Development and Testing of the NPT30-I2 Iodine Ion Thruster

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Abstract: This paper presents the development and first tests results of the NPT30-I2 iodine ion thruster. The NPT30-I2 is a 1.5 U fully integrated and intelligent propulsion system using a gridded ion thruster to generate thrust. The system can provide 1.1 mN of thrust and a total impulse of up to 4000 N·s. This paper presents the current development stage as well as the results of the different ground tests. This include the specific experiments performed for predicting the corrosion and deposition of iodine on different parts of the hardware, thermal testing and the first results of the experimental testing of the plasma ignition of the NPT30-I2.

Nomenclature

A	=	Amplitude of oscillation
A^*	=	Area at the throat
C	=	Correlation coefficient in an orifice discharging to vacuum
E	=	Energy of activation
I_b	=	Ion beam current
l	=	Ratio of length from emission to arrival point to thruster radius
m	=	Mass of the ion
M	=	Molecular mass
n	=	Number of monolayers formed by sorption
p_s	=	Vapor pressure
p_t	=	Stagnation pressure
q	=	Ion charge
R	=	Universal gas constant
T	=	Temperature
T_t	=	Temperature of stagnation
V_b	=	Net voltage
α	=	Sticking coefficient
γ	=	Adiabatic gas constant
$\dot{m}$	=	Mass flow rate
$\dot{\varphi}_{arr}$	=	Density flux arriving to a spacecraft surface
$\dot{\varphi}_{em}$	=	Density flux emitted from a spacecraft surface

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I.Introduction

Over the last years the growth of miniaturized satellites has seen an unprecedented development of small satellite missions, used alone or in constellations. Until May 31st 2018, a total of 855 CubeSat missions have been launched [1]. More and more often, there is a growing need for propulsion systems for orbital maneuvers, controlled reentry or attitude related changes. The propulsion systems inherited from past missions were usually unscalable to these small systems due to the loss of performances, increase in cost and lead times as well as the focus on sub-system miniaturization and optimization instead of in the development and optimization of a complete miniaturized propulsion system.

The miniaturization of propulsion systems will enable a new scope for small satellite missions, extending their mission lifetime and their overall mission capacity. Electric propulsion systems play a significant role in these missions, due to their high total impulse characteristics and their low mass of propellant -making them ideal for miniaturization. In this paper we focus on plasma-based thruster technologies, more specifically in gridded ion thrusters. Most of the current missions which use these kind of propulsion systems use xenon as propellant, although the research done on other propellants is growing exponentially. The NPT30 works both with xenon and iodine as a propellant, although this article is only focused in this second configuration. The authors believe that the use of iodine will significantly reduce the costs of development, testing and propellant cost for the missions, as well as simplifying delivery, integration and launch.

II.System considerations

A. Iodine-powered gridded ion thruster

Gridded ion thrusters are used in space since 1960. They are based on the physical principle of accelerating electrostatically charged particles for producing a high-speed ion beam. The propellant, which is injected in a discharge chamber, is typically ionized through the emission of electrons from a hollow cathode with DC current, although it can also be produced with RF and microwave fields. Early studies already identified the advantages of the use of heavy, often rare gases in these systems due to their low ionization potentials and high storage densities, although some of these substances such as mercury or cesium have been mostly abandoned due to the high risk of deposition into the spacecraft surfaces and safety considerations [2].

In a gridded thruster, the positive ions which are created in the plasma chamber enter the acceleration grids, where they are accelerated through a DC or RF voltage [3]. In the first case, the positively charged flow of ions has to be neutralized by using a cathode-neutralizer. Assuming that the speed of ions is far bigger than that of the neutrals escaping the thruster, which is the case in reality, the thrust T can be estimated as [4]:

$$T \approx \dot{m}_i v_i = \frac{I_b m}{q}\sqrt{\frac{2qV_b}{m}} \tag{1}$$

showing that the thrust is given by the ion beam current I_b, the ion mass and the effective voltage V_b applied to the grids.

The dependence of the thrust on the mass of the ions therefore drives the choice of the propellant towards the heavier ones (for decreasing the power to thrust ratio), in addition to the mentioned requirement of the ionization properties. Xenon is currently the most common propellant used in plasma based electric propulsion, even though it has a high and unstable pricing and complex storage requirements. During the last decade, many research groups focused their efforts on investigation of alternative propellants. Among them, iodine seems to be one of the most promising candidates as having a good compromise of storage properties, ion cost when ionized, and the ion mass [5]. ThrustMe is developing iodine-based gridded ion thrusters since the company creation in 2017 and at this stage the thruster is being integrated with the combined propellant storage and flow control unit, and operation is ensured by an internal power processing and control unit.

