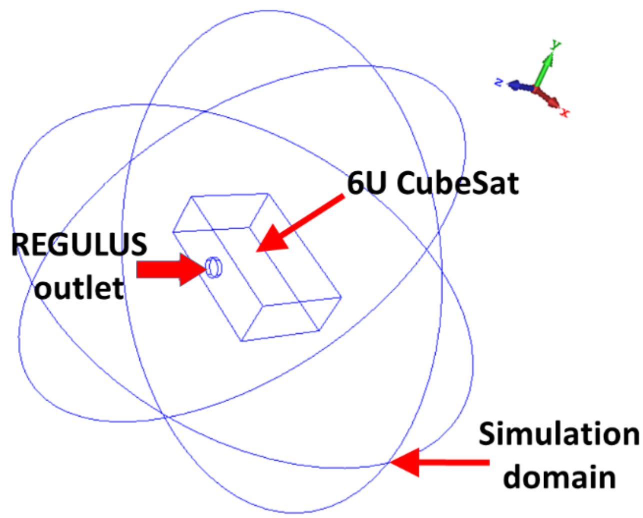

Figure 5: Schematic of the computational domain adopted in the simulation of the plasma plume generated by the REGULUS platform when installed in a 6U Cubesat.

We have considered the density and velocity distributions for the ions produced by the thruster. In the following, the latter have been compared whether MEPT is operated with xenon (see Figure 6) and iodine (see Figure 7) propellant; results are reported in the *x-z* symmetry plane (see Figure 5). When the thruster is operated with xenon the ions density distribution (see Figure 6a) is roughly symmetric and is peaked in correspondence of the thruster outlet (maximum value around 5×10^{17} m^{-3}). Moreover, the density decreases of orders of magnitude (up to 10^{12} m^{-3}) moving in the positive *z* direction, while it becomes negligible (roughly 10^{8} m^{-3}) in the negative *z* direction. The plume is significantly spread (almost 180° aperture), but this was expected since the absence of a confining magneto-static field. While expanding away from the thruster outlet, the ions speed (see Figure 6b) increases up to 15000 m/s, maintaining a roughly axisymmetric pattern. Exactly the same considerations can be done for ions density and velocity distributions when the thruster is operated with iodine propellant (see respectively Figure 7a and Figure 7b). Therefore, we can conclude that a qualitative agreement can be found between numerical and experimental results. In fact, the computation of similar propulsive performances is expected provided that almost identical results are obtained for ions parameters distributions. Anyhow, there is no point in calculating the thrust produced by the configurations at hand, provided that no magneto-static field has been considered. Moreover, in order to accomplish a proper comparison against experiments, the chemistry of xenon and iodine propellants should be followed in both the plume and the plasma source[19].

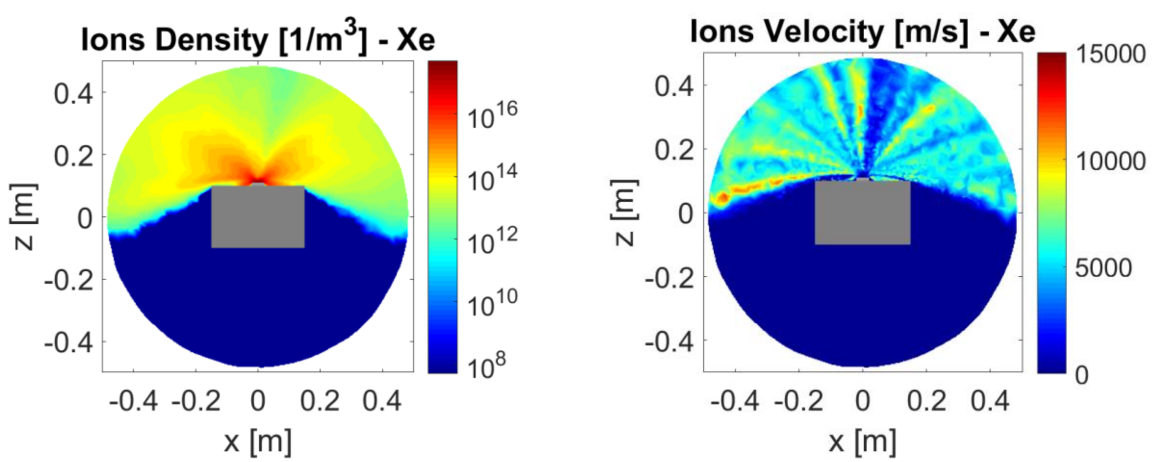

Figure 6: Computation performed with xenon propellant. Results projected in the x-z plane (see Figure 5). a) ion density map, b) ion velocity map as a function of the position in the computation domain.

