Characterization of a 20 kW-class Hall Effect Thruster

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Abstract: Within the framework of the ESA TRP "Very High-Power Hall-Effect Thruster for Exploration", SITAEL developed and tested a new 20kW-class Hall thruster, the HT20k, together with the associated high current cathode, the HC60. The experimental characterization, carried out in SITAEL IV10 vacuum facility, ranged from 10 to 20 kW of discharge power and from 250 V to 1 kV of discharge voltage. During a 250 hours test campaign to characterize the thruster and assess the channel erosion, the HT20k demonstrated efficiency levels up to 68% and thrust values larger than 1 N. In addition, total specific impulse values of 3000 s were demonstrated at 800V and 20 kW.

Nomenclature

ΔV	=	delta V
d	=	average channel diameter
h	=	channel height
b	=	ceramic wall thickness
V_d	=	discharge voltage
P_d	=	discharge power
T	=	thrust
I_{tot}	=	total impulse
$I_{sp,a}$	=	anodic specific impulse
η_a	=	anodic efficiency
I_{sp}	=	total specific impulse
η	=	total thrust efficiency

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I. Introduction

Since their first appearance in western electric propulsion community, Hall Thrusters (HTs) received lots of attention due to their unique features: high thrust-to-power ratio, high efficiency, a nearly optimum specific impulse for a large variety of missions, high reliability and easy scalability. These advantages resulted in a constant growth in the use of Hall thrusters both for scientific and commercial applications.

Hall thrusters provide the best thrust-to-power ratio among the EP systems, allowing reasonable trip times and significant mass and cost savings compared to typical chemical thrusters. In addition, high power systems can boost the payload capability towards geostationary, cislunar and deep space missions. They could enable mass savings, launch flexibility, long interplanetary transfers and, depending on the total mission ΔV, more rapid missions with no gravity-assist constraints .

Orbit transfer in the Earth-Moon system, Near Earth Objects (NEOs) exploration, inner solar system and Mars robotic exploration and interplanetary transportation are some near- and long-term missions that could benefit from high power electric propulsion. Due to the rapid decrease of solar radiation flux with the distance from the Sun, high-power solar electric propulsion is inappropriate for missions beyond Mars orbit. Most likely, the near-term scenarios in which the adoption of such propulsion systems is already foreseen include NEO[1] and Mars exploration, large-payload space tug from LEO to GTO-GEO orbit and Cislunar missions.

Indeed, the increasing electric power available onboard modern spacecraft and the improvements in solar cell technology is paving the way to the use of high power EP systems in the Earth-Moon system. Platforms able to produce 20 kW of power are now a reality in the space communication satellite market (e.g. the SSL-1300 platforms, used by Intelsat 30, Intelsat 31, DIRECTV 14, and telecommunication satellites). Furthermore, power levels up to 25 kW are planned for the next future[2].

Hence, the development of high power Hall thrusters (>10 kW) represents an important milestone to improve the propulsion systems capabilities for space exploration.

SITAEL has recently developed and tested a new 20 kW-class Hall thruster, the HT20k, together with a high current hollow cathode, the HC60. These activities were funded by the European Space Agency under the Technology Research Project (TRP) No. AO/1-8031/14/NL/KML"*Very High-Power Hall-Effect Thruster for Exploration".*

II. Overview of High-Power Hall Thrusters

In the field of high power Hall Thrusters, the first prototype was the Fakel SPT-290, which operated from 5 to 30 kW of discharge power and was able to produce up to 1.5 N of thrust[3,4]. Later, the Fakel SPT-200 (a smaller version with 200 mm of outer channel diameter), was tested up to 13.2 kW of discharge power [5].

Whereas in Russia and former USSR countries, the very high-power Hall thruster technology was already mature during the early '90s, in western countries, most of the research efforts in this field have been performed in the last 20 years. In particular, the first very high-power prototype developed in the USA was the NASA T-220, a 10 kW-class HT[6]. This prototype, greatly inspired by Russian SPT thrusters, was developed and tested at NASA Glenn Research Center in 1998.