B. Iodine as a space propellant

From a brief technical viewpoint, iodine is a halogen, non-conductive and found as a solid at standard conditions, with a density of 4.93 g/cm^3. It is usually bought in the form of small crystals or beads, what can reduce the effective density up to 50% when filled into a larger container. It can be used as a self-pressurizing propellant, as its vapor pressure is relatively low at ambient temperature (10 Pa), and increases fast with temperature, to approximately 6000 Pa at 100ºC. The main drawback for the use of iodine is its reactivity, which will be discussed afterwards.

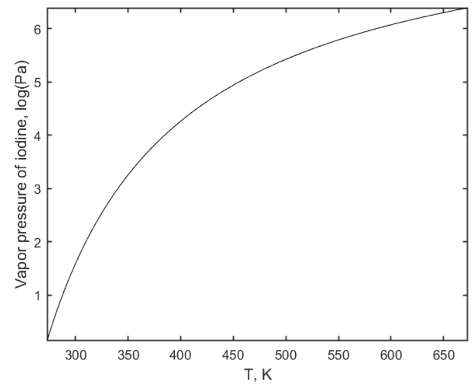

Figure 1: Vapor pressure of iodine as a function of the temperature in logarithmic scale

Its vapor pressure characteristics make iodine easy to store, in non-pressurized vessels, and the weakness of its intermolecular covalent bonds at the surface makes the van der Waal forces between them easy to overcome for sublimation. This sublimation processes can be used for controlling the flows through a thermal management loop. From an economical viewpoint, the prices for xenon can be highly oscillating following the market, whereas iodine remains relatively stable because of its availability in large quantities. The difference in price can be typically 20 times, given commercially available data. Not only will the cost of the propellant itself impact the overall mission budget for propulsion, but also reduced qualifications for non-pressurized systems, simplified filling and delivery etc. will play a significant role in the economical tradeoff.

C. Surface chemistry of iodine

As part of the halogens, iodine has a high electronegativity, or tendency to attract electrons in the covalent bond. Although the electronegativity of iodine is much lower than that of fluorine, it is enough to cause it to have a strong tendency to react with most of the substances commonly found in spacecraft. In the case of iodine, it is usually the presence of defects and local depassivation of the oxides layers which may create an anodic region in the piece and lead to strong galvanic corrosion. This may in turn create as well strong damage along the thickness of the structure.
The toxicity of iodine is elevated in all its chemical phases and must be handled carefully. This includes no direct manipulation of it without appropriate protection, and extraction and respiratory systems which are able to filter inorganic gases[4].

III.2. Design principles for the NPT30

The design of the NPT30 has been done to maintain the performances achieved with the NPT30 xenon thruster [3] [5] , while minimizing the space occupied by the propellant delivery system. In its nominal configuration, the propulsion system fits into a 1.5-unit CubeSat structure. The system contains the thruster itself, the iodine propellant management system, and the power processing unit ensuring generation of the RF power for plasma generation, high voltage for ion acceleration, high current source to power the thermionic cathode, control of the propellant storage and flow control system, communication with the OBC, and contain various diagnostic modules as well as generation of several additional DC powers (such as acceleration

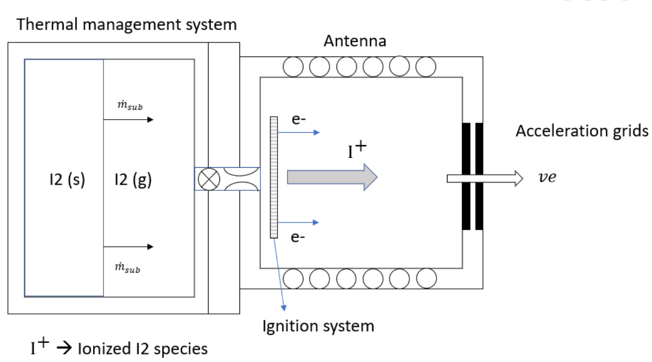

Figure 2: Schematics of the NPT30 ion thruster

[4] Further information about the toxicity of iodine can be found in national and local safety institutions, such as INRS, NIH

grids and cathode biases). The general operating algorithm is as follows:
1)Iodine, which is stored in the tank in solid form, and initially at ambient conditions, is heated up until the thermal management system reaches the steady pressure and temperature conditions needed.
2) At this point, the gas passes through the channel and the calibrated orifice until it reaches the plasma chamber, after going across the expansion chamber which homogenizes the flow. The flow value is mainly set by both the tank temperature and the calibrated orifice geometry.
3) The ignition system initiates the inductively coupled plasma inside the plasma channel, which is sustained using the helical RF antenna around the plasma chamber.
4) The ions are accelerated through the acceleration grids, and the beam is neutralized using the halogen-resistant thermionic cathode.
The propulsive characteristics of the NPT30 ion thruster are shown in Table 1. The values of the thrust and the total impulse depend on the applied power and internal configuration of the module; for the experimental campaign presented here the power range was fixed to approximately 35-60 W.

