Identification, Evaluation and Testing of Alternative Propellants for Hall Effect Thrusters

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Abstract: Recent mission analyses have shown a need for higher power electric propulsion (EP) systems for both Earth orbit raising and deep space applications. Therefore, the development of high power EP systems is being emphasized as the necessary step towards possible future missions of large satellites. Traditionally, xenon has always been the propellant of choice for both performance and operative reasons. In spite of its several technical advantages, the high price of xenon suffers of remarkable fluctuations, posing serious budget concerns. To reduce the propellant cost in high power electric propulsion applications, the identification of a more cost-effective alternative to xenon becomes necessary. Funded by the European Space Agency under the ARTES 5.1 programme element, Sitael performed a set of three experimental campaigns to test a 5 kW class Hall thruster. The tests allowed to characterise the performance of the thruster with pure xenon, pure krypton and different Xe-Kr blends. A characterisation of the erosion rates with different propellant mixtures were performed. In the present paper, the performance and erosion results of the last campaign, using pure krypton in both the thruster and the cathode, are presented and compared to those of previous campaigns. The comparison shows the impact of changing the propellant on the lifetime of the thruster. Finally, a simplified analysis is presented, which shows how to select an operative point to perform an alternative propellant-based lifetime test.

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Nomenclature

A = Channel Cross-Section
$AMFR$ = Anode Mass Flow Rate
e = Elementary Charge
E = Ion Sheath Edge Energy
g_0 = Reference Gravitational Acceleration
I_D = Discharge current
I_{sp} = Total impulse
I_{tot} = Total impulse
ICT = Initial Compatibility Test
k_B = Boltzmann Constant
m = Electron Mass
M_i = Ion Mass
n = Plasma Density
PVT = Performance Verification Test
P_D = Discharge Power
P_W = Power Loss to the Wall
q = Ion Charge
S = Channel Lateral Surface
T = Thrust
T_e = Electronic Temperature
v_B = Bohm Velocity
V_D = Discharge Voltage
η_i = Current Efficiency
ϕ_s = Sheath potential

I. Introduction

Xenon has been the propellant of choice for several EP applications and, although it has major advantages as a propellant (namely, a low ionization energy, high atomic mass and easy storage and flow metering), its relatively high price and scarcity hinders its utilization in high power thrusters. Moreover, xenon price suffers of remarkable fluctuations, posing serious budget concerns. In the near future, the identification of a suitable alternative propellant may enable two main benefits: the independence from the natural-resource market and the reduction of EP development and qualification costs.

The present study, funded by the European Space Agency under the ARTES 5.1 programme element, aims at assessing the influence of alternative propellants on EP systems designed to operate with xenon. Several studies were performed in the past few years aimed to assess the effect of different gaseous and condensable propellants on HT performance[6-9]. Besides the impact on thruster performance, a proper propellant selection must take into account several aspects of both physical and operative nature, including the propellant ionization energy and atomic mass, its compatibility with the cathode technology, the long-term storage capability as well as the handling and safety aspects.

The need to adapt an existing propulsion system led to the identification of krypton and Kr-Xe mixtures as the optimal propellant candidates. The investigation took into account not only the change in performance of the propulsion subsystem but also the effects of the selected propellants on the thruster lifetime and their impact, at system level, on the overall cost and duration of a set of mission scenarios[4]. As experimentally shown by Nakles[6], Kim[7], and Linell and Gallimore[10], krypton allows for relatively good performances at a cost that can be almost one tenth of the xenon cost. Due to its low atomic mass, krypton permits a 25% increase in specific impulse (assuming no offsetting losses) with respect to xenon. Moreover, krypton presents no re-deposition threats and a trivial redesign of the mass flow system. However, the use of krypton implies a reduction of the thrust efficiency and, due to the high pressure needed for its storage, an increase of the tank weight.

