Investigation of a 5 kW class Hall-effect thruster operating with different xenon-krypton mixtures

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Cosimo Ducci[1], Tommaso Andreussi[2], Alexey Arkhipov[3], Andrea Passaro[4], Mariano Andrenucci[5]
Sitael S.p.A., Space Propulsion Business Unit, Pisa, 56121, Italy

and

Alexandra Bulit[6] and Clive Edwards[7]
ESA-ESTEC, 2201 AZ Noordwijk, The Netherlands

Abstract: The HT5k thruster, a 5 kW class Hall effect thruster developed by Sitael, has been extensively tested over a power range that spans between 2 and 7 kW, with an applied discharge voltage between 300 V (high thrust mode) and 700V (high specific impulse mode). The thruster is typically operated with xenon but, since the development of high power electric propulsion systems can be critically affected by the propellant cost, investigations on alternative propellants, funded by the European Space Agency under the ARTES 5.1 programme element, have been carried out. Due to the relatively low cost and its affinity with xenon (in terms of both performance and handling), krypton has been identified as the alternative propellant choice. Then, the HT5k thruster performance for operations with different krypton-xenon mixtures have been assessed in a test campaign carried out in Sitael's IV-10 large vacuum facility. The full operating envelope of the thruster has been tested. In the present paper, experimental investigations of the thruster performance and plume characteristics with pure xenon, pure krypton and krypton-xenon mixtures are presented. As expected, increasing the fraction of krypton leads to a reduction of the thruster efficiency and an increase of the specific impulse.

I. Introduction

A strong interest in high power Hall-Effect thrusters (HET) is quickly rising for a number of applications: Final positioning and station-keeping of GEO satellites; Spacecraft transfers from LEO to GEO (or from LEO to other high altitude orbits); Interplanetary missions. High power HETs are especially appealing, since they can be operated in high thrust mode, to complete a target mission in a shorter time, or in high specific impulse mode, to maximize propellant saving.

[1] Test Manager, Sitael S.p.A., c.ducci@alta-space.com.
[2] Project Engineer, Sitael S.p.A., t.andreussi@alta-space.com.
[3] Project Engineer, Sitael S.p.A., a.arkhipov@alta-space.com.
[4] Former Project Manager, Sitael S.p.A., passaro.andrea@gmail.com,
[5] Head of Space Propulsion, Sitael S.p.A, m.andrenucci@alta-space.com.
[6] Electric Propulsion Engineer, TEC-MPE, ESA, Alexandra.Bulit @esa.int.
[7] Spacecraft Engineer, TIA-TTS, ESA, Clive.Edwards@esa,int.

An emerging hurdle in high-power electric propulsion (EP) systems development is the use of Xe as baseline propellant for virtually all the most mature EP concepts. Although Xe has several advantages as a propellant, namely low ionization energy, high atomic mass and easy storage and flow metering, its relatively high price and scarcity hinders the use of xenon in high-power thrusters. Moreover, xenon price suffers of a remarkable fluctuation according to the financial market speculation which poses serious budget concerns. To reduce the thruster cost and improve savings for satellite providers as well as for the EP ground tests, while retaining comparable performance with respect to Xe operations, more economical propellants need to be identified.

Several studies were performed in the past few years to assess the effect of different gaseous and condensable propellants on HET performance.[1-6] However, due to tightly interwoven performance and system level aspects, no systematic trade-off between thruster and subsystem issues was carried out so far. Linell and Gallimore[3] compared high-voltage xenon and krypton operations using the NASA-173Mv1 HET and showing that the propellant utilization efficiency is about 5 to 10% higher for Xe. At the same time the authors suggested several design options to improve the performance of HET operation with krypton (longer discharge chamber, higher discharge voltages and high channel neutral densities). Another important aspect is covered by the work of Kieckhafer and King[7] which demonstrate that the erosion rate due to sputtering is lower for krypton than other propellants at very high energies.

Concerning the testing of alternative propellants, in 2009 Sitael performed an extensive test campaign aimed at studying the possibility of extending LEO mission's duration by collecting the atmospheric molecules and using them to propel EP systems in order to counteract the drag force. In the frame of this activity, Sitael verified both theoretically and experimentally the performance of an HET thruster operating with atmospheric propellants.[8] In particular, the thruster was successfully operated with molecular nitrogen, molecular oxygen and a mixture O2/N2. In addition, the endurance test (500 hrs) performed with an O2/N2 mixture allowed Sitael to assess the effectiveness of the HET technology in sustaining long-lasting activities with reactive propellants. As a matter of fact, this activity still represents one of the rare studies concerning the testing of EP systems with alternative propellants and probably the first, at least in Europe, concerning atmospheric propellants.