Parameter	Value
Thrust	0.4-1.1 mN
Total impulse	1000-4000 N·s
Wet mass	1.7 kg
Total power	30-60 W

Table 1: Technical specifications of the NPT30

D. Deposition studies

One of the hurdles on the way of the iodine-based propulsion system development is linked to both physical and chemical properties of iodine, which can be condensed on the spacecraft surfaces and lead to long-term effects like degradation of the optical properties, etching of the conductive and insulation materials etc. Several studies have been done in the past to try to quantify the amount of propellant which is condensed on the surfaces of a spacecraft [6] [7]. This effort has been particularly interesting in the cases where the propellants have a vapor pressure such that it can form potentially a layer at the temperatures of operation at the surfaces of the spacecraft.
A distinction must be made as well between processes which are due to chemical interaction and the ones which are purely due to phase change processes.
When the gas strikes the surface of a material, it will interact through sorption mechanisms whose intensity will strongly depend on the base material. Although the interest of this article is not to quantify these interactions, as they correspond to the chemical interactions on the surface, and will be studied experimentally in orbit, some of these impinging molecules will be attracted by the surface ones by their van der Waals forces, and retained on it a time which is a function of the oscillation period of the atom in the surface, t0 [8]. The growth of the layer of adsorbed propellant is a function of the arrival flux of material, the surface temperature, the activation energy, and a sticking coefficient which has to be determined empirically.

$$n = \alpha \dot{\varphi}_{arr} t_0 e^{\frac{E}{RT}} \tag{2}$$

In the case of these neutrals, once the substance has interacted to form a monolayer, the deposition and sublimation mechanisms of iodine are determined by the vapor pressure at the temperature of the surface and by the surrounding pressure, which will remain at extremely low values in space. Assuming that this surrounding pressure is negligible, we can express the rate of sublimation from the surface in equilibrium according to a Hertz-Knudsen type law:

$$\dot{m} = \frac{p_s(T)}{\sqrt{\frac{2\pi RT}{M}}} \tag{3}$$

This flux of neutrals can have typical values for an ion thruster between 30-40% of the total flux exited from the thruster. Several studies propose correlations in order to find the density of neutrals at a given surface far from the grids. Reynolds proposes a geometrical correlation between this density and the density at a given point, under the conditions of molecular flow and diffuse emission [9]:

$$\dot{\varphi}_{arr} = \dot{\varphi}_{em} \frac{\cos(\alpha_1)\cos(\alpha_2)}{l^2} \tag{4}$$

Figure 3 shows the temperature of condensation on the spacecraft surface as a function of the distance from the exit plane, for an object placed in front of this surface, which is the worst case possible for condensation of propellant issues. This temperature decreases with distance, as the amount of flux follows this trend. Even if the temperatures of condensation are usually below those of most of the components of missions which will be exposed to iodine two different in-orbit experiments have been already been planned in order to characterize this deposition, especially for surfaces that can reach very low or cryogenic temperatures, such as optical detectors or solar panels.

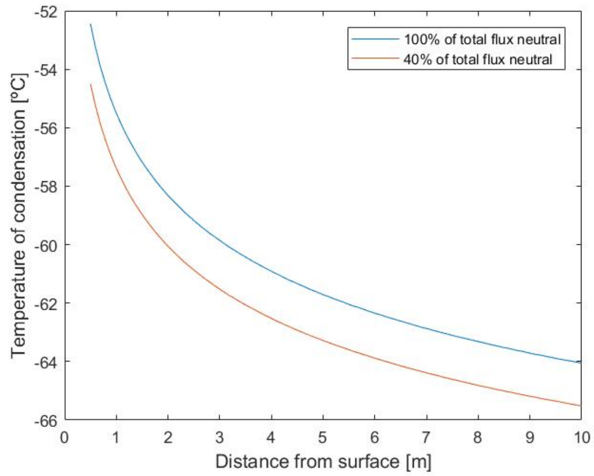

Figure 3: Temperature of condensation of neutrals for a gridded ion thruster as a function of the distance from the exit plane

