Progress on the Development of an Iodine-fed Hall Effect Thruster

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Abstract: The paper deals with the results of an ongoing activity carried out by the Department of Civil and Industrial Engineering (DICI) and the Department of Chemistry and Industrial Chemistry (DCCI) of the University of Pisa (UniPi) in collaboration with SITAEL SpA, aimed at the development of technologies for Iodine-fed Hall Effect Thrusters. A feeding system architecture is described and the results of reduced order numerical models of the feeding system are illustrated, in both steady and unsteady state conditions. An activity for iodine interaction with materials is in progress. The experimental setups for material characterization tests are described. Material samples can be heated from room temperature up to 300 °C and exposed to iodine at high (soakage test) or low (flow test) concentration, simulating the condition at which the materials will undergo in the propulsion system, in the vacuum facility or in the spacecraft. Calibration and preliminary soakage test results are illustrated. On the thruster unit side, the candidate thruster and cathode are presented along with the modifications needed to operate them on iodine. Finally, a description of the foreseen test campaign and associated facilities is presented.

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Nomenclature

Dt = thermal throttle diameter
k_{tt} = thermal throttle operative constant
L = thermal throttle length
$\dot{m}$ = iodine mass flow rate
P_{tank} = iodine storage pressure
T_{th} = thermal throttle temperature

I. Introduction

Currently, all satellite platforms equipped with Hall and ion thrusters run on xenon as propellant. Xenon has several useful properties for Electric Propulsion (EP) applications, such as high atomic mass, low first ionization energy and a large ionization cross section, which implies an easier generation of the plasma with respect to other options[1]. However, given its increasing application in several high technology industries, its availability and price tends to fluctuate substantially, burdening the development of a space project. An additional drawback is that its storage conditions at supercritical state require a high-pressure tank (of about 150-200 bar)[2], a pressure regulation system and a distribution system to supply the gas at low pressure into the thruster discharge chamber. Being stored in a supercritical state complicates the load operations and security issues for people involved, limiting also the applicability of this thruster technology in smaller missions, where restrictions on pressurized systems can be a major showstopper. As a consequence, alternative propellants have been investigated, such as condensable metals (i.e. Mg, Zn, Bi, Li) and a non-metallic condensable propellant, i.e. iodine[1-4]. Eventually, a successful alternative propellant will allow both reducing the utilization cost and increase the envelope of application of EP technologies. Several conditions make iodine a good candidate for replacing xenon in EP applications[1]. Its atomic mass of 126.9 amu is close to the 131.3 of xenon and it has similar ionization properties on a monoatomic gaseous state. Iodine allows for solid storage at ambient pressure and below 100 ºC at a density of 4.9 g/cm^3 (three times the density of supercritical xenon at 200 bar), with an impact on the operational and performance issues (simpler loading and handling procedures, longer shelf-life, higher specific impulse density, etc.). Finally, when comparing cost and availability, iodine presents several advantages with respect to xenon, having a cost ten times lower and almost an unlimited availability in the high purity required. The drawback for iodine is its chemical reactivity. Iodine is a halogen and, in spite of being the least reactive of this group, it still has an important effect on numerous materials of interest for space applications. This feature imposes new constraints on the selection of the materials used in the propulsion system and poses significant qualification issues for iodine adoption in space. However, there is little and sparse information available in the literature referring to how materials used in space behave in the presence of iodine.

The paper presents the progress of the I2HET project carried out by the University of Pisa (UniPi) and Sitael S.p.A, in the framework of a TRP ESA program. Section II describes the developments related to an iodine feeding system for Hall thrusters up to 500 W and its associated technologies, Section III deals with research on iodine-material interactions and Section IV presents an overview on the development status of the project as well as Sitael efforts in development of a novel low-power HET.

II. Iodine Feeding Systems Development

Plasma thrusters generally operate with small mass flow rates (in the order of the mg/s) and propellant at low pressures in the injection system (e.g. the anode in the case of Hall thrusters, at about 10 kPa). Moreover, high storage densities are required to reduce the volume and weight of the stored propellant and its tank.

When the propellant is a noble gas supercritical, pressures (between 150 and 350 bars) are used to achieve high storage densities. This high storage pressure needs to be reduced to deliver the propellant to the thruster unit (i.e. thruster and cathode). In order to have a stable behaviour and good performance, the thruster needs the mass flow rate to be controlled quite accurately.

To comply with the high storage densities, accurate mass flow rate and low injection pressures, typical xenon feeding systems[6,7] consist of three basic subsystems: a propellant storage assembly, a pressure regulator and a mass flow rate controller. The first two can be categorized as the high pressure stages and the third one as the low pressure stage. These components are accompanied by their respective instrumentation (pressure and temperature sensors) and the necessary latch valves to interrupt the flow of propellant when the thruster is turned off or to assure the isolation of certain components in case of malfunctions. The basic schematics of supercritical feeding systems are summarized in Fig. 1.

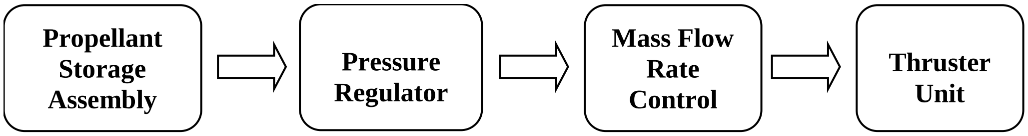


Figure 1. Propellant Feeding System basic architecture.

The case is different for iodine, which is stored in solid state and then is sublimated to convey the vapor to the thruster. As the propellant is sublimated inside the tank, there will be equilibrium of phases inside it; hence the state of the system (pressure and temperature) will be located along the Clausius-Clapeyron curve. It is important to remark that the presence of liquid iodine inside the tank is an unwanted effect, so it is desirable that the system works always below the triple point of iodine. As illustrated in Fig. 2, where the phase diagram of pure iodine is represented, avoiding the presence of liquid iodine means that the system will always operate at pressures below 12 kPa and 386 K, largely reducing the structural requirements of the system. Another effect of having equilibrium of phases inside the tank is that the pressure inside the tank can be regulated through the control of its temperature. This has several consequences at system level: 1) the system no longer has a high pressure stage; 2) the pressure at which the vapor is delivered to the thruster can be controlled through the temperature at which it is generated. This means that an active pressure regulation system for the flow is no longer necessary, as the pressure at which the propellant is fed can be solely controlled through the thermal control system of the storage assembly. As a result, the first two elements of the system represented in Fig. 1 are combined, giving place to a much simpler architecture, depicted in Fig. 3.