From the theoretical side, Shagayda[9] recently presented a novel scaling model for the performance prediction of Hall effect thrusters based on both analytical assessment of the plasma parameters and on available experimental data. The model was used to predict HET performance for different kinds of propellants including krypton, argon and bismuth. According to the theoretical model, a 5 kW thruster operating at 300 V discharge voltage, would provide a thrust of about 300 mN and a specific impulse of approximately 1900 s when operated in xenon as compared to ~200 mN and 2000 s for krypton propellant. As a consequence, the predicted thrust efficiency penalty is of about 0.71 (~29% reduction) while the gain in specific impulse is of approximately 5%. However, the use of krypton appears to be highly beneficial for the specific impulse for discharge powers in excess of 10 kW.

A proper propellant selection must takes into account several aspects, chief among them the ionization energy, atomic mass, compatibility with the cathode technology, impact on thruster performance, long term storage capability and handling/safety on-ground procedures. As an example bismuth, with its high atomic mass and low ionization energy appears to be advantageous for high-thrust missions (orbit rising). However, even if the use of bismuth represents an effective cost-saving option to xenon, its condensable nature imposes significant development issues including high temperature heaters along the mass flow system, reconfiguration of solar arrays and sensitive instruments to avoid risks of metal deposition and special handling procedures for on-ground testing. [2] Quite recently, the Air Force Institute of Technology - with the support of Busek - examined the use of iodine as an alternative propellant to xenon for low-power missions.[6] Preliminary analyses indicated that the specific impulse is lower for iodine at most of the operating conditions investigated but it can reaches xenon performance at higher voltages. However, iodine brings together a serious oxidation issue and the technical hurdle of sustaining the injection of gaseous propellant (being solid at room temperature). In addition, the major drawback of a iodine HET is the cathode operation. Since common thermionic cathodes operate on xenon, both propellants are needed on-board increasing the system complexity and reducing storage savings.

On the other hand, krypton presents no re-deposition threats, trivial redesign of the mass flow system and, due to its low atomic mass, a 25% increase in specific impulse (assuming no offsetting losses) with respect to xenon. However, as experimentally shown,[1,5] this advantage comes at the expense of the thrust efficiency.

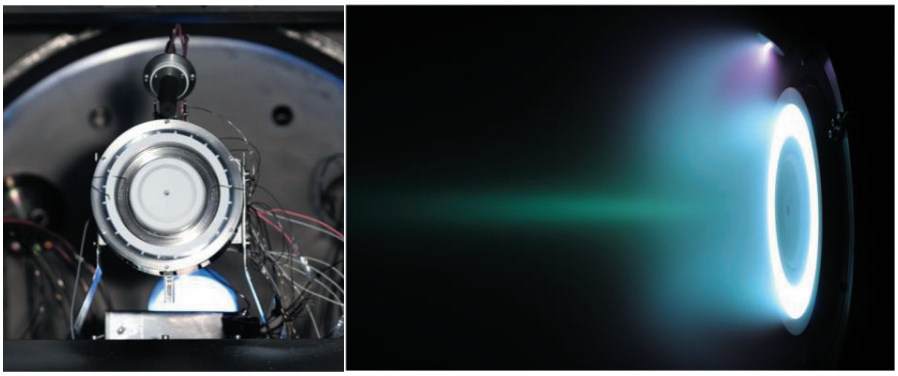

Figure 1. The HT5k thruster on the thrust stand (left) and during operation with xenon (right).

In the framework of the present research, funded by the European Space Agency under the ARTES 5.1 programme element, Sitael carried out a careful evaluation of alternative propellants (APs), considering all the most important driving requirements, to better understand the potential gains and consequences of utilizing APs. In order to minimize the changes on both the propulsion subsystem and the spacecraft system, the preliminary APs evaluation focused on the gaseous propellants. Based on the analysis of possible mission scenarios, pure krypton and krypton-xenon mixtures were thus selected as promising alternatives. An Initial Compatibility Test (ICT) campaign was then performed on the HT5k thruster, Sitael's 5kW class HET (see Fig. 1), with four different mixtures of krypton and xenon. Moreover, a simple semi-empirical model describing the thruster behavior with alternative propellants was developed in order to predict the thruster performance. The results of the ICT campaign were then compared with the reference thruster performance (using xenon propellant) and with the requirements of the mission scenarios previously identified.