IV.Testing of the NPT30 iodine thruster

E. Material testing

Extensive research has been conducted related to the use of materials commonly found in the NPT30 xenon version of the thruster and other potentially interesting materials for use with iodine. These include 25 materials and coatings which range from aluminium alloys (2024, 6082, 7075), to superalloys and refractory metals, together with the study of potentially resistant coatings such as tantalum oxides. These materials were submitted to a hot iodine environment (100ºC), for more than 120 hours, and the physical properties such as weight and electric conductivities monitored when applicable. In collaboration with the LMS laboratory of the École Polytechnique, a microscopic study has been performed for all the samples which were exposed to iodine corrosion, performing SEM-X-ray micrography with a quantum 600 FEG-ESEM electronic microscope.

The nature of iodine corrosion mechanisms is dependent on the surface characteristics, the temperature and other physical properties and the iodides formation chemical processes. Iodine has a strong tendency to cause pitting in the surfaces, which in turn can lead to potential failure. In addition, due to the strong oxidizing nature of iodine, it has a strong tendency to react exothermically with materials. This is the case, for instance, of the aluminium iodide formation, catalyzed with water, which has a standard enthalpy of formation of -302.9 KJ/mol.

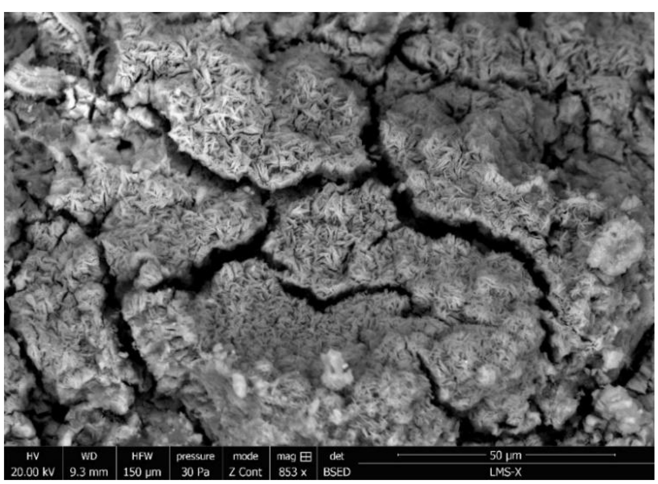

Figure 4: Aluminium 6082 micrography, BSED detector, 853x

Figure 5 and Figure ***6*** show examples of generalized corrosion in two of the samples. In the nickel structure, there are spots of deposited iodine which coexist with zones in which the base material has reacted to form iodides which appear clearly on the X-ray analysis. The preparation of the surfaces is crucial, and the defects on the original surfaces are

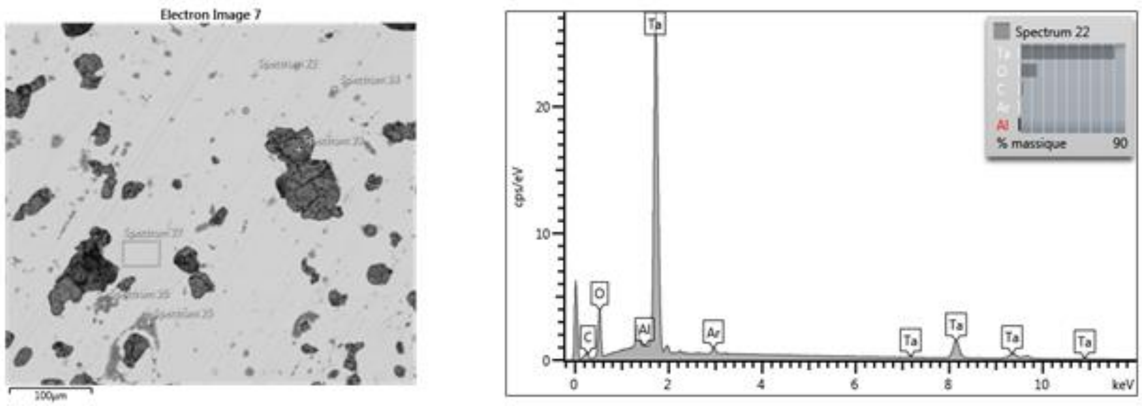

Figure 5: X-ray micrography analysis of an Al7075-T6 alloy coated with Ta2O5

extended to the coatings, being nucleation points for the growth of defects. This was the case in Figure 5, where the tantalum pentoxide structure was covered with spots where iodine was able to get to the base metal and corrode it.