After a preliminary evaluation of the possible advantages and drawbacks of the selected propellants, an initial compatibility test (ICT) was performed, both on Fakel SPT-100 and SITAEL HT5k, to assess the impact of pure krypton and three different Kr-Xe mixtures on the performance of the two thrusters. The results of the ICT campaign for the HT5k, which are presented in details in Ref. 1, are consistent with similar characterizations performed, e.g., by Nackles et al. in Ref. 6 and highlight the influence of krypton on the performance of the thruster. The activities then focused on the verification of the thruster performance over long duration firings. A first performance verification test (PVT) campaign was performed operating the HT5k for 500 hours with a mixture of krypton and xenon (75% Kr and 25% Xe). The results of the first PVT campaign allowed to assess the impact of krypton on the thruster wall erosion, showing a critical increase of the erosion associated with the use of krypton. Based on the experimental results obtained during the project, a further comparison at system level between krypton, Kr-Xe mixtures and xenon was performed. The critical aspects of the selected alternatives, in particular concerning the reduction of the thruster lifetime, are highlighted in Ref. 4. Following this system analysis, a second PVT campaign was performed to improve the insight on the erosion process. The HT5k ceramic channel was replaced with a new one and a 150-hour firing test with pure krypton was carried out. Moreover, to assess the capability of the whole EPS to operate with krypton, during this second PVT campaign the cathode was operated with krypton. Finally, a new characterization of the HT5k thruster unit was performed.

The present work summarises the test activities performed during the different phases of the project and the main results obtained. A detailed overview of the test campaign, which includes a description of the thruster unit and of the diagnostic system, is presented in Section II, where the outcomes of the ICT campaign are summarised. In Section III, the results of the two PVT campaigns are described, focusing in particular on the second campaign. Critical aspects associated with the adoption of krypton as propellant are analysed in Section IV, where a possible strategy is proposed to exploit such alternative propellant in the life-testing of new thrusters.

II. Test Activities

The experimental investigation focused on the operation of SITAEL HT5k, a 5 kW class Hall thruster designed to operate with xenon, with the selected alternative propellants, i.e. with pure krypton and with different mixtures of xenon and krypton. The investigation consisted of three main test campaigns:

- An Initial Compatibility Test (ICT);
- A Performance Verification Test (PVT1) with a 75%Kr-25%Xe mixture;
- A Performance Verification Test (PVT2) with pure krypton.

A. Test setup

The HT5k, installed on a thrust stand, is coupled with the HC20 cathode, a LaB_6 high-current hollow cathode developed by SITAEL in the past few years[3].

The tests were performed at SITAEL in the IV10 vacuum facility, which is especially designed for long endurance testing of high power electric thrusters. This facility, one of the largest available in Europe for EP systems testing, is designed to reduce the facility effects on thruster performance, in terms of contamination, background pressure and electromagnetic effects due to the chamber walls. The thruster unit was mounted inside the chamber on a single axis thrust stand, whose main features are reported in Ref. 1. The gas feeding system adopted during the test campaigns consists of two different gas cylinders coupled with the gas panel (for xenon and for krypton). Two different mass flow controllers (mounted on different gas lines) control separately the krypton and the xenon mass flow to the anode. The connection between the two lines is located just before the IV10 feedthrough. Two valves are placed between the mass flow controllers and the connection to separate the two lines (one valve closed and one open) in order to operate the thruster with pure propellants. A detailed description of the test setup, including a schematic overview of the feeding system, is reported in Ref. 1.

During the PVT campaigns, the AED tele-microscopy system was installed inside IV10 in order to investigate erosion phenomena (see Ref. 4 for more details). Since the whole system is mounted inside the vacuum facility, AED has an optimal view of the thruster and it can operate without opening the vacuum chamber. The resolution of the measured profiles is approximately 30 μm and, in order to assess the progression of erosion, AED acquisitions were performed at regular intervals of 30-50 hours.

B. Test description

During the ICT campaign the thruster was tested with pure xenon, pure krypton and mixtures of xenon and krypton with 75%, 50% and 25% of krypton. A functional characterisation of the thruster was performed for each propellant option, showing stable operations for a wide set of regimes (discharge voltages from 250 to 600 V and power levels between 2 and 7 kW). As reported in Ref. 1, observations showed that increasing the xenon fraction in the propellant mixture increases the thrust efficiency. Nonetheless, efficiencies of about 50% were achieved with a high percentage of krypton. After the functional characterisation, a 10-hour continuous firing test was performed, using a 75%Kr-25%Xe mixture, in which the thruster showed a stable discharge current trend with no issues in term of flame out or thruster overheating.