In the following sections, the HT5k thruster and the test setup are presented. The HT5k design is based on magnetic coils and it allows a great flexibility in terms of topology and intensity of the magnetic field. The ICT campaign was performed in Sitael's IV10 vacuum chamber, one of the biggest facilities in Europe especially intended for testing high-power electric propulsion systems (up to 25 kW). In Section III, the thruster performance for the different krypton-xenon mixtures are presented and the ICT results are compared with the thruster nominal operation.

II. Test description

The initial compatibility test was performed at the end of 2014 in Sitael to investigate the performance of the HT5k thruster when operated with the selected alternative propellants, i.e. with pure krypton and three different mixtures of krypton and xenon. More in details, the HT5k was installed in the IV10 vacuum chamber and a full performance characterization was carried out using pure krypton and three Xe\Kr mixtures with a krypton mass flow rates corresponding respectively to 75%, 50% and 25% of the total anodic mass flow rate (AMFR). The main functional parameters of the HT5k thruster (thrust, specific impulse, and efficiency) have been recorded for each alternative propellant. Reliable ignition and stable operation of the thruster at the selected points were observed during the whole ICT campaign.

A. Test item: HT5k

The HT5k is a high power Hall Effect Thruster designed for operating in the 2 to 7 kW power range and especially intended for GEO and interplanetary applications. The thruster is based on a very flexible magnetic circuit composed of two main coils and two auxiliary coils in order to modify the intensity and the topology of the magnetic field. Due to this characteristic, the magnetic field has been modified to optimize the performance.

The nominal performances of the thruster are listed in Table 1.

Parameter	Unit	High Thrust Mode	High I_{sp} Mode
Nominal Operating Power	W	5000	4900
Nominal Discharge Voltage	V	300	600
Nominal Discharge Current	A	16.7	8.2
Thrust	mN	295 ± 5	205 ± 5
Xenon Flow Rate (anode)	mg/s	16.5	8
Cathode Flow Rate	mg/s	1	1
Specific Impulse (anodic)	s	1820	2610
Specific Impulse (total)	s	1720	2320
Total Impulse (expected)	MNs	~ 8.0 (7500 hrs)	~5.5 (7500 hrs)
Thruster Mass (Specific Mass)	kg (W/kg)	12.5 (400)	

Table 1. HT5k Performance with xenon.

The HT5k, as well as any Hall thruster, can be operated in a wide range of operating conditions that spans from the *High Thrust Mode*, suitable for orbit insertion, raising or repositioning to the *High Specific Impulse Mode*, typically used for station-keeping applications. The HT5k, installed on the thrust stand and during operation is shown in Fig. 1. The HT5k is usually equipped with the HC20 LaB_6 high-current hollow cathode developed by Sitael in the past few years. The major reason for using a LaB_6 cathode, compared to conventional refractory metal or impregnated-dispenser cathodes, is the robustness, high current density and long life exhibited by LaB_6 electron emitters.

B. Test setup

In Figure 2 the scheme of the gas feeding system is illustrated. Two different gas cylinders were coupled with the gas panel (for xenon and for krypton). The cathode has been fed only with xenon during the test (at the end of the test both cathode and anode have been fed with krypton to verify the possibility to use the krypton to operate the cathode). For the anode, two different mass flow controllers (mounted on different gas lines) have been used to control separately the krypton and the xenon mass flow. The connection between the two lines is positioned just before the 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.