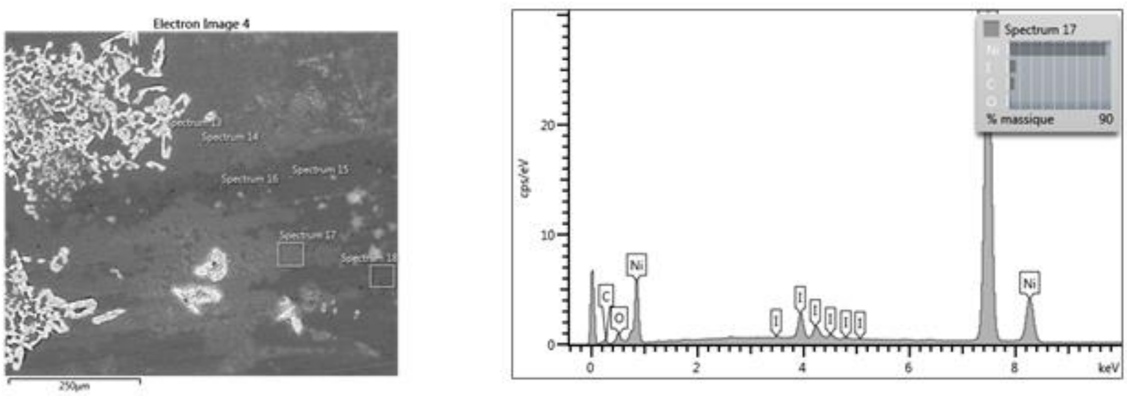

Figure 6: X-ray micrography of a nickel sample

F. Flow control

The precise control of the flow of iodine is of special importance, as drives the stability of the plasma and the mass flow rate through the thruster, which in turn modifies the thrust values. A flow with oscillations lower than 5 % during the whole duration of the firings can be attained by thermally regulating the system to control the upstream stagnation pressure of the gas, and by using calibrated orifices to be able to inject it precisely. A setup has been created for testing the selected configurations of calibrated orifices at different temperatures.

The experimental setup consists of a helicon type vacuum chamber, pumped by an Edwards XDS 35i primary pump and a Pfeiffer TC400 turbomolecular pump with 355 l/s of pumping speed for N2. The pressures are monitored in the entire pressure regimes through a piezoelectric gauge, a Pirani/Bayard-Alpert PBR 260 and capacitive gauge MKS 627F. The minimum residual pressures during the experimental campaigns are on the order of 10e-06 Pa, whereas the pressures during operation can increase up to 10e-02 Pa. Both the Pirani gauge and the setup pumping pressure for iodine have been calibrated by using an MKS mass flow controller for xenon, precisely calibrating the pressure at different volumetric flow rates, and comparing these values with the ones obtained through a calibrated orifice in the case of iodine.

For mitigating the risks of corrosion of the pump associated with the use of iodine, a loop setup of cold gas traps has been created for being able to pump the gas through the traps during operation. These traps are operated with liquid nitrogen, what reduces the vapor pressure at the temperatures of pumping to a value lower than 10e-08 Pa, far inferior to the lowest values of operational pressure in the chamber, 10e-06 Pa.