It is important to remark that in the first two campaigns (ICT and PVT with 75%Kr-25%Xe) the cathode operated with pure xenon.

After the ICT, the first Performance Verification Test was carried out, as reported in Ref. 4. Initially, the thruster fired for 30 hours using pure xenon to assess a reference condition for the channel erosion. Then, the endurance test started with the thruster operating with a 75%Kr-25%Xe mixture. The test lasted for approximately 500 hours, during which the thruster operated with a discharge power of 4.5 kW and a discharge voltage of 350 V.

The final stage of the experimental investigation was the second Performance Verification Test, in which both the thruster and the cathode ran on pure krypton, seen in Fig. 1. Initially, the performance of the thruster unit running fully on krypton was verified along the whole envelope of the thruster. Afterwards, the thruster operated for 150 hours at a nominal discharge power of 4.5 kW and at a discharge voltage of 350 V. Every 40 hours of operation the thruster was switched off in order to take erosion measurements with AED and to measure the thrust. The performance values are presented in Table 1, showing that no significant changes in the thruster behaviour were observed.

Figure 1. Thruster firing with pure krypton during the second PVT campaign.

AMFR	V_D	I_D	***Power***	***T***	***Anodic efficiency***	***Anodic*** I_{sp}	***Endurance firing time***
[mg/s]	[V]	[A]	[W]	[mN]	[s]	[s]	[hh:mm]
9.7	350	12.9	4515	205.0	0.48	2154	31:26
9.6	350	12.9	4515	203.5	0.48	2161	66:15
9.5	350	12.8	4480	201.4	0.48	2161	113:26
9.5	350	12.8	4480	201.9	0.48	2166	152:38

Table 1. Measured thruster performance during the second PVT campaign.

III. Test results

A. Effect of krypton and Kr/Xe mixtures on the thruster performance

Stable operations and reliable thruster ignitions were observed for the full operating envelope of the thruster. As expected, increasing the fraction of krypton leads to a reduction of the thruster efficiency and an increase of the specific impulse. The plasma expansion outside of the thruster was assessed by means of plume measurements, showing an increase of the beam divergence when increasing the percentage of krypton in the propellant mixture. Nonetheless, even in the pure krypton case an anodic thrust efficiency of 40%-50% was observed. As already stated in Ref. 1, during the ICT it was observed that the peak of thrust efficiency shifts from 4-4.5 kW for pure xenon towards higher power levels, about 6.5 kW, for pure krypton. Results from PVT2 have confirmed this behaviour.

It is important to remark that HT5k is equipped with auxiliary coils that allow optimizing the magnetic field topology during the test, depending on the different operative conditions regarding discharge voltage, mass flow rate and type of propellant.

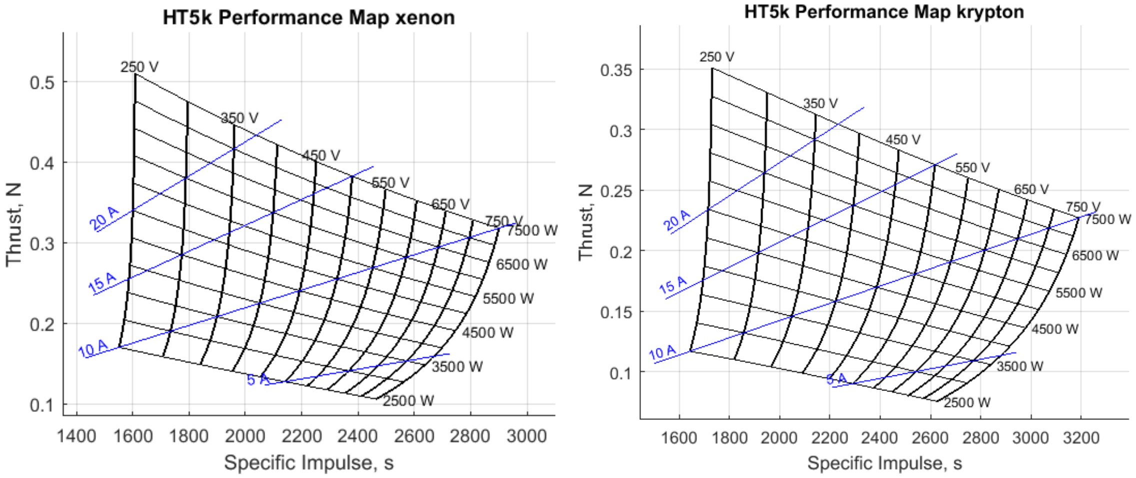

Figure 2. Performance maps for HT5k operating on xenon and on krypton.