In the following years, especially from 2000 to 2005, NASA GRC extensively worked on high power Hall thruster prototypes. The NASA-457M, a 50 kW-class HT, was tested up to 72 kW of discharge power, producing 2.9 N of thrust[7]. Later, it was tested with krypton up to 1 kV of discharge voltage and with specific impulses up to 4500s[8]. Another 50 kW Hall thruster, the NASA-400M, was designed and tested at NASA GRC. As confirmed by the experimental results in terms of specific impulse and anodic efficiency [9], the thruster was conceived to have better performance with krypton with respect to the NASA-457M.

A new push to the development of high-power HTs has been taking place since the beginning of this decade, first with testing of an updated version of the NASA-457M (labeled NASA-457M v2)[10] and then, with the NASA-300M, a 20 kW-class thruster. The latter demonstrated 73% of anodic efficiency at 500 V and 20 kW of discharge power with xenon and 68% at 600 V and 20 kW running on krypton[11]. This thruster was later upgraded to a magnetically-shielded version, the NASA-300MS[12].

Recently, NASA GRC and Jet Propulsion Laboratory are collaborating to develop a 12.5 kW magnetically-shielded Hall thruster, the HERMeS[13].

Other high-power Hall thruster prototypes are the Aerojet Rocketdyne XR-12, tested at a power level of 12 kW[14,15] and Busek BHT-20k[16]. In Europe, Snecma developed the PPS-20k ML. A maximum thrust of 1050 mN was obtained at 22.4 kW of total power and with an anodic specific impulse of 2700 s[17].

	Voltage [V]	Discharge Power [kW]	Thrust [N]	Anodic Efficiency	Anodic Specific Impulse [s]	Outer channel diameter [mm]
SPT-200	200-600	2-13.2	0.15-0.552	0.44-0.63**	1422-2950***	200
SPT-290	Up to 600	5-30	Up to 1.5	Up to 0.7	Up to ~ 3000	290
NASA T-220	300-500	6.2-10.7	0.318-0.524	0.52-0.62	1801-2550	220
NASA-300M	200-600	10-20	Up to 1.13	0.57-0.73	1709-3154	300
NASA-400M	200-600	4-47	0.27-2.1	0.43-0.72	1320-3370	400
NASA-457M	300-650	9-72	0.37-2.9	0.46-0.65	1741-3245	457
BHT-20k	200-500	5-20	Up to ~ 1	0.51-0.69	1430-2630***	
XR 12	175-450	2-12	Up to 0.8	Up to 0.68	Up to 2550	
PPS-20k ML	100-500	2.6-23.5*	Up to 1.05	~0.6**	Up to 2700	320

**Total Power **Total Efficiency ***Total Specific Impulse*

Table 1 Performance comparison of different high power Hall thruster operating on Xe.

III. Thruster and Cathode Design

The 20 kW-class Hall thruster available at SITAEL, the so-called HT20k, resulted from the activities performed at SITAEL between April 2015 and June 2017 in the framework of ESA TRP "*Very High-Power Hall-Effect Thruster for Exploration"*.

This TRP project was aimed at performing all necessary preliminary activities to develop a European very high-power Hall thruster capable of high performances in terms of thrust, thrust-to-power ratio, efficiency and lifetime capabilities. Such precursor activities included the design, manufacturing and long-duration testing of the thruster and the associated high-current cathode.

The thruster design is based on the extensive experimental and theoretical heritage of SITAEL in the field of HTs. Specifically, a theoretical scaling methodology has been used to size the HT20k and for the preliminary estimation of its performance envelope[18-21], along with the design of a hollow cathode based on a model developed in-house[22].

The main design drivers of the HT20k were compact design, reduced mass and volume, high versatility in terms of specific impulse and power levels and capability of having acceptable performance with alternative propellants (e.g. krypton). In particular, the HT20k target performance, at a discharge power of 20 kW, was a thrust efficiency higher that 60%, about 1 N of thrust, a specific impulse of 2500 s and a total impulse greater than 30 MNs.

A. Thruster Scaling

The HT20k was scaled according to the scaling model described in detail in Ref.21, where a thruster of optimized performance (i.e. Fakel SPT-100) is taken as a reference.

Given a fixed discharge power, P_d, of 20 kW, a wide range of configurations (defined in terms of channel geometry and discharge voltage) were analyzed. For each configuration, performance results and the required magnetic field peaks were estimated.