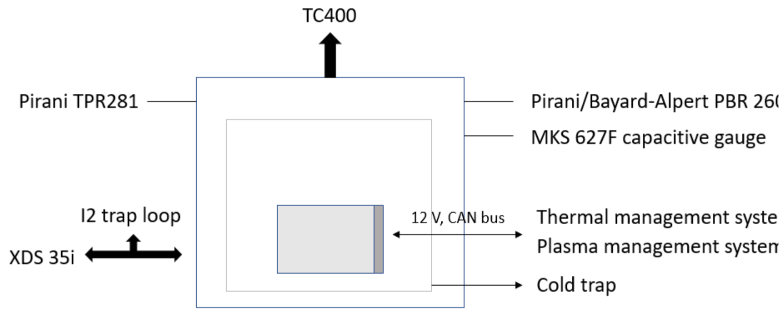

Figure 7: Experimental setup for the NPT30 testing

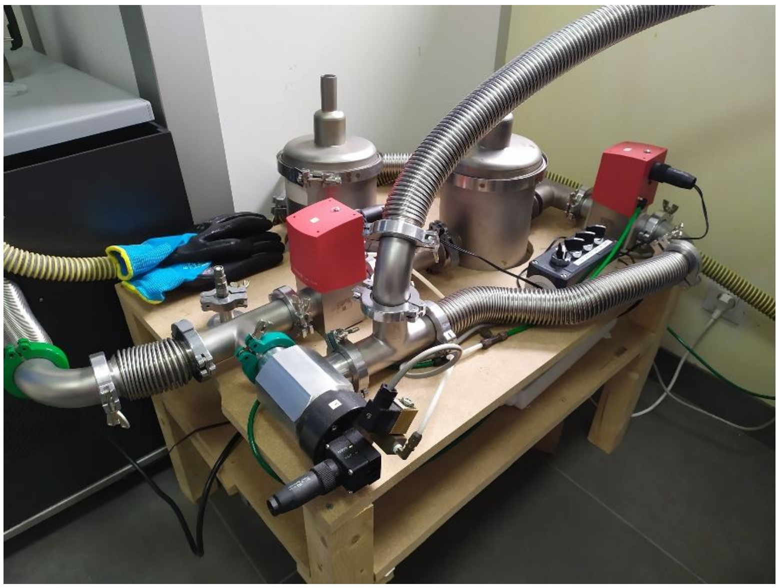

Figure 8: Cold trap system for the testing of the NPT30-I2

The mass flow rate can be estimated during the firings through the calibrations of pumping speed performed before, by continuously monitoring this value, and the curve can be integrated to obtain the mass of iodine consumed during the experiment. In addition to this method, it can be calculated by measuring the weight changes of the propellant distribution system during the experimental campaigns, or, once coupled with the rest of the thruster, by direct plasma measurements. Figure 9 shows one of these firings, in which a calibrated orifice was used to produce a flow close to 2 mg/s during approximately one hour. These firings were performed at temperatures from 60 to 110ºC for several configurations, to be able to correlate precisely the flows to the plasma chamber. As described before the flow can be then calculated empirically for this test in mg/s with iodine through the following equation:

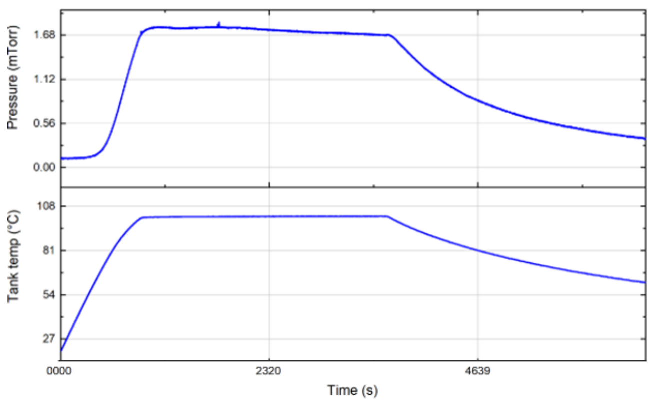

Figure 9: Pressure at the chamber and temperature of the tank for a firing

$$\dot{m} = 4 \cdot 10^{-8}\, T^4 - 4\ \cdot 10^{-6} T^3 + 2 \cdot 10^{-4} T^2 - 3.2 \cdot 10^{-3} T + 0.0177$$

where the mass flow rate in this configuration equals to 1.9 mg/s for the maximum temperature.

The flow through the channel becomes choked due to the low-pressure conditions at the exit, and remains choked through the whole duration of the experiment. Iodine behaves as a perfect gas at the temperature and conditions encountered, and the flow through the channel is fast enough -on the order of microseconds-, to consider in first approximation that it is adiabatic. The mass flow rate can be approximated by a 1D isentropic theory, so it can be described as:

$$\dot{m} = C \frac{\gamma p_t A^*}{\sqrt{\gamma R T_t}} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{5}$$

where C is a coefficient to take into account the compressibility effects at the exit of an orifice discharging into low pressure conditions [10].

In addition to this, modelling of boundary layer effects and heat transfer can provide a better picture of the flow across the system, especially in the areas where viscous efforts dominate, such as close to the walls. The low Reynolds numbers present in the nozzle due to the pressures and size of it make this boundary layer effects important, and therefore they have been included in the analysis of the system.

G. System tests

The NPT30-based iodine propulsion system prototype with decreased tank volume was installed into the 60 cm diameter cylindrical vacuum chamber equipped with both turbo and cryogenic pumping system, with a pumping capacity for iodine more than 10000 l/s. The size of the propulsion unit prototype is 1U, and the tank capacity by iodine is around 100 grams. For practical considerations of easy access and module flexibility, the tank was not fully thermally insulated, and had a quick access port for re-filling. An image of the module installed to the chamber is shown on Fig. 10 below.