As the resulting thruster performance maps show in Fig. 2, the behaviour of the thruster is quite similar for both krypton and xenon, except for a shift of about 100 s along the I_{sp} axis and a proportionality factor of about 1.4 along the thrust axis. The highest values of discharge voltage and power outside the tested range were extrapolated from the experimental data.

B. Measurements of ceramic channel erosion

The evolution of the channel shape due to erosion was assessed during the two PVT campaigns. The erosion caused by plasma-wall interactions represents the main limiting factor of a HT lifetime. However, since this process is critically connected with the characteristics of the plasma flow inside the channel, the investigation of the thruster lifetime through analysis or simulations is often impossible or extremely difficult. This kind of analyses adopt a semi-empirical sputtering-yield function that is calibrated against experimental measurements. In particular, the threshold energy, i.e. the minimum energy of impinging ions that is able to produce a sputtering of the ceramic surface, depends on the particle mass and on the wall properties and, so, it changes for different propellants. Even if some estimates are available for xenon, at the beginning of the present work only few conflicting experimental data were available for krypton. If the impact of krypton on the wall erosion is assessed through empirical fittings like the one described in Ref. 5, the erosion rate for similar plasma characteristics increases by a factor of ~1.5. On the other hand, experimental results presented in Ref. 7 suggested that the erosion with krypton should be less than with xenon. Although, at the present day, only full qualification test campaigns can guarantee that a thruster is able to operate for the required total firing time, the assessment of the effect of propellant on the thruster lifetime represented a major objective of the project.

The evolution of the channel shape of the HT5k has already been reported in Ref. 4 for xenon and Xe/Kr mixtures, corresponding to ICT and PVT1 campaigns. The comparison between the erosion rates measured for pure xenon and for the Xe/Kr mixture showed a significant increase of the wall erosion. Given the thruster configuration and considering the thruster lifetime to be inversely proportional to the erosion rate at BOL, the ratio between the total impulses with xenon and with the mixture is found to be

$$\frac{I_{tot}^{Xe}}{I_{tot}^{Mix}} \approx 1.82\,. \tag{1}$$

The assumption that, given the thruster geometry, the total impulse ratio only depends on the ratio of erosion rates can be partially justified by simple scaling relations, as illustrated in Ref. 11. This might not yield an accurate prediction, since the change of propellant implies a change in the operating conditions of the thruster and, in particular, the comparison of Eq. (1) is performed at different discharge voltages. However, the trend of erosion progression is clearly assessed by the performed test campaign and it is confirmed by the second performance verification test.

Indeed, since the reduction of total impulse when the thruster operates with krypton (reported in Ref. 6), or with Xe/Kr mixtures, represents a fundamental factor for the development of EP systems based on such alternative propellants, the second PVT campaign aimed at further assessing the erosion rate for pure krypton. As already stated in Section II, during the PVT2 campaign, the HT5k and the cathode operated with pure krypton. Erosion measurements of the ceramic channel were performed with AED at different times during the test campaign. The profile of both the inner and ceramic walls was measured every 15º starting from the cathode position. The times at which the profiles were measured are the same as the ones in which the thrust was measured, shown in Table 1. The data contained in the pictures was processed and the curves corresponding to the profiles of the ceramic walls were obtained at each azimuthal position.

The erosion measurements showed a change in the profile of up to 3 mm by the end of the 152 hours of the endurance test. An important azimuthal dependence of the erosion was assessed, as for the PVT1 campaign. The azimuthally averaged profiles for each test are presented in Fig. 3, together with the values of the erosion, and the estimated erosion rate, which is calculated as the ratio between the measured erosion and the elapsed firing time during that test.