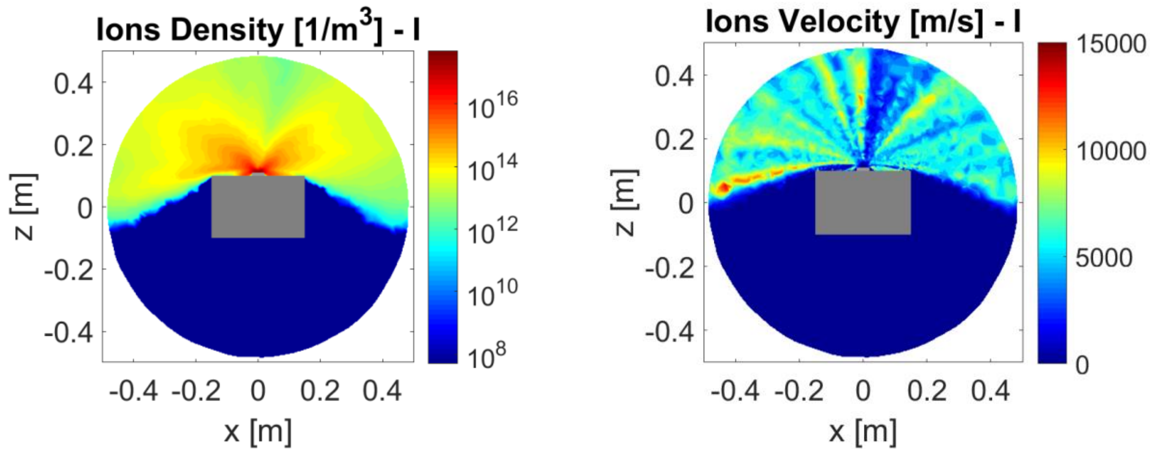

Figure 7: Computation performed with iodine propellant. Results projected in the x-z plane (see Figure 5). a) ion density map, b) ion velocity map as a function of the position in the computation domain.

Finally, it is worth noting that mild asymmetries can be noticed in the results presented. The latter can be attributed to the adoption of the PIC methodology coupled to an unstructured mesh, which intrinsically introduce noise in the results[16].

III.Fluidic line

A. Concept description

The fluidic subsystem of REGULUS (see Figure 8) has the objective to deliver a pre-determined mass flow rate when the motor is activated. The mass flow must be constant within a ±5% of nominal rate in order to obtain the required motor performance and efficiency throughout the lifespan. As shown in Figure 8, the fluidic subsystem is composed of a tank, a flow regulator, and an injector. The entire subsystem is fabricated with additive manufacturing technologies to comply with the strictest volume and mass budgets. All components that are wetted by the propellant (in both solid and gaseous state) are made of materials that present very high chemical compatibility with iodine, for instance Nickel superalloys such as Inconel and Hastelloy, whereas FKM, FFKM, and PTFE[20] sealing is used at the fluidic interfaces. The tank is filled with solid iodine propellant and can be designed bigger (or smaller) independently from the rest of the fluidic system. In REGULUS, the tank module has also a structural purpose: the four "legs" that stretch from the tank are used to fix the entire subsystem to the rest of the motor structure. When the tank is heated, the iodine in gaseous state enters the flow regulator module, which is the technologic core of the fluidic subsystem. It has the delicate duty of maintaining the mass flow rate constant, while the motor is thrusting by means of a pair of actuators and pressure and temperature transducers. The injector serves for two different purposes: the first is to increase the thermal resistance between the hot motor and the fluidic subsystem and the second is, naturally, to deliver the iodine inside the motor, where it is turned into plasma.

The entire subsystem is thermally controlled through a closed-loop control, using several temperature transducers and two thin-foil heaters. The thermal control is used to (i) sublimate the solid iodine into gas, (ii) perform a coarse control of the mass flow rate, (iii) to avoid the re-condensation of the iodine along the fluidic line, and (iv) to keep the temperature below the maximum threshold to avoid the electronic components from over-heating failures and to avoid the liquid state of the iodine ($T < 115°C$ everywhere). Finally, the fluidic subsystem has a connector that is used as electronic interface to the electronics.