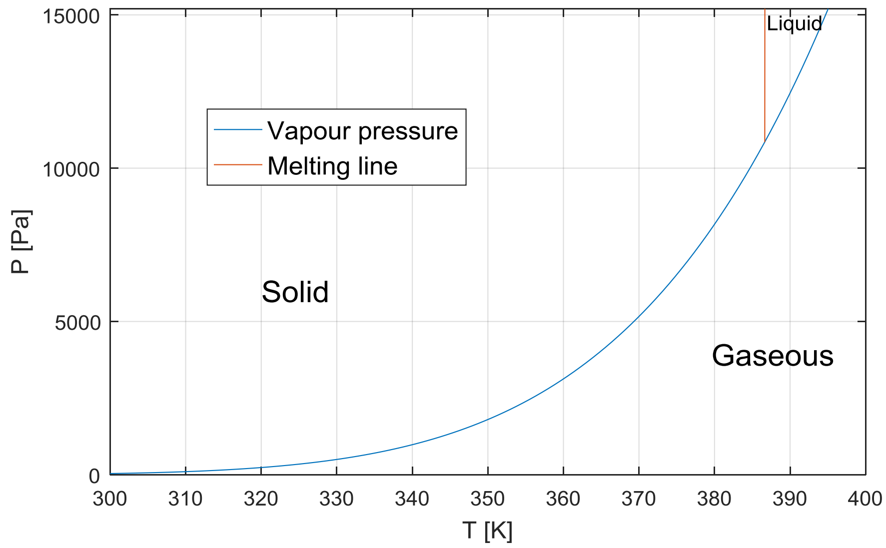


Figure 2. Phase diagram of pure diatomic iodine.

Past works on the development of iodine feeding system architectures for electric propulsion are reported in Refs. 1, 8 and 9. In the architecture described in these references the whole tank is maintained at a certain temperature and pressure, so that a good isolation of the system and a significant amount of heating power for starting the system is required. As a consequence, due to the significant thermal inertia of the tank, the fast controllability of the sublimation pressure through the temperature might be reduced.

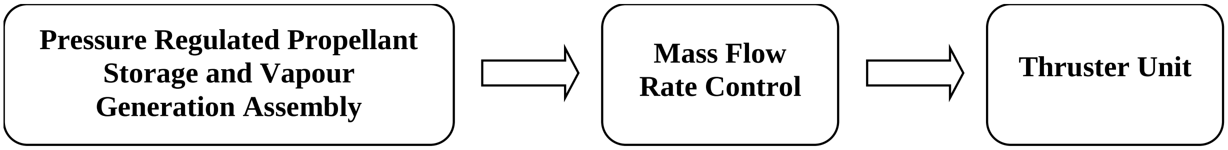


Figure 3. Iodine Propellant Feeding System basic architecture.

A. UniPi Iodine Feeding System

UniPi is currently studying different architectures of iodine feeding systems. The architecture herein proposed is shown in Fig. 4, and described in Ref. 5 with more detail. It consists of a slender body containing the solid iodine. The heat for vaporizing the iodine is supplied through one of the bases of the cylinder by the sublimator assembly. This assembly is a cup-shaped metallic body externally heated by electric resistors, whose temperature is measured and controlled. Internally the assembly has a metallic body (called filter), which is in close contact with the solid propellant. The filter function is to keep the propellant in place and to convey the heat directly to the solid-vapor interphase. A piston, pushed by a spring, provides the contact of the iodine against the filter. The rest of the feeding system consists of an on-off valve and a thermal throttle for the mass flow control.

The gross regulation of the mass flow rate is made by controlling the sublimator temperature, and the fine control by means of the thermal throttle. The main features of this concept are:

- Low power requirements, as only a small surface of the iodine is heated;
- Absence of important thermal control issues, given that only a small part of the system is at high temperature (and can be easily insulated);
- Short response time, since the involved thermal inertia are small;
- Requirement of control only on the temperature of the system, simplifying diagnostics and control;
- Reliability, as only one active component (the valve) is present;
- Good throttleability;
- Scalability.

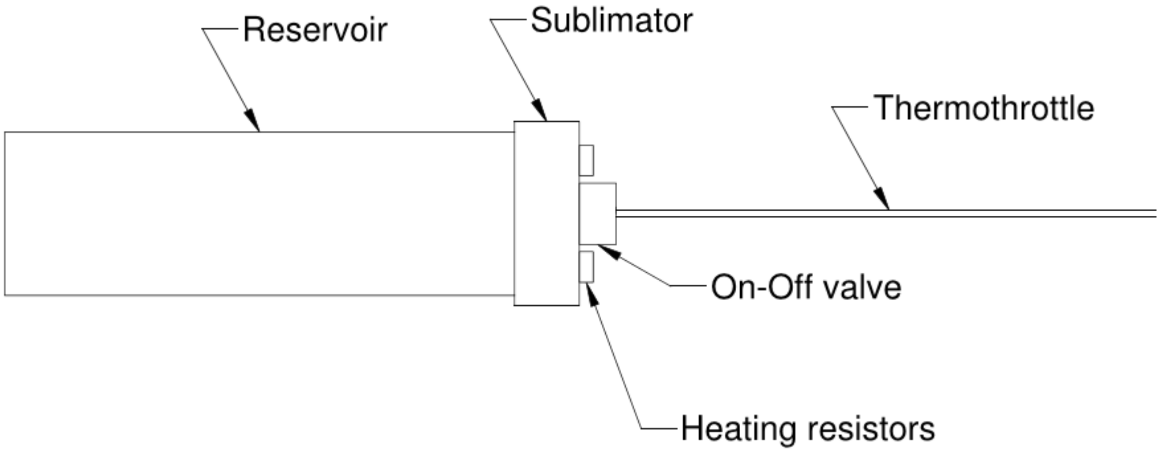


Figure 4. Proposed feeding system scheme.