As noted in Ref. 4, the erosion progression at the exit of the channel slowed down during the PVT1 and, at the end of the 500 hours, the erosion rates were reduced by a factor of two. On the contrary, we observed a slight increase of the erosion inside the channel, which is associated with the change in curvature of the wall profiles (from convex to concave). The same trend, which was also observed for the SPT100 in 6, can be noted in the PVT2 campaign, even though the limited firing time does not allow for a clear assessment. It is however important to note that, on average, the erosion rates measured for pure krypton operations is higher than that measured during PVT1 for the mixture.

In order to compare the results of the two PVT campaigns, we have to select similar conditions. Notice that the first PVT campaign was performed after the ICT campaign and in two subsequent phases, which corresponds to a first 30-hour firing with xenon and a following 500-hour firing with the propellant mixture. Hence, at the beginning of the first PVT campaign, when the erosion rate was measured for xenon, the ceramic channel was already eroded by the ICT characterization. The second PVT campaign, instead, was carried out using a new ceramic channel. To compensate for this difference, the second acquisition performed for the PVT2 was then selected as initial profile. The comparison between xenon and krypton erosion rates for the inner and outer walls are shown in Fig. 4.

Using the same scaling description adopted for Eq. (1), the reduction of the total impulse can be approximately estimated as

$$\frac{I_{tot}^{Xe}}{I_{tot}^{Kr}} \approx 2\,. \qquad (2)$$

IV. Alternative Propellant-based Lifetime Test Campaign

As we described in Section III, a Hall thruster designed to operate with xenon can operate with krypton, or with Kr-Xe mixtures, with a limited degradation of the thrust and efficiency and a ~25% increase of the specific impulse. The significant cost reduction that the choice of such alternative propellant implies is, in some cases, enough to justify the selection of krypton with respect to xenon. Ref. 11 takes into account the typical mission scenarios of geostationary telecommunication platforms, and shows that the trade-off between transfer time and costs can be in favour of krypton. The trade-off, however, strongly depend on the target mission and there are many cases in which, even considering its higher price, xenon represents the optimal choice. This might be the case also for very high-power systems, i.e. propulsion systems with a nominal power level greater than 15 kW, like those foreseen for space-tug applications or deep-space mission. Even though for these power levels the cost of xenon propellant can represent a significant share of the overall EPS cost, the extreme performance that are the target of these systems often justifies the choice of xenon instead of krypton.

As we highlighted in the previous section, one of the main results that has been assessed by the performed experimental campaigns is the reduction of the thruster lifetime associated with the adoption of krypton as propellant. Even if the development of long-life thruster configurations can mitigate the importance of this issue, the increase of the channel erosion may represent a further obstacle for the development of krypton-based propulsion systems. However, this drawback can have a positive impact on the development of high-power thrusters.

Since EP systems are designed to operate for several thousand hours, one of the main limitation for the development of new prototypes is the cost associated with the life-tests. Provided the availability of a suitable testing facility, in many cases the propellant cost by itself represents a major obstacle for the completion of a space-qualification campaign. This is even more critical for systems with a power level of 15 kW or more, which operate with up to 50-60 mg/s of xenon of anodic mass flow rate.

The test campaigns carried out in the framework of the present project showed that a propulsion system designed to operate with xenon can be fired with krypton without any change of the thruster unit. Moreover, the impact of the change of propellant has been clearly assessed, both in terms of performance and in terms of thruster lifetime. What is really important about the thruster lifetime is not the precise amount of its reduction, which may depend on the specific configuration, but the clear assessment of the increase of sputtering with krypton. It is thus possible to consider the adoption of krypton as a conservative choice to test the thruster lifetime, at least for what concerns the channel erosion.