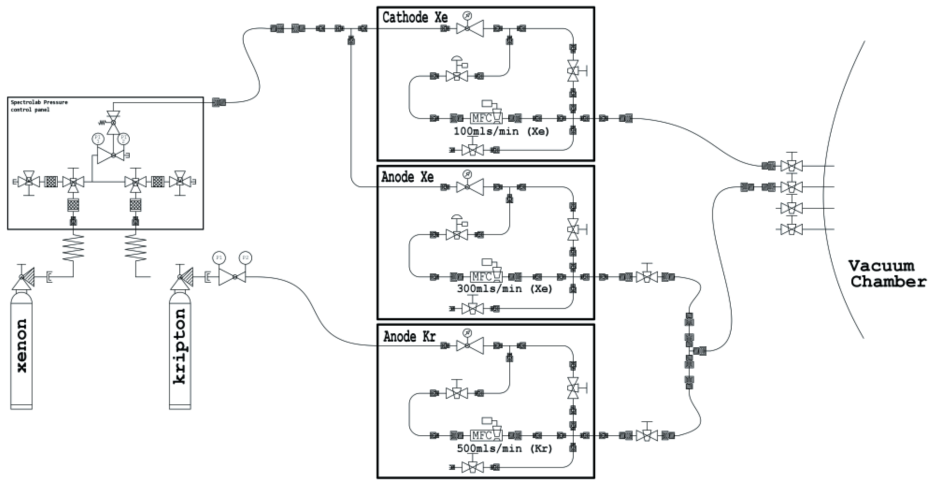

Figure 2. Gas feeding system scheme used during the test.

In Figure 3, a schematic of the thrust stand adopted during this test is represented, and in Table 2 the main thrust stand characteristics are shown. The thrust stand is mainly composed by a basic platform (1), a tilting platform (2), a sliding frame (5), a measure and calibrator module (6) and a thruster support (7).

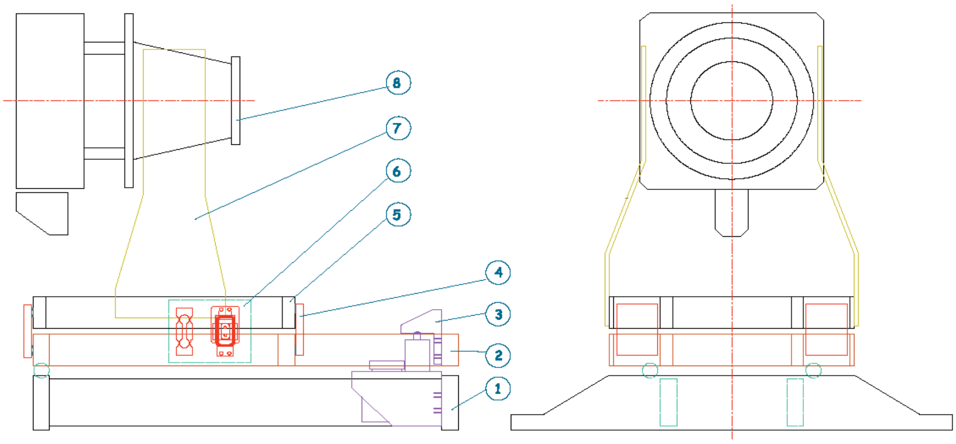

Figure 3. Schematic of the thrust stand.

Thruster max weight	20 kg
Thruster max size	ϕ 350 mm
Max Thrust	500 mN
Resolution	1 mN or better
Accuracy	1% (F.S.)

Table 2. Thrust stand characteristics.

Before the test start, the thrust stand was calibrated using a calibrated load cell. The thrust measures were then carried out at the thruster shut down to avoid any disturbances on the thrust signal (e.g. thermal drift). After each thrust measurement, using an electromagnet installed on the thrust balance, a known force was applied on the thrust stand (in two opposite directions) to verify the thrust stand calibration (the one performed with the calibrated load cell) for two different values of thrust.

C. Test matrix

In Table 3, the operating points investigated during the test for the different propellants are shown. A complete characterization has been carried out (taking into account the capabilities of the laboratory power supplies in terms of maximum current and voltage) for pure xenon, pure krypton and for the mixtures: 25%Kr-75%Xe, 75%Kr-25%Xe, 50%Xe-50%Kr.

Mixture	AMFR	Vd							
		250	300	350	400	450	500	550	600
Pure xenon	6			x	x	x	x	x	x
	8	x	x	x	x	x	x	x	x
	10	x	x	x	x	x	x	x	x
	12	x	x	x	x				
	14	x	x	x	x				
	16.5	x	x	x	x				
	18	x	x	x					
	20	x	x	x					

Mixture	AMFR	Vd							
		250	300	350	400	450	500	550	600
Kr / Xe mixtures	5					x	x	x	x
	6	x	x	x	x	x	x	x	x
	8	x	x	x	x	x	x	x	x
	10	x	x	x	x				
	12	x	x	x	x				
	14	x	x	x	x				

Table 3. Operating points tested during the performance characterization of the HT5k operating with different krypton-xenon mixtures.