B. Thermal Throttle Typologies and Modelling

The thermal throttle is the selected strategy for the fine control of the mass flow rate. It consists of a small diameter pipe, which introduces a pressure loss due to viscous effects and a sonic section at its exit. As the viscosity of the vapor changes with the temperature, the temperature of the pipe is controlled to change the pressure loss along the pipe and hence the mass flow rate. The choking of the flow can be obtained either by the presence of a reduced section at the pipe exit or only by the heat addition and viscous friction with the walls, without any area change. The constant area case requires pipes with smaller diameters, to keep the pipe as short as possible. Nevertheless, the smaller the diameter , the higher the sensitivity of the system blockage to impurities.

The authors developed a model of vapor generation and feeding process[5] with a thermal throttle having a restricted sonic section at the end. The model has been modified for analyzing thermal throttles of smaller diameter without a restricted section. As explained in Ref. 5, the model considers the sublimation process in the tank, the passing through the filter and the sublimator body, the pressure loss induced by the latch valve and the effect of the thermal throttle.

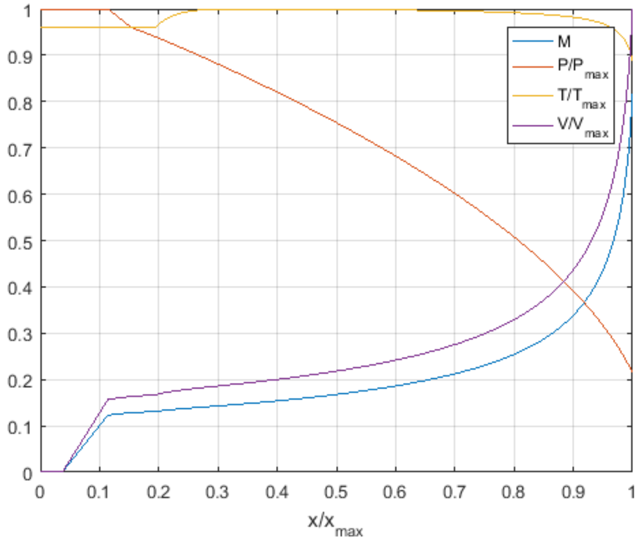


Figure 5. Normalized properties distribution along the feeding system.

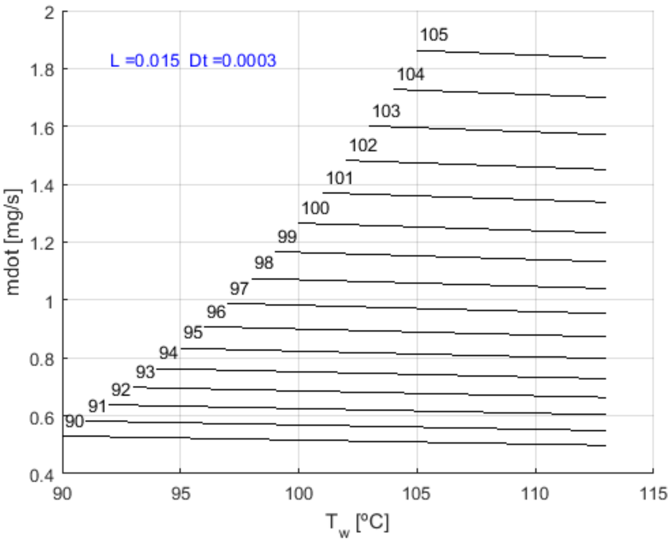


Figure 6. Performance map of the feeding system (mass flow rate vs. thermal throttle temperature, for different sublimator temperatures).

The thermal throttle modelling generally assumes a Hagen-Poiseuille flow with corrective coefficients that keeps into account the changes in density along the pipe[1, 4]. As Ref. 5 explains, the model developed in the frame of the present project makes use of the Shapiro-Hawthorne method[11] for implementing the 1D thermal fluid equations of the gas flow along the pipe. Figure 5 presents a typical output of the code, showing the distribution of pressure, temperature and velocity (each one normalized with respect to their maximum value), and the Mach number.

This model allows for obtaining performance maps of the iodine feeding system for different configurations, such as the one reported in Fig. 6. The performance map of the depicted case corresponds to a feeding system equipped with a thermal throttle of constant diameter (without restricted section).

The mass flow rate, $\dot{m}$, can be related to the tank pressure, P_{tank}, and thermal throttle temperature, T_{th}, through Eq. (1) as follows:

$$\dot{m} = k_{tt}\frac{P_{tank}}{\sqrt{T_{th}}} \qquad (1)$$

where the constant k_{tt}, which characterizes the behavior of the thermal throttle for a certain configuration (pipe length, internal diameter and throat diameter, if present), can be calculated from the results used to build the map in Fig. 6. This constant is a weak function of the gas pressure in the sublimator and of the temperature of the thermal throttle, so the one corresponding to the nominal condition is chosen as a fixed value used for selecting the thermal throttle design and for the unsteady analysis presented in the following section.

C. Non-Stationary Model

The need to understand the behavior of the system during transient conditions, (i.e. during the heating of the sublimator, the opening of the valve and the throttle up and down) led to the implementation of a simplified non-stationary thermal-fluid model of the sublimator, the filter and the iodine (both solid and vapor). The model considers the heat exchange between the different elements, i.e. between the filter and the solid iodine on the one hand, and between the sublimator body and the iodine vapor on the other. The thermal throttle effect on the pressure and on the mass continuity inside the tank is considered by means of Eq. (1).

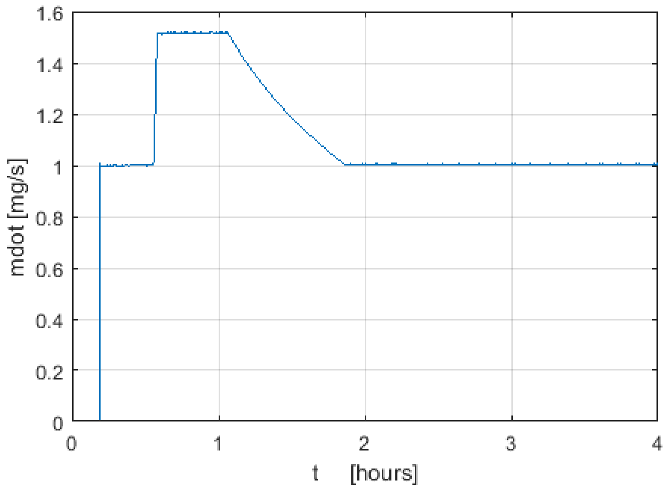


Figure 7. Mass flow rate response of the feeding system.