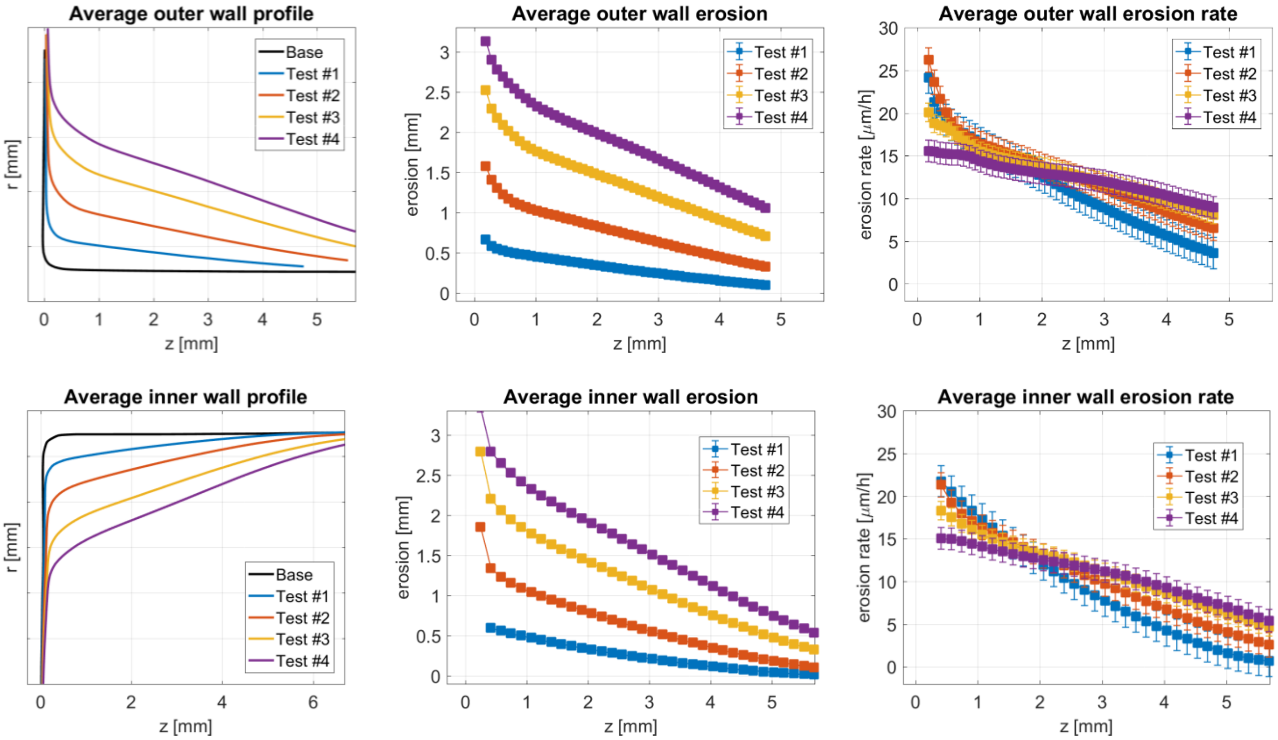

Figure 3. Inner and outer averaged walls profiles, erosion profiles, and erosion rates.

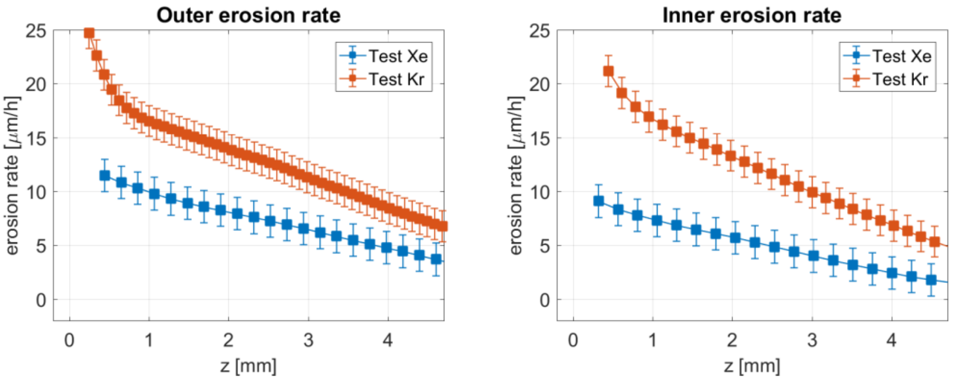

Figure 4. Comparison of inner and outer wall erosion rates with xenon and krypton

In order to carry out a representative life test using an alternative propellant, the erosion of components that directly interact with the plasma is only part of the problem. A simple analysis, however, highlights that all other interactions between the plasma and the thruster can be summarised in terms of

1) exchange of momentum, which is the result of the interaction between the currents inside the plasma and the magnetic circuit;
2) exchange of energy, which takes into account the power deposited by the plasma to the walls and the power to the anode.