III. Results and discussion

D. Thruster performance

The initial compatibility test was performed in Sitael at the end of 2014. In Figure 4 - Figure 8 the main results collected during the test are reported.

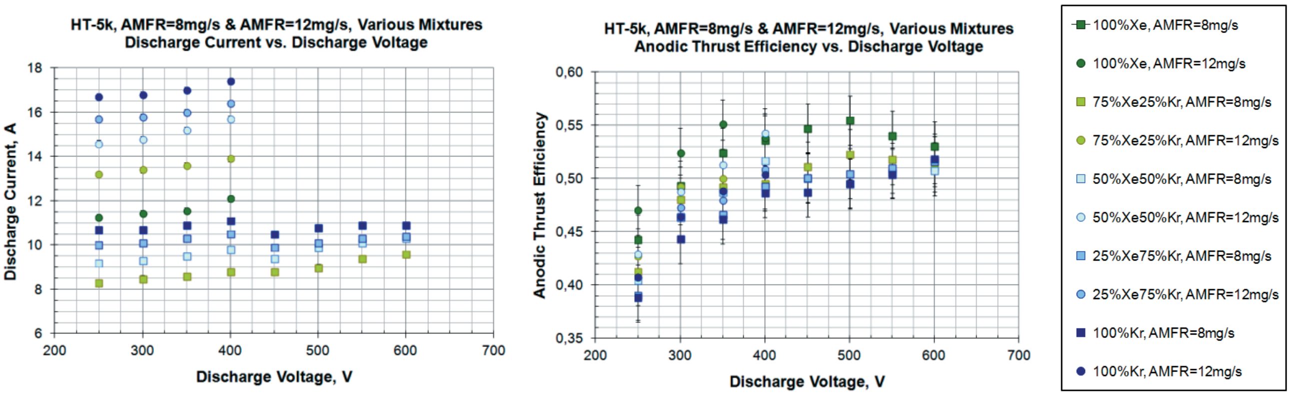

Figure 4. Discharge current (left) and anodic thrust efficiency (right) as functions of discharge voltage for various mixtures at different mass flow rates.

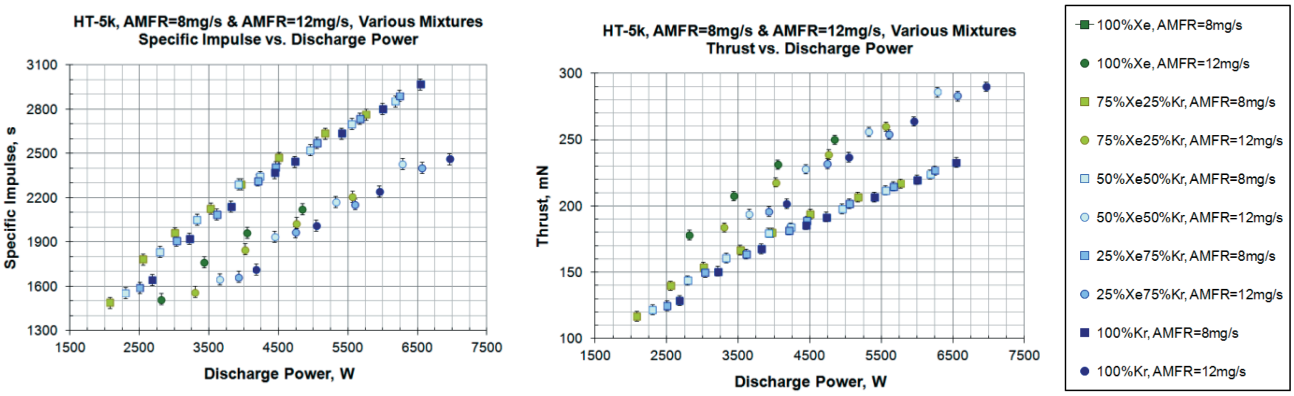

Figure 5. Specific impulse (left) and thrust (right) as functions of discharge power for various mixtures at different mass flow rates.