The model allows for verifying the following critical quantities:

- the minimum power required to sustain a certain mass flow rate;
- the duration of the valve-opening transient;
- the expected throttling transient times.

A typical output of the model is presented in Fig. 7. It corresponds to a case with the following operative parameters:

- initial conditions at room temperature;
- maximum heating power on the sublimator for the startup of the system of 10 W;
- nominal mass flow rate of 1 mg/s;
- throttling up to 1.5 mg/s at 40 minutes of operation;
- throttling down to 1 mg/s again at about 1 hour of operation;
- steady state operation at 1 mg/s up to 4 hours after startup.

III.Iodine-Material Interaction

The introduction of iodine as a propellant for electric thrusters gives place to a new set of challenges with respect to materials interaction. Being a halogen, iodine tends to react in different ways with the materials present in the propulsion system, the test and diagnostics facilities and the spacecraft. A literature survey[9, 10] highlighted that data on the interactions of iodine with materials of interest for space applications barely exists, and often are not complete, or the test conditions are not representative. This evidence imposed the need to develop the capability of performing tests on materials exposed to iodine at various conditions in terms of temperature pressure and state (be it neutral or plasma in a molecular or atomic form).

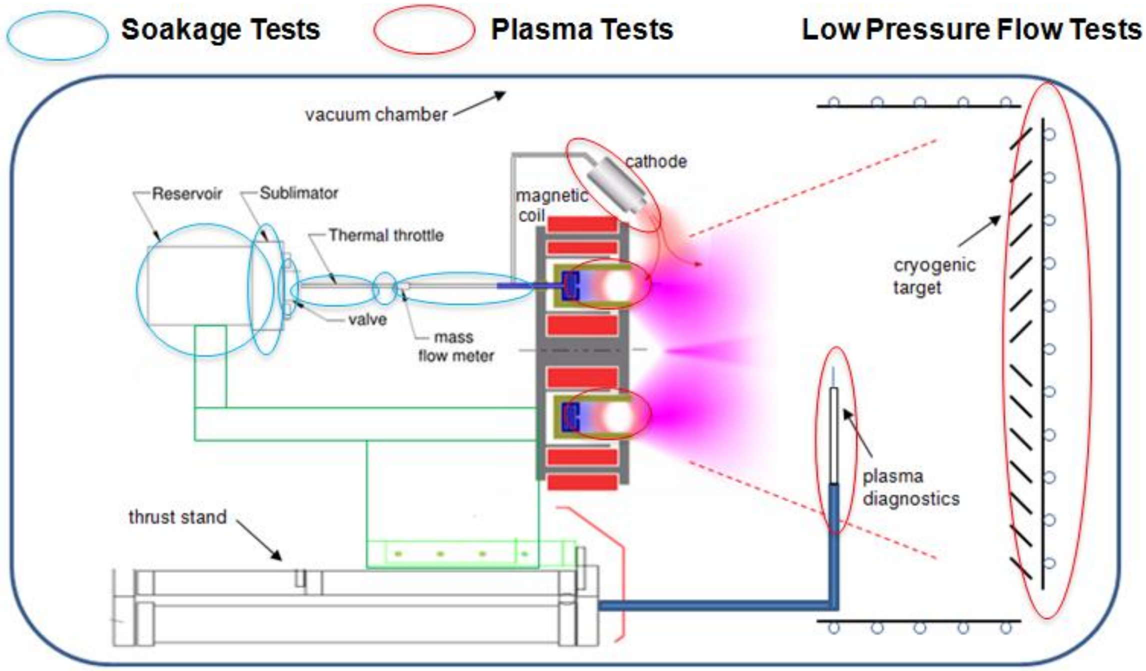


Figure 8. Tests for materials involved in the experiment.

The tests have the aim to verify materials performance in the conditions they will encounter during thruster operations. It is important to study iodine influence on materials in conditions as close as possible to the operative ones, mostly without oxygen and moisture. Despite the apparently favourable storage conditions of iodine with respect to gaseous propellants, its chemical properties require that materials undergo severe conditions such as a full immersion in iodine vapors. Various approaches have been considered, based on the iodine conditions that the different components will encounter during the operative life, as illustrated in Fig. 8. The two main considered approaches are to expose materials in static and dynamic procedures. The first one involves soakage tests representing the most severe conditions, where the materials will be immersed in iodine saturated vapors and the samples will be heated from ambient temperature up to at least 300°C. In the second approach, the test materials will be immersed in a low pressure iodine vapor flow. The third type of tests envisages placing the materials as targets in front of iodine plasma. These preliminary tests are fundamental to characterize the material corrosion behavior.

A. Soakage Test

Iodine soakage tests have been conceived with the aim to expose materials to gaseous iodine, as occurs in the propellant feeding system, the piping and the anode inner surfaces. Consequently, a test facility has been set up to perform the exposure of material samples to a static iodine saturated vapor. The tests are carried out in absence of oxygen and water, to avoid any reaction or formation of iodine compounds. Every part of the test facility is made of materials with mechanical properties that remain unaltered before, during and after the work conditions. Before testing, the samples are mechanically or chemically treated to remove any traces of impurities (e.g. grease) and oxides (in case of metal samples). Sample handling and storage before and after test is performed assuring no contaminations that may jeopardize the experiment. A heating system allows the sample temperature for being regulated and maintained from room temperature to 300 °C +/- 1°C, for the desired exposure time. The schematic of the soakage test facility is shown in Fig. 9. Temperature calibrations have been carried out, to correlate the sample temperature with the heater temperature, as illustrated in Figs. 10 and 11. Preliminary tests on stainless steel samples have been carried out, as illustrated in Figs. 12 and 13.