In the typical design of a Hall thruster, the channel dimensions, in terms of average diameter, d, and channel height, h,are scaled to keep the physical processes in the channel unchanged with respect to the reference thruster. Once the plasma density and the discharge voltage are fixed, the channel frontal area, dh, scales linearly with the mass flow rate, which is in turn proportional to the discharge current. As a consequence, a thruster operating at any power can be derived by choosing the appropriate values of the channel cross section $d \cdot h$. On the other hand, with this simple approach, when scaling up to very high-power levels, the overall thruster dimensions increase significantly.

Therefore, to obtain a more compact solution, the HT20k design approach consisted in choosing a particle density higher than the one of the reference thruster. Higher plasma densities imply increased wall losses. Nevertheless, the effect of these losses in determining the overall thruster performance tends to become progressively less relevant as the discharge power and the discharge voltage are increased.

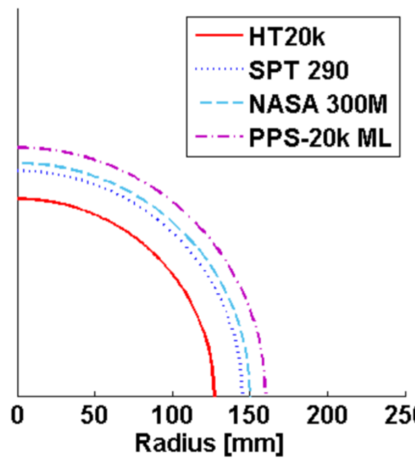

Figure 1 Outer channel radius comparison for various 20 kW-class Hall thrusters.

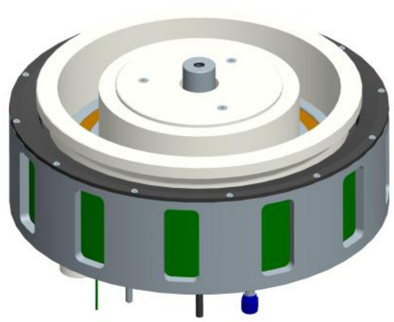

Figure 2 CAD drawing of the HT20k and HC60 (centerally-mounted).

As a result, a relatively compact high-power thruster, with respect to HTs of the same power level, is obtained (Figure 1). At the same time, a high thrust efficiency is also maintained.
Furthermore, a Hall thruster designed in this way is expected to operate better with alternative propellants (e.g. krypton).

Krypton, which has higher ionization energy than xenon, leads to reduced thrust efficiency. Despite this, the ionization processes inside the thruster can be improved thanks to the higher plasma density and the overall performance with respect to “traditional” HT designs operating on krypton is thus increased.

Among all the investigated configurations, the one compliant with the design drivers in terms of performance and envelope was selected, which corresponds, as seen in Figure 1, to a thruster with an outer channel diameter of 254 mm.

B. Thruster Design

The HT20k thruster design comprises magnetic coils, screens, pole extensions, a discharge channel made of boron nitride and a central cathode, the HC60, specifically developed for this thruster.

The magnetic circuit was designed to provide an optimized magnetic field at the exit of the channel and it is able to produce magnetic induction peaks on the channel centerline up to 40 mT, without any magnetic saturation in the circuit. This high value allowed an extensive thruster characterization from low to high voltages.

As the reduced dimensions of the HT20k can negatively influence the thermal behavior of the thruster, leading to very high temperatures for various thruster components, a proper thermal design is fundamental. Thermal simulations were performed to evaluate the overall thermal stresses of the HT20k design. All the dominant power losses were included, i.e. the power deposition to the walls, to the anode and the power dissipated by the coils, together with the heat loads coming from the centrally-mounted cathode. With the purpose of investigating the structural integrity of the HT20k design, thermo-mechanical analyses were carried out. Proper gaps were taken into account to avoid mechanical interferences between different components due to thermal expansion.

C. High Current Cathode

An orificed hollow cathode has been designed to be coupled with HT20k. The cathode, called HC60, was designed to provide currents up to 60 A at mass flow rates between 2 to 6 mg/s with both xenon and krypton propellants. The cathode lifetime, as computed with the aid of a numerical model previously developed at SITAEL[22], is expected to be higher than 10^4 hours. The cathode mass, without cables, is about 450 grams.