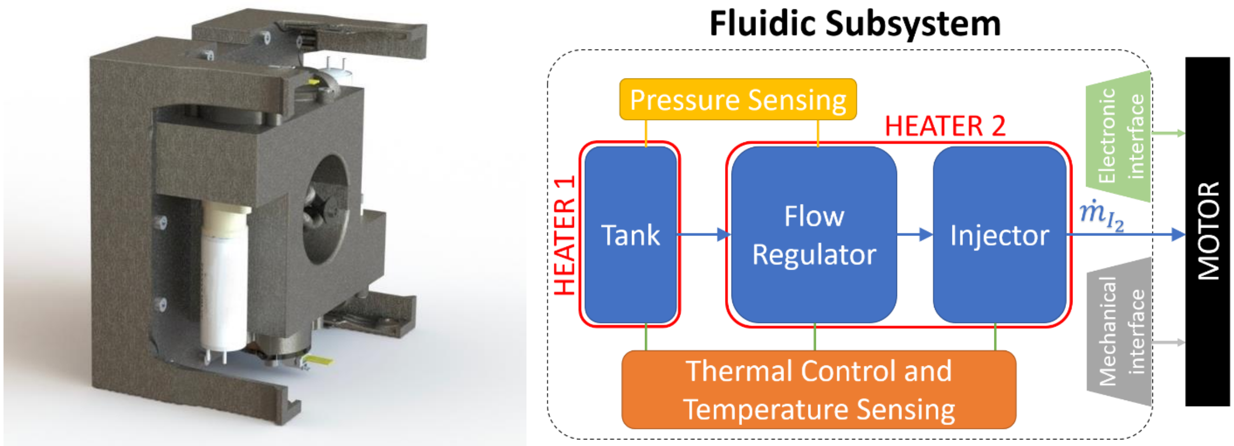

Figure 8:Picture and schematic of the fluidic line of REGULUS.

B. Functional tests

The fluidic line can be considered functionally verified if it provides the nominal mass flow rate with a ±5% accuracy. Given the control strategy described in Section III.A, this requirement is met if pressure and temperature upstream the injector are maintained at their nominal values with a tolerance of respectively ±3% and ±6%[21]. The latter condition must be ensured with a realistic thermal environment, characterized by mechanical interfaces, thermal paths and temperature oscillations which are representative of those likely encountered in orbit.

In order to perform these tests, we have adopted the following roadmap:

- We have developed a qualification model of the fluidic subsystem, representative of the system's physical form and functionality, although some of the components (for example the heaters) are commercial off-the-shelf (COTS), and not flight ones.
- We have tested the qualification fluidics in vacuum at ambient temperature (20-30 °C), verifying its correct behavior. Figure 9 shows an example of such tests, evidencing that both temperature and pressure are maintained within the tolerance; in particular pressure presents a remarkable stability (oscillations within ±1%). It is worth noting that the average mass flow rate during the test was estimated at 0.11 mg/s by means of a net mass loss measurement. This value differs within 10% to the nominal 0.1 mg/s, nonetheless this result is considered acceptable since, at the beginning of the firing, a peak in the mass flow due to transition from static to dynamic conditions is observed.
- We have developed a dedicated set-up for the simulation of a variable temperature environment, capable of providing between -40/+80 °C;
- We are currently testing the stability of the fluidics in a variable temperature environment, in order to check its ability to maintain a sufficiently stable pressure and temperature levels.

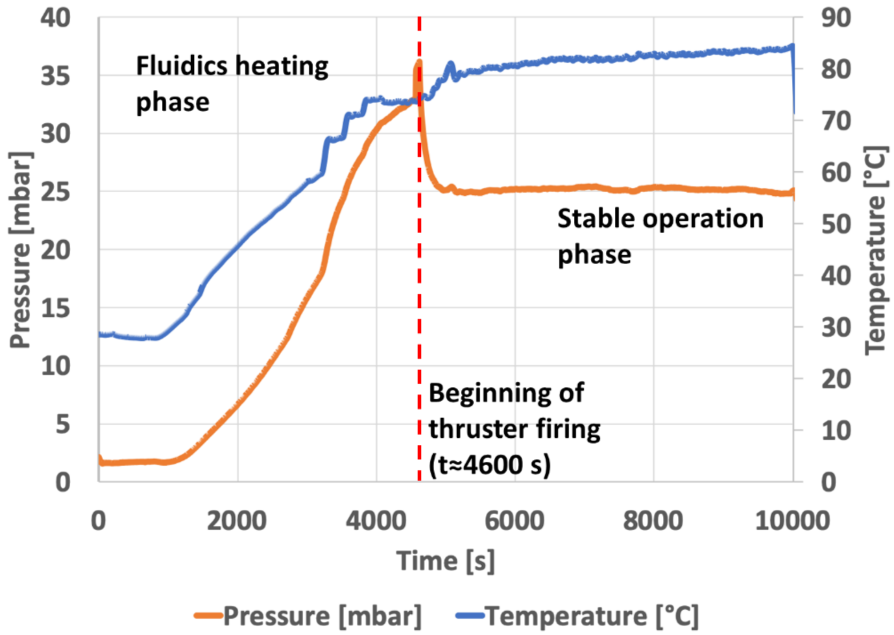

Figure 9: Pressure and temperature readings during heating and firing test.

IV.Conclusions

In this paper we have described the know-how on iodine handling, simulation and testing acquired during the design of the REGULUS platform. First, the MEPT has been tested with both xenon and iodine to verify that the propulsive performances achieved with these two propellants are comparable. Second, the plasma plume generated by REGULUS has been simulated whether produced by xenon or iodine; numerical results have also confirmed that the performances achievable with these two propellants are comparable. Finally, the design of the fluidic line of REGULUS has been outlined along with the description of the results of functional tests. Specifically, it has been observed that the requirements on the stability of pressure and temperature upstream the injection are met if the fluidic line is operated in vacuum and at ambient temperature (20-30 °C). Further tests to confirm these results in a variable temperature environment (-40°C/+80°C) are currently ongoing.

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