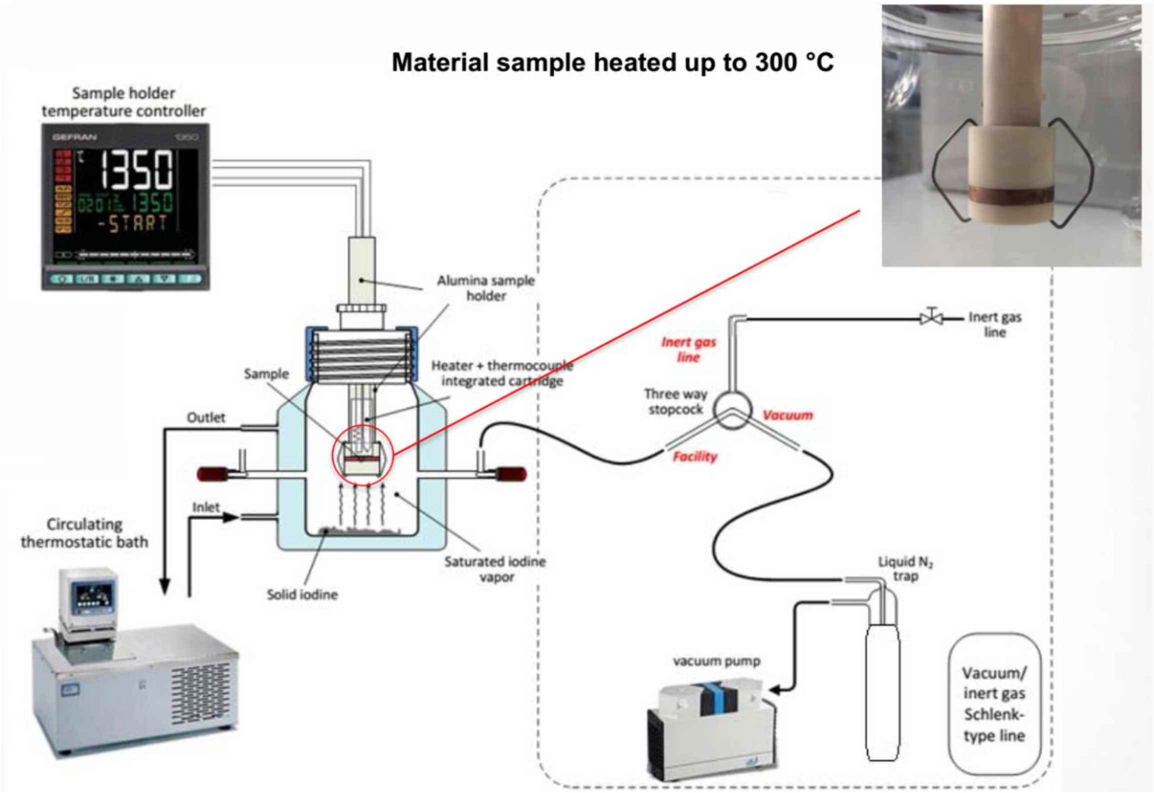


Figure 9. Soakage test setup schematic.

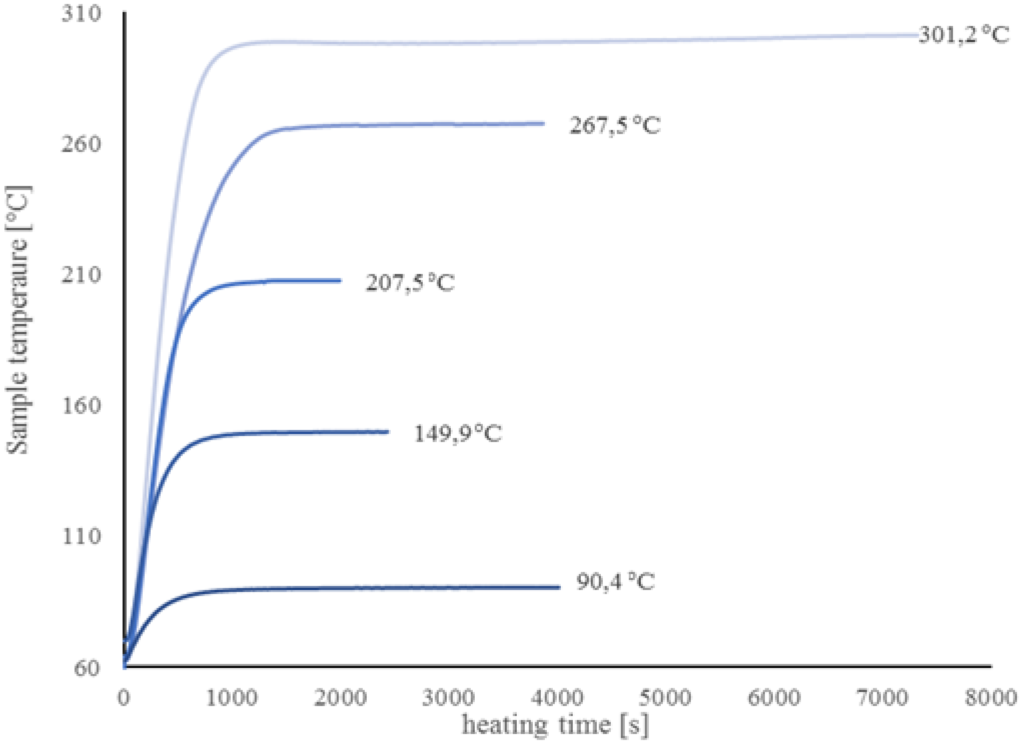


Figure 10. Temperature trend measured on the sample during heating at several exposure temperatures.