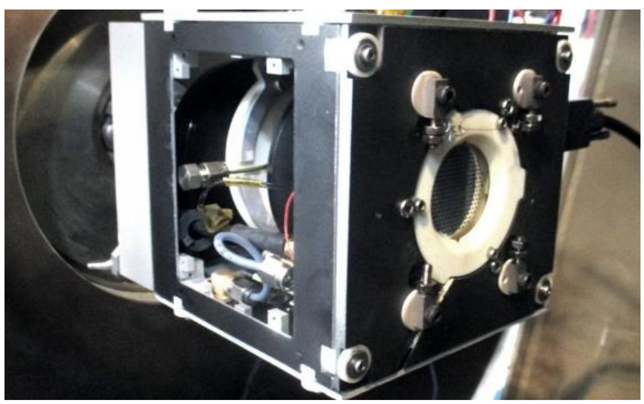

Figure 10: View on the NPT30-I2 propulsion module in the process of installation to the vacuum chamber.

Experiments have been performed at a fixed flow rate of approximately 0.1 mg/s. Background pressure during all measurements was maintained below 1.3×10^{-5} mBar. The plasma ignition tests, as well as first beam acceleration tests demonstrated successful control of these processes; standard algorithms used for the NPT30 Xenon version required only slight adaptation to be fully compatible with the iodine propellant. Images of the propulsion system during the plasma ignition and acceleration tests are given on Fig. 11 below.

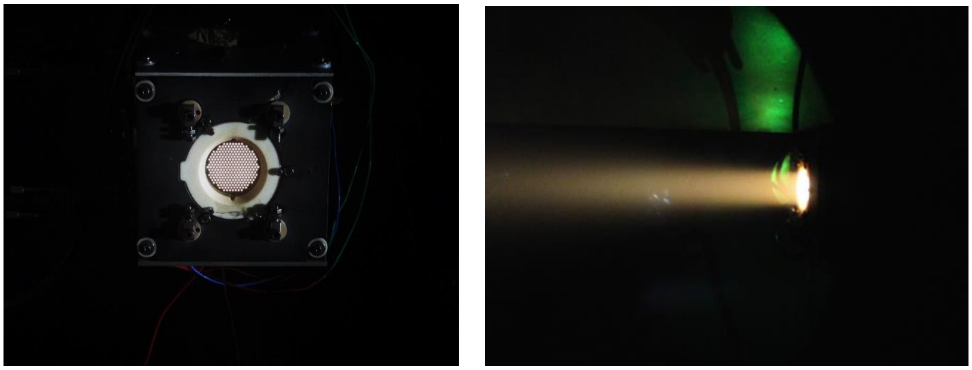

Figure 11: View on the NPT30-I2 propulsion module during plasma ignition (left) and beam acceleration (right) tests.

Operation of the NPT30-I2 at a fixed flow rate is possible in two configurations: 1) high thrust (I_{sp} < 1000 s) when the thrust values can reach up to 1.2 mN at 65 W of the input power, and 2) high Isp (I_{sp} > 1500 s) when the thrust can reach up to 0.7 mN in the similar power range. Both configurations accept using the same set of acceleration grids. Difference between the high thrust and high Isp configurations results from the different matrix of RF power values used for the plasma generation.

During the experimental campaign presented here only the high thrust configuration of the NPT30-I2 was tested (Isp<1000 s). Range of the total power was limited by approximately 35-60 Watts, which corresponds to the acceleration voltage range of 500-1200 V. The ion beam was analyzed using the 4-grid RFEA fixed on a translation arm on the axis of the beam, and beam divergence was obtained from a 2D scanning array installed in the chamber. The resulting IVDFs, as well as calculated thrust and Isp values are given on Fig. 12 below. It is seen that all the IVDFs have well defined mono-energetic profiles, with the energy peaks corresponding to the acceleration voltage values. The thrust varies in the range about 0.6-1 mN, and the Isp changes from about 700 s to 1000 s.