The cathode has a lanthanum hexaboride (LaB_6) emitter, selected based on its features of longer expected lifetime and lower evaporation rate at the required discharge current despite higher work function compared to the traditional dispenser emitters[24]. A LaB_6 cathode relaxes the gas purity requirements due to reduced sensitivity to contaminants and does not require a lengthy activation procedure to initiate the electron emission.

The cathode includes a heater, used to preheat the emitter during the ignition phase, which allows establishing the discharge with 165 W of heater power at 5 mg/s of xenon and 500 V of applied voltage between keeper and cathode. Heaterless ignitions were performed as well at the expense of higher keeper voltage and mass flow rate, namely about 900 V and 12 mg/s of Xe, respectively. Similar ignition parameters were used to start the cathode with krypton. HC60 was initially characterized in a stand-alone setup, showing a successful operation with both propellants in the investigated range of operating conditions as detailed in Ref. 25. The cathode was then coupled with HT20k, both centerally-mounted and in external configuration, as is discussed in the following sections.

IV. Experimental Campaigns

The HT20k was characterized with xenon during two experimental campaigns. The first one was carried out from August to October 2016, whereas the second one from March to May 2017.

A main limiting factor for the development of a 20 kW thruster, besides the high costs of any test campaign with xenon as propellant, is the availability of suitable test facilities. In fact the facility shall be able to guarantee high vacuum levels and to manage the thruster plume. Secondly, a proper diagnostic system is also necessary.

D. Test Facility and Diagnostic

The two experimental campaigns were performed in SITAEL's IV10 vacuum facility, the largest vacuum chamber currently available in Europe for electric propulsion testing. IV10 technical specifications are reported in Table 2. The dimensions of the chamber are the primary characteristics to be considered to allow for a free expansion of the beam so as to keep the points of particles impingement as far as possible from the thruster. Of more importance is a proper pumping system able to guarantee high vacuum levels.

Vacuum Chamber	
Inner diameter	5740 mm
Inner free diameter	5400mm
Length of the cylindrical section	6000 mm
Opening cap diameter	5740 mm
Vacuum vessel total length	9400 mm
Internal Free Volume	>160 m^3
Ultimate Vacuum	< $3*10^{-9}$ mbar
Operating Vacuum	< $3*10^{-6}$ mbar

Table 2: Main technical specifications of the IV10 vacuum facility.

Thrust Stand	
Max. tolerable thruster weight	75 kg
Max. admissible thruster size	ϕ 400 mm
Max. Thrust	3 N
Min. Thrust	30 mN
Resolution	2 mN
Accuracy	1%

Table 3 Characteristics of the thrust stand.

Figure 3 The IV10 test facility.

The ultimate pressure measured in SITAEL IV10 is 10^{-9} mbar, whereas the four-stage pumping system allows a pumping speed of more than 300.000 l/s on Xe and a background pressure lower than 5×10^{-5} mbar in case of HT20k firing.

The chamber is fully lined with LN2 cooled shrouds, capable of full thermal space simulation also in case of high heat-load items. The low temperature allows the test article to undergo radiative cooling in operating and non-operating conditions.

The technical characteristics of the IV10 chamber are adequate to eliminate the facility effects on thruster performance measurements due to contamination, background pressure and electromagnetic effects of the chamber wall, thus making the facility well suited for 20 kW-class thruster testing.

Regarding the diagnostics, a new single axis thrust stand was designed for this campaign. The thrust stand is able to operate with thrusters of relatively larger sizes and weights and to measure up to 3 N of thrust. The thrust stand is also equipped with an electromagnetic calibrator, added to check the proper functioning of the stand during the test and is capable of generating a reference force when requested.

In order to investigate the erosion phenomenon affecting the HT20k ceramic channels, the Advanced Electric propulsion Diagnostic (AED) system was used[26]. AED is an automatic system, made of two structured light vision systems, joined with a robotic rotating arm that enables the measurement of the thruster channel profile at different times. The two laser-camera systems are used to perform the analysis of both the inner and outer ceramic walls when the thruster is off and after an appropriate cooling time. As a result of the images taken by the AED system, the channel profile can be reconstructed and its evolution can be assessed. In the framework of the present project, the AED system was upgraded to be compatible with an outer channel diameter of up to 300 mm.