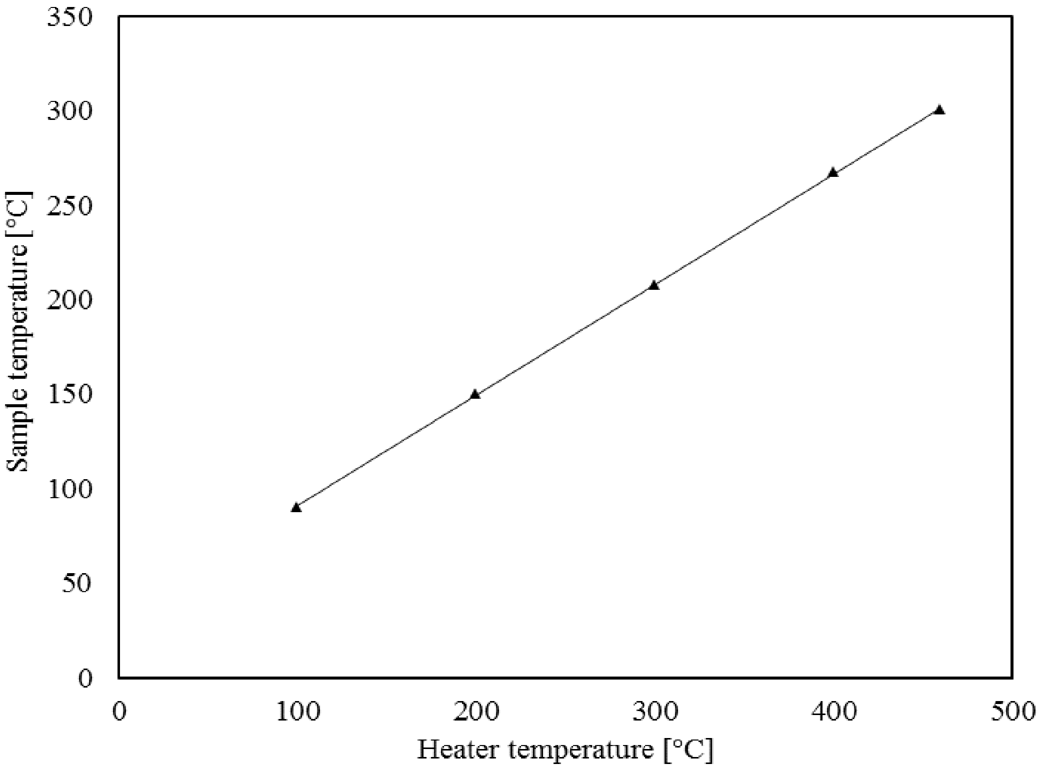


Figure 11. **Sample temperature vs. heater temperature.**

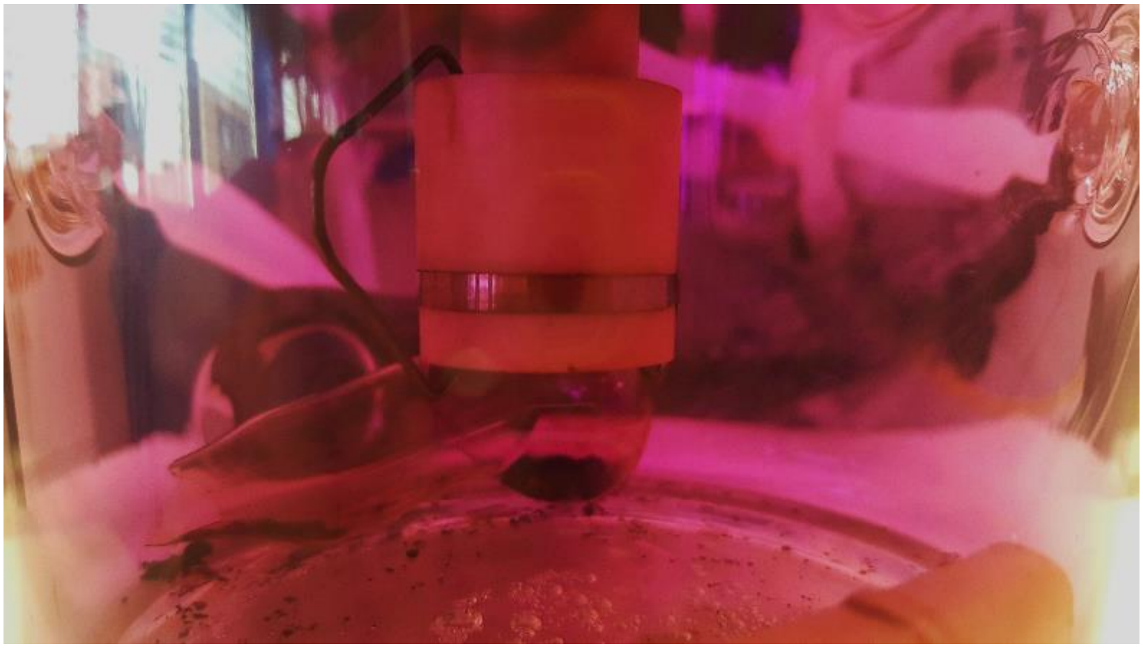


Figure 12. View of a steel sample during a soakage test.

a) **b)**

Figure 13. Two different stainless steel samples after a soakage test (∅24mm, thickness 4mm); a) Aisi-304, b) Aisi-316

B. Flow Test

In this kind of test, the materials undergo less severe exposure conditions. The flow test is a dynamic test for quantifying iodine interaction with materials. The test setup is a partial modification of the soakage test facility, as illustrated in Fig. 14. The material samples are wetted by a flow consisting of a mixture of an inert (nitrogen) gas and iodine vapor at a concentration similar to the one found during thruster test in vacuum. To collect comparable data, the flow test is carried out on material samples of the same dimensions used for iodine soakage test. Again, the tests are carried out in absence of oxygen and water to avoid any reaction or formation of any iodine compounds. The heating system allows for regulating and maintaining the sample temperature from room temperature to 100 °C +/- 1°C, for the desired exposure time.