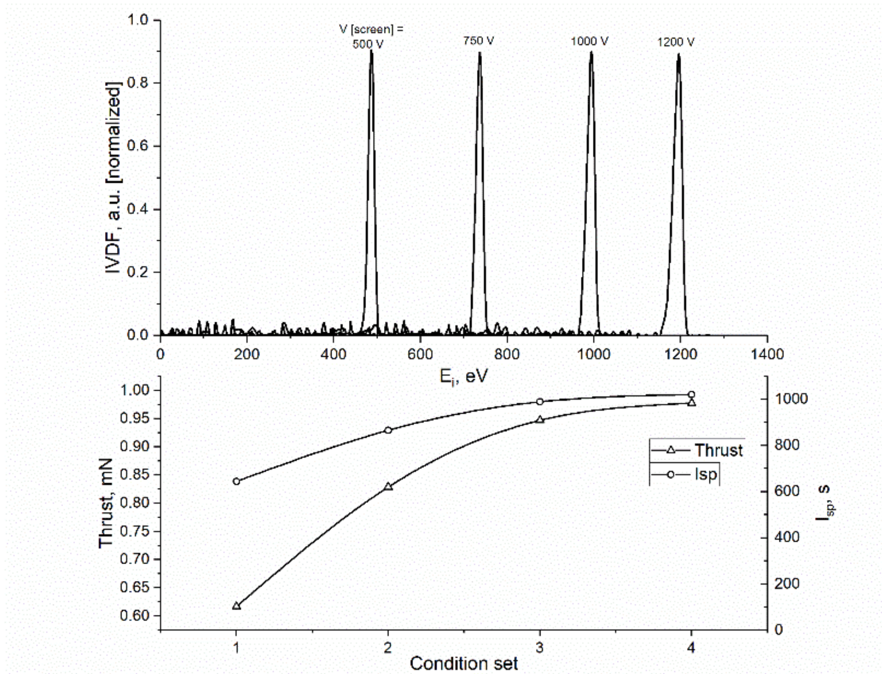

Figure 12: Ion velocity distribution functions (top) and thrust/specific impulse (bottom) for the NPT30-I2 thruster prototype. acceleration (right) tests.

IV.Conclusions

This paper presents the development and testing of the NPT30 ion gridded thruster, a 1U/1.5U (prototype/flight model) cubesat unit capable of delivering of up to 4000 Ns of the total impulse at a thrust level of the order of 1 mN. The development was focused on various aspects such as iodine propellant storage and reliable flow control, corrosion risk mitigation, hardware optimization for achieving stable ignition and operation of a plasma discharge and acceleration stages. Iodine corrosion has been studied to be able to predict and estimate the degradation rates of the materials present on the thruster and potentially in a spacecraft, and all key materials have been identified. Flow control was achieved using the orifice-based configuration with a thermally managed propellant tank, where the system design was based on the analytical model presented here. Experimental verification of the flow control system demonstrated generation of the stable iodine flows well corelated with the temperature settings. The plasma ignition and beam acceleration tests have shown successful control of these processes; standard algorithms used for the NPT30 Xenon version required only slight adaptation to be fully compatible with the iodine propellant. Beam measurements in the high thrust / low Isp configuration have confirmed predicted performances of 0.6 – 1 mN thrust and 700 – 1000 s Isp. Future experiments will be focused on studies of a high specific impulse configuration with the Isp values above 1500 s, as well as preparations for the pre-flight endurance testing.

Acknowledgments

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References

[1] T. Villela, C. A. Costa, A. M. Brandao, F. T. Bueno and R. Leonardi, "Towards the Thousandth CubeSat: A Statistical Overview," *International Journal of Aerospace Engineering,* p. 13, 2019.

[2] P. Grondein, T. Lafleur, P. Chabert and A. Aanesland, "Global model of an iodine gridded plasma thruster," *Physics of Plasmas,* no. 23, 2016.

[3] D. Rafalskyi and A. Aanesland, "A Neutralizer-Free Gridded Ion Thruster Embedded Into a 1U Cubesat Module," in *35th International Electric Propulsion Conference*, Atlanta, Georgia, USA, 2017.

[4] D. M. Goebel and I. Katz, "Fundamentals of Electric Propulsion: Ion and Hall Thrusters," 2008.

[5] D. Rafalskyi and A. Aanesland, "Performance tests of a complete electric propulsion system based on cathode-less gridded ion thruster," in *Space Propulsion*, Sevilla, 2018.

[6] W. C. Lyon, "Propellant Condensation on Surfaces near an Electric Rocket Exhaust," *Journal of Spacecraft and Rockets,* vol. 7, no. 12, 1970.

[7] J. J. Scialdone, "Self Contamination and Environment of an Orbiting Spacecraft," *NASA Technical Note D-6645,* 1972.

[8] J. J. Scialdone, "Contamination Control and Plume Assessment of Low-Energy Thrusters," NASA Goddard Space Flight Center, Greenbelt, Maryland, 1993.

[9] T. W. Reynolds and E. A. Richley, "Distribution of Neutral Propellant from Electric Thrusters onto Spacecraft Component," NASA Lewis Research Center, Cleveland, Ohio, 1969.

[10] D. A. Jobson, "On the Flow of a Compressible Fluid through Orifices".