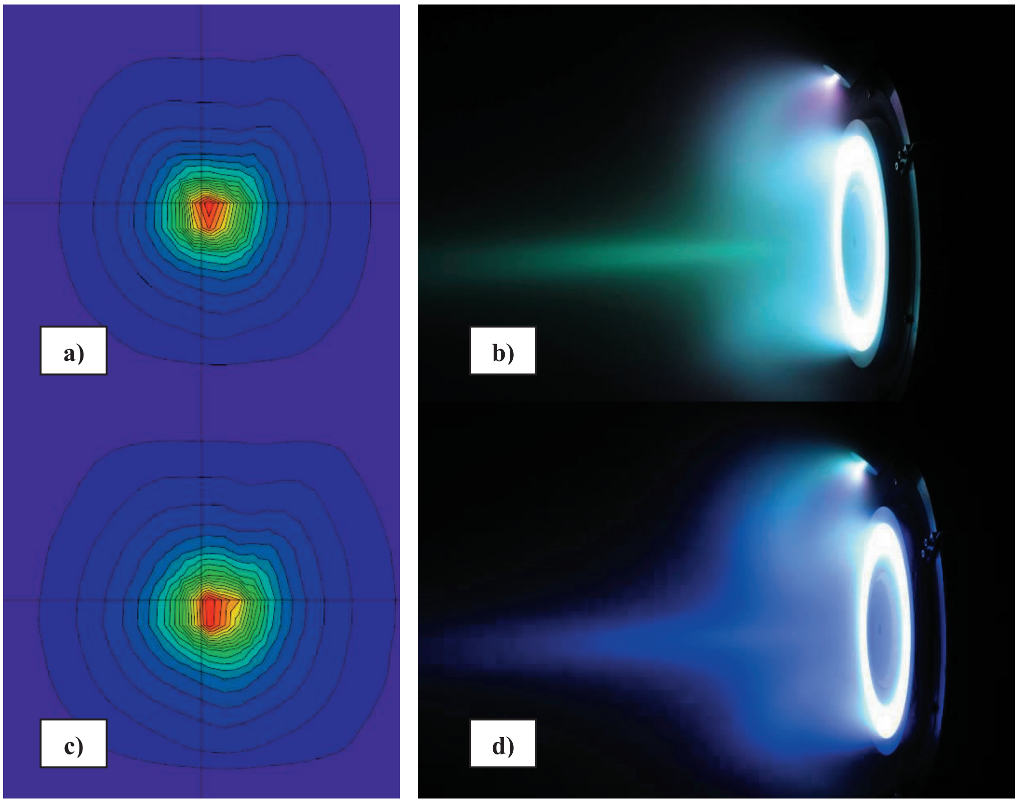

Figure 6. 2D distribution of ion current density (a) and photograph (b) of HT5k operating with pure xenon at AMFR=12mg/s, Vd=400V and Pd=4744W. 2D distribution of ion current density (c) and photograph (d) of HT5k operating with pure krypton at AMFR=12mg/s, Vd=400V and Pd=6960W.

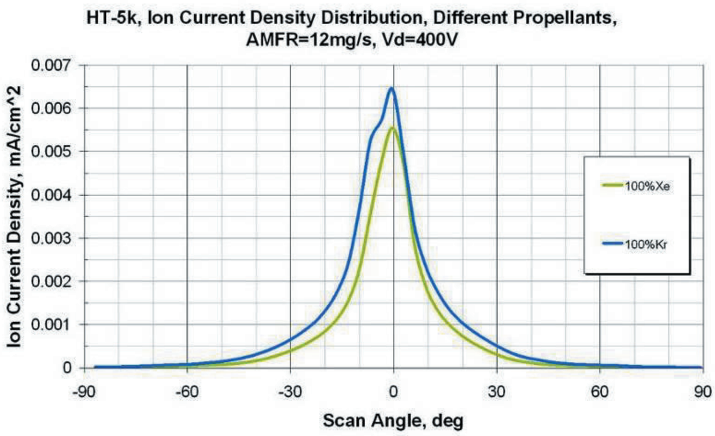

Figure 7. Distribution of ion current density of HT5k operating with different propellants (xenon and krypton) at AMFR=12mg/s and Vd=400V. The bump in the distribution is present only with the krypton (more tests are necessary to investigate this behaviour).