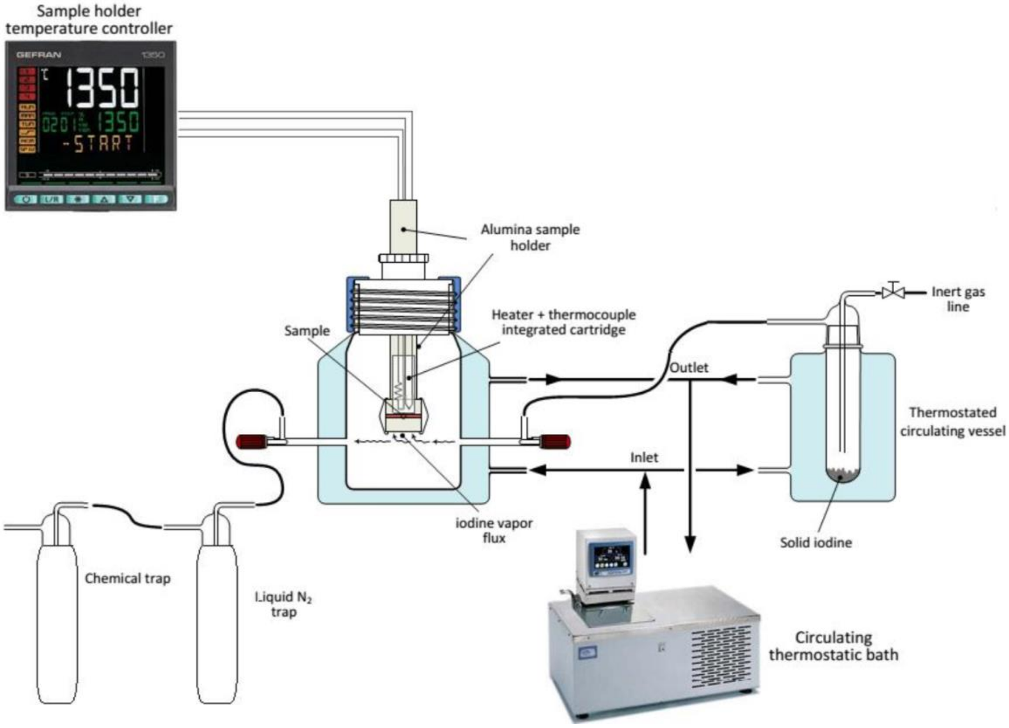


Figure 14. Flow test setup schematic.

IV. Iodine-fed Propulsion Subsystem Development

In the I2HET project we are focusing on the possibility to build a propulsion system that uses iodine as propellant, stored in solid phase. Other authors reported successful experiences firing Hall Effect thrusters with iodine[1-4]; however, few information is available in literature, e.g. in terms of thruster performance and compatible materials.

The main goal of the I2HET project is the successful integration of an original iodine feeding system with a new low-power HET derived from the Sitael HT100, the iHT100. The HT100 is a low-power (<300 W) thruster designed to be installed on small and mini satellites[14]. The use of iodine on this class of low-power Hall Effect thrusters results in compact and lightweight propulsion systems. These elements make the iHT100 an interesting option for satellite up to 200 kg.

Thanks to its physical and chemical characteristics, iodine used as HET propellant shows a comparable behavior with some advantages in terms of divergence of the ion beam, specific impulse and efficiency with respect to xenon. This opens the way towards new applications and new mission scenarios.

The iHT100 will be one of the smallest Hall Effect thrusters ever tested with iodine and the first in Europe. The propulsion system will be completed with a breadboard power processing unit and the Sitael hollow cathode HC1 (xenon).

A. Thruster

The HT100 is a low power EP thruster with a nominal operating power of 175 W, shown in Fig. 16. It can be operated in a power range between 100 and 300 W, it has efficiency peak of about 40% and the specific impulse is in the range between 900 and 1300 s. The HT100 is a device capable of providing thrust levels in the 4-15 mN range. Its design is based on permanent magnets and the total mass is lower than 450 g.

The HT100 design has been analyzed in order to identify the most critical components in terms of iodine exposition during the thruster operating phase. The attention was focused on all the components which are in contact with iodine during the thruster operating phase (purple colored in Fig. 15):

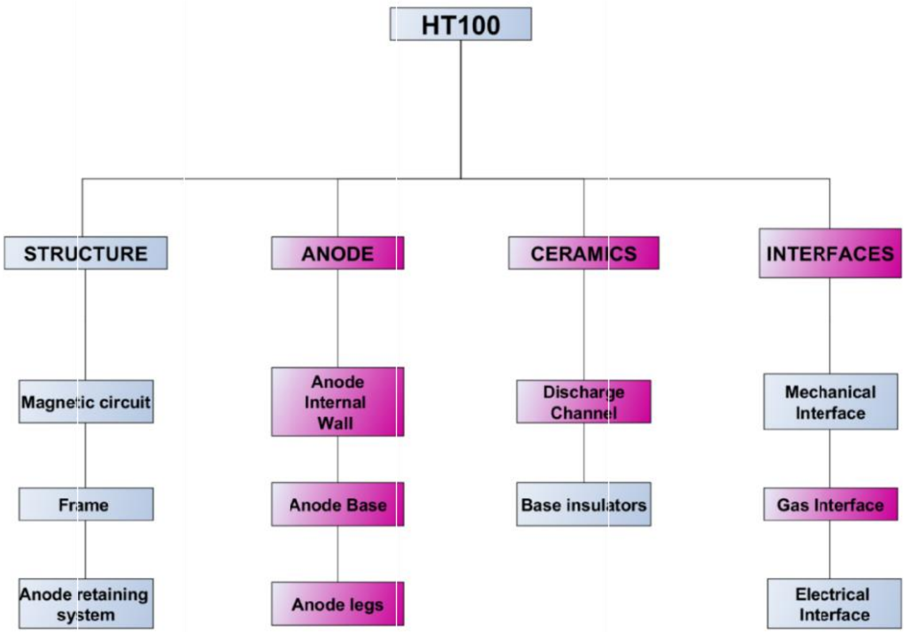


Figure 15. HT100 Product Tree

The iHT100 development efforts are devoted to design a highly reliable thruster with high performance considering the xenon HT100 as reference and a fault-free total life-time of about 2000 h. The nominal operating point of the thruster is slightly lower than 200 W with a mass flow rate of about 0.7 mg/s (Xe). The same mass flow rate and power level is expected when moving to iodine as propellant.