The exchange of momentum corresponds to the thrust generated by the plasma flow, which can be easily assessed with a characterization campaign. The power deposited to the anode, which is mainly due to the electron flux, can be assumed to depend on the discharge current and the discharge power alone. The power loss to the walls can be modelled with a more accurate description by considering the classical sheath theory. Following Hobbs and Wessons[13], the power loss to the wall is given by

$$P_W = nSF\left(T_e, M_i\right), \tag{2}$$

where S is the wall surface and where

$$F\left(T_e, M_i\right) = k_B T_e \left(\frac{k_B T_e}{2\pi m}\right)^{1/2} e^{\frac{e\phi_s}{k_B T_e}} + q\frac{v_B}{2}\left(E - \phi_s\right) \tag{3}$$

is a complex function of the electron temperature and of the propellant properties[12]. The plasma density can be written in terms of the specific impulse and discharge current as

$$n = \frac{\eta_i I_D}{e g_0 I_{sp} A}. \tag{4}$$

Assuming that the electron temperature is the same for the operation with krypton and xenon, it is easy to show that the ratio between the function calculated for xenon and for krypton is ~1-1.2. Notice that the assumption on the electron temperature, as well as the one for the anode loss, is conservative if we consider $V_{d\mathrm{Kr}} > V_{d\mathrm{Xe}}$. Even if the discharge voltages differ, inside the thruster channel the electron temperature is limited by the saturation of the wall sheath, which occurs at similar temperatures for krypton and xenon.

It is thus possible to define a strategy to assess a conservative value of the thruster lifetime. The first step is to perform an accurate characterization of the thruster performance with both xenon and krypton. Then, given a nominal operating condition with xenon, it is possible to highlight among the krypton operating conditions those that satisfy the following constraints

Discharge power

$$P_{D\mathrm{Kr}} \geq P_{D\mathrm{Xe}} \tag{5}$$

Discharge current

$$I_{D\mathrm{Kr}} \geq I_{D\mathrm{Xe}} \tag{6}$$

Thrust level

$$T_{\mathrm{Kr}} \geq T_{\mathrm{Xe}} \tag{7}$$

Wall power losses

$$P_{W\mathrm{Kr}} \geq P_{W\mathrm{Xe}} \tag{8}$$

An example of the proposed approach is illustrated in Fig. 5 for the HT5k. The selected operating conditions with xenon is at 4.5 kW of discharge power and 300 V of discharge voltage. The map in Fig. 5 shows the region of krypton operations in which the constraints are satisfied. Inside this region, a good candidate for the life test with krypton can be selected, e.g. the point at 7 kW and 350 V. Notice that, for the selected point, the most critical constraints are those on the thrust and on the power flux to the walls. The region can be defined in a more precise way by considering directly the experimental points, after the characterization campaigns. Moreover, it shall be remarked that the region corresponds to conservative assumptions. In particular, the stress on the thruster structure due to the exchange of forces (up to 1 N for a 20kW HT) may be not a critical factor for the thruster lifetime and lower values of thrust can be acceptable. In this case, the available region of operations is mainly limited by the P_W condition. For example, accepting a limited degradation of the thrust, we can select the point at 6.5 kW and 350 V to simulate the thruster operations with xenon.