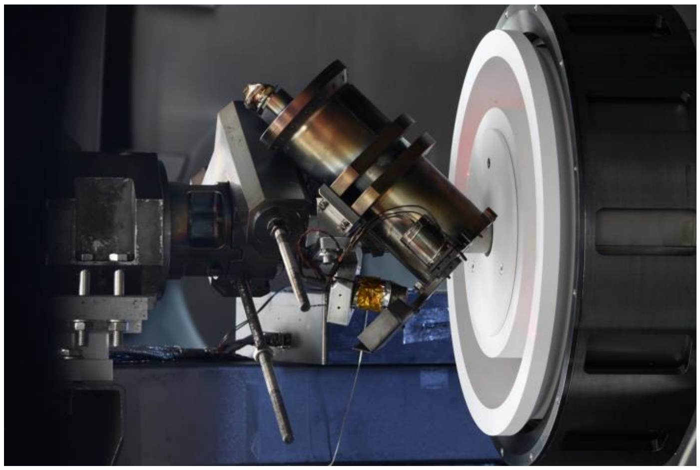

Figure 4 HT20k with the Advanced EP Diagnostic (AED) System.

E. First Test Campaign

During the first campaign, the thruster was only equipped with a centrally-mounted cathode and it was characterized with Xe from 300 V to 800 V of discharge voltage and from 10 to 20 kW of discharge power (in addition with a point at 1 kV and 10 kW of discharge power).

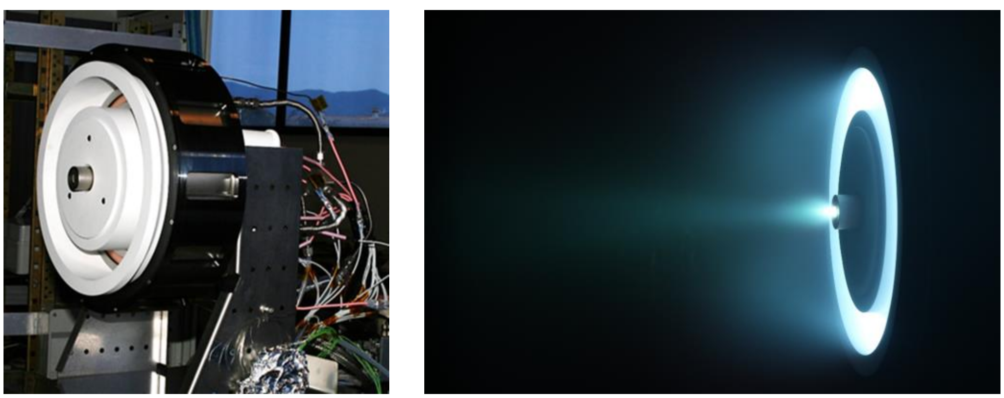

Figure 5 HT20k mounted on the thrust stand for the first campaign (left), firing during characterization (right).

The aim of the first test campaign was to find the optimal magnetic induction peak that minimizes the amplitude of the discharge current oscillations. During the campaign, the HT20k was tested with magnetic induction peaks ranging from 20 mT to 30 mT.

In this configuration, the thruster demonstrated a peak of anodic efficiency of 68% and it was able to produce thrust levels larger than 1N at 20kW of discharge power. Moreover, the thruster unit demonstrated a total specific impulse of 3060 s at 800 V of discharge voltage. On the other hand, a maximum anodic specific impulse of 3800 s was reached at 1 kV and 10 kW of discharge power.

After the characterization, the HT20k was fired for 30 hours at 20 kW and 400 V of discharge voltage in order to assess its thermal behavior. The thermal transient, shown in Figure 6, was acquired by three thermocouples placed on the back-plate of the thruster. Two of them were located in the proximity of the inner and outer coils and a third one on the cathode back flange. The thruster reached steady-state conditions after approximately 4 hours. The steady-state temperatures were 402 °C and 408 °C for the inner and outer coil, respectively, and 390 °C for the cathode back flange.