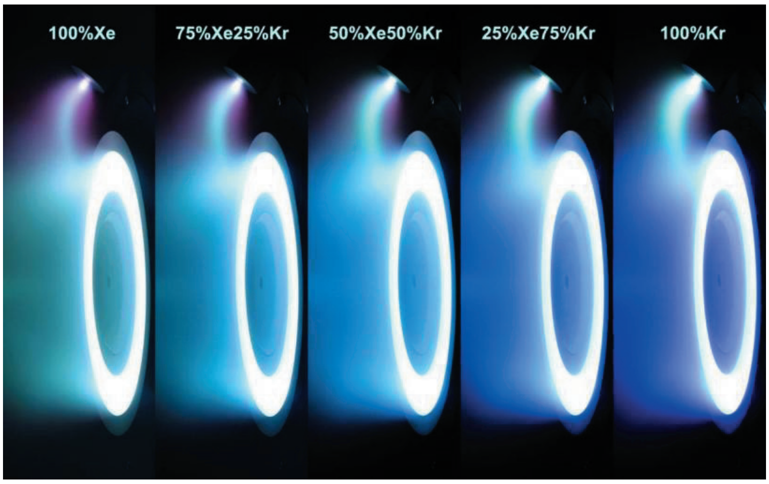

Figure 8. Photograph of near field plume region of HT5k operating with different mixtures.

The most important outputs of the test are summarized here below:

- The HT5k thruster has operated in a wide range of discharge voltages (250-600V) and powers (2-7 kW). The discharge was stable within the entire operating envelope covered during the test. In addition, thanks to the presence of two auxiliary coils, the magnetic field of the thruster has been optimized during the test for different conditions of discharge voltage, mass flow rate and type of propellant.
- The thruster was capable to reach high thrust efficiencies even with pure krypton as propellant (see Figure 4). In this case for most of the investigated points, the anodic thrust efficiency was in the range 40%-50%. For high voltage operation points (up to 600V), thrust efficiency has reached values slightly higher than 50%. Values of the anodic specific impulse have been found higher than 2000 s for most of tested operating points with maximum values close to 3000 s (see Figure 5).
- In general, with the transition from pure xenon to pure krypton the maximum of the thrust efficiency is shifting towards higher power levels. For pure xenon the maximum is found near to 4000-4500W whereas for pure krypton and for all the mixtures the thrust efficiency trend is growing at power levels higher than 6500W.
- The thruster has performed a 10-hour continuous firing test using a mixture with 75% of krypton and 25% of xenon. The discharge power was 4500W at a discharge voltage of 350V. With this operation conditions, the thruster reached a considerably high thrust efficiency of 48%. During the continuous firing test the thruster showed a stable discharge current trend with no issues in terms of flame out. This preliminary test was performed to verify the thruster capability to sustain the discharge for long periods. At the present the HT5k is performing an endurance test (500h) at the selected operating point (350V, 4500W) in order to validate the performance and to study the erosion effects using an alternative propellant (75%Kr-25%Xe).
- Plume measurements indicated that beam divergence calculated for 95% of registered ion current density is in a range of 35-37 degrees for pure xenon and 38-42 degrees for pure krypton. As expected, values of beam divergence for xenon/krypton mixtures depends on the amount of krypton in the mixture: higher the percentage of krypton in the mixture, higher the beam divergence.

IV. Conclusion

A test campaign was carried out for the 5kW Hall effect thruster designed and manufactured by Sitael, aimed at its functional characterization with potential alternative propellants. The HT5k was tested with pure krypton and three different xenon/krypton mixtures with 75%, 50% and 25% of krypton. The comparison of the performance when the thruster is operated with APs and with pure xenon has been performed. The test results, which are presented in details in Sec. III, are in substantial agreement with previous tests performed on different HET models[1,3,5] and with analytical predictions[9,10]. Stable operations and reliable thruster ignition were observed for the full operating envelope of the thruster. Thruster operations, in terms of thrust, discharge current, specific impulse and efficiency, have been characterized for different discharge voltages and anode mass flow rates. The beam divergence was assessed by means of plume measurements, showing an increase of the beam divergence when increasing the percentage of krypton in the propellant mixture. Similarly, the thrust efficiency decreases when the krypton fraction is increased. Nonetheless, even in the pure krypton case an anodic thrust efficiency of 40%-50% was recorded. In addition, the thruster has worked during a long firing test(10h) at fixed operating point (350V, 4500W) with a mixture of 75%Kr -25%Xe without any discharge instabilities or flame out. At the present the HT5k is performing an endurance test (at the same operating conditions: 350V, 4500W) of 500h to validate the performance and to study the erosion effects using a mixture of 75%Kr - 25%Xe as propellant.

Acknowledgments

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