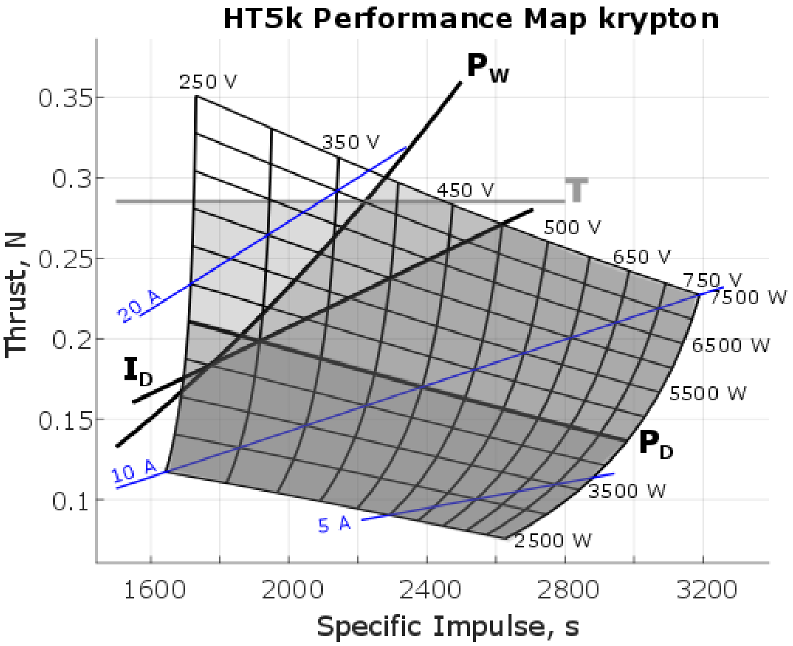

Figure 5. Performance map with krypton. The map shows the constraints imposed to simulate the operating conditions with xenon at 4.5 kW and 300 V.

V. Conclusion

Funded by the European Space Agency under the ARTES 5.1 programme element, an extensive experimental campaign was performed at SITAEL to test a 5 kW class Hall thruster operated with alternative propellants.

During the first phase of the project, pure krypton and different Kr/Xe mixtures were tested in an initial compatibility test. The objective of the test was to identify the performance envelope and the functional parameters of the HT5k thruster, a 5 kW class Hall thruster developed by SITAEL. The thruster performance and plume characteristics while operating with pure xenon, pure krypton and krypton-xenon mixtures were assessed in a test campaign carried out in SITAEL's IV-10 large vacuum facility.

In the second phase of the project, two performance verification tests were carried out in order to understand the effects of the selected propellant on the thruster lifetime. The propellant in the first case was a 75% Kr-25% Xe mixture for the thruster and pure xenon for the cathode, while in the second case both the thruster and the cathode were fed with pure krypton. In particular, during the first PVT campaign, the HT5k thruster was operated for approximately 500 hours at the nominal power of 4.5 kW and a discharge voltage of 350 V. Then, after the replacement of the ceramic channel, the second test campaign started, during which the thruster was operated for approximately 150 hours. During both tests, thruster was switched off every 30-50 hours to perform erosion measurements and take thrust measurements. The two short-endurance tests allowed for the characterization of thruster performance in terms of thrust and specific impulse, as well as the erosion evolution of the channel walls. The erosion measurements were performed using the Advanced EP Diagnostic (AED) system, a tele-microscopy system developed by Sitael and designed to reconstruct the shape of a Hall thruster channel at different instants during its operational lifetime[4].

This paper presents the results of the experimental campaigns, as well as a comparison between them. In particular, the temporal evolution of the thruster performance and channel walls profiles are reported and analysed. The data gathered provide a valuable insight into the nature of the erosion mechanisms and their influence on the thruster performance with alternative propellants. Moreover, the effect of the selected alternative propellant on thruster lifetime and performance were extrapolated.

The successful completion of the test campaign and the promising results obtained show that krypton can be taken into account as a plausible propellant candidate for future high-power Hall thrusters. Moreover, the use of krypton can be effective also for the development of HTs even if the selected propellant is xenon. Indeed, the present paper provides a strategy to exploit the reduced cost and the higher erosion rates associated with the use of krypton in the life-testing of new thruster prototypes. In particular, after a thorough characterization of the thruster behaviour with both xenon and krypton, the nominal operating conditions with xenon are transposed in an equivalent operating condition with krypton, which conservatively simulates the effects of long-term firings on the thruster. Due to the raising interest toward very high-power systems, for which the propellant cost represents a major issue, the proposed strategy may represent a cost-effective approach to verify the thruster lifetime.

Acknowledgments

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