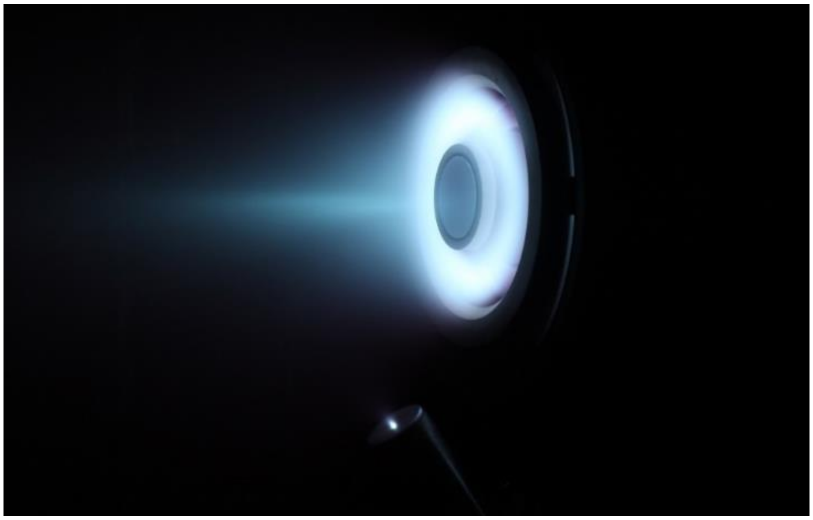


Figure 16. Magnetically Shielded HT100 firing at SITAEL premises

B. Cathode

The Sitael HC1 is a hollow cathode featuring a lanthanum hexaboride (LaB_6) emitter, which provides electrons via thermionic effect. HC1 is shown in Fig. 17, before and during a stand-alone characterization campaign. The cathode assembly includes a heater, used to increase the emitter temperature to thermionic emission values before applying the keeper voltage to start the discharge[12]. The cathode specifications can be summarized as follows:

- Discharge current 0.3 - 1 A
- Discharge power ≤30 W

- Heater power ≤50 W
- Ignition voltage ≤300 V
- Mass flow rate (Xe) 0.08 - 0.5 mg/s
- Lifetime ≥4000 h
- Mass (without cables) ≤50 g.

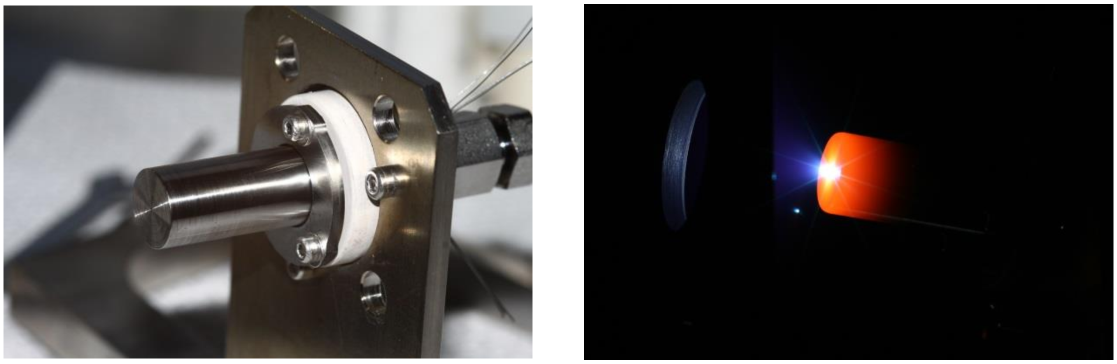
In the framework of the I2HET program the cathode will be fed with xenon. Similar tests where a xenon-fed cathode (with porous tungsten BaO-based or cerium hexaboride emitters) was coupled with an iodine-fueled thruster are described in the literature[13]. An assessment of the cathode compatibility with iodine has been performed as well, and a tailoring of the design is ongoing to minimize the effect of iodine reactiveness on the cathode lifetime. The operation of the cathode with iodine would allow for avoiding the complexity of a dual-propellant system, and preliminary tests demonstrated a successful operation of LaB_6 cathodes with iodine, as found in the literature[1].

Figure 18. Sitael LFF Simulator.

C. Test Campaign

A short endurance test of the iodine fed Sitael iHT100 coupled with the Sitael HC1 cathode (operated with xenon) and the UniPi iodine feeding system will be performed in Q3 2018 to validate the design effectiveness.

The test will be performed at Sitael, Pisa premises, in the IV-9 LFF vacuum chamber, shown in Fig. 18. IV-9 consists of a vessel of about 2.5 m x 1.2 m of diameter. A smaller chamber of about 1 x 0.4 m of diameter is connected by a gate valve to the main chamber. The ultimate pressure should be lower than 10^{-8} mbar, whereas the maintained background pressure during thruster operation should be below 10^{-5} mbar to guarantee acceptable thruster performance. Sitael is working on the upgrade of the facility in order to improve its iodine compatibility and performance, adding cold heads, cryogenic screens and cold traps.



a) b)

Figure 17. a) HC1 assembled before the characterization. b) HC1 operating in triode mode with keeper and anode.

A complete characterization of iHT100 performance will be carried out using a thrust balance and a diagnostic system based on Langmuir probes. The obtained performance will then be compared with the one measured using xenon as propellant (see Table 1).

First, a preliminary characterization of the thruster with xenon as propellant will be performed. Then, the test will be switched to iodine. Periodic thrust measurements will be carried out during the test, to assess the degradation of the thruster performance due to operation on iodine.

Performance	Value
Thrust Level	4-15 mN
Specific Impulse	900-1300s
Total Impulse	>60 kNs per thruster
On-Off cycles	>2000 per thruster

Table 1. HT100 performance

V.Conclusions and future developments

Progresses on the different activities related to the development of an iodine-fed electric propulsion system have been presented. The results on the upgraded steady model of the feeding system demonstrated the importance of the thermal throttle design in the architecture of the system. The outcomes of an unsteady thermal analysis seem to demonstrate that the selected architecture exhibits adequate responsiveness and power consumption.

On the materials compatibility side, given the lack of useful available data for designing the systems, an experimental approach has been chosen. The different experimental tests have been illustrated and the associated facilities have been described. The tests are intended to represent as close as possible the environment in which each material will interact with iodine during the thruster operation, controlling iodine concentration and sample temperature in absence of oxygen and moisture. Calibration tests demonstrated that the sample temperature can be set up to 300 ºC with good accuracy.

The selected thruster and cathode have been presented together with their xenon nominal behavior. A description on how the systems will be adapted to ensure a reliable operation on iodine has been made. An outline of the test facilities and diagnostics selected for the experimental campaign, including thrust stands and plasma diagnostics has been illustrated.

From the programmatic point of view, it is remarked that the I2HET Requirement Review at system level has been successfully completed and the design activities of the thruster unit and feeding system are ongoing. Parallel UniPi efforts are devoted to test the compatibility of iodine with a number of different materials. The Design Review of the project is scheduled for the end of 2017, whereas the test campaign will begin in the third quarter of 2018.

Acknowledgments

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