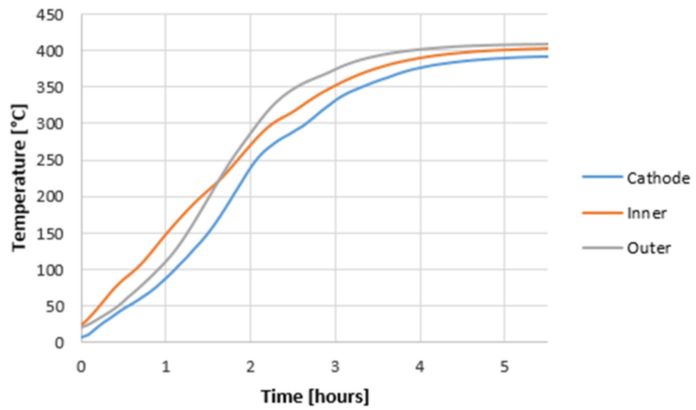

Figure 6 Thermal transient of the HT20k at 400 V and 20 kW.

F. Second Test Campaign

During the second test campaign, the HT20k was characterized at lower discharge voltages and with a different relative position of the electrodes.

Two spacers were placed, respectively, between the anode and the ceramic channel and between the cathode holding assembly and the thruster back flange. As a result, a shorter discharge channel was obtained and the central cathode was moved backward. To gain redundancy, an externally-mounted cathode was also added.

The thruster was characterized at a constant value of the magnetic induction peak (20 mT), at discharge voltages ranging from 250 V to 450 V, and both in external and central cathode configuration. This second experimental campaign allowed the evaluation of the thruster performance at low voltages for different cathode positions and to compare the resulting performance data with those obtained from the first campaign.

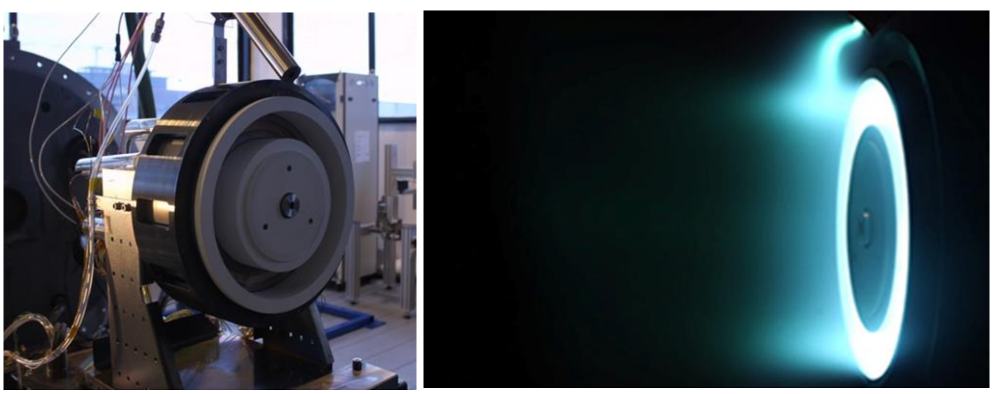

Figure 7 HT20k mounted on the thrust stand for the second campaign (left) and firing at 300 V and 15 kW during the 150 hours test (right).

As shown in Figure 8, higher thrust levels were measured as the power increased. The thruster produced a thrust up to 5% higher with respect to the previous characterization, which also means higher values of efficiency and specific impulse.

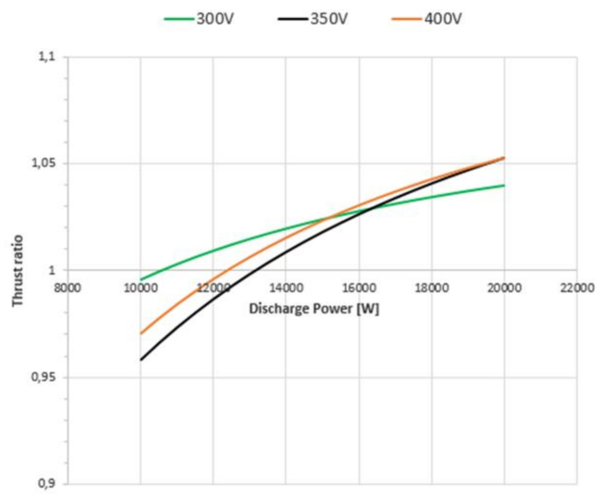

Figure 8 Comparison of the HT20k between the first and the second campaign with the central cathode at various discharge voltages. The ratio is made on the measured thrust between second and the first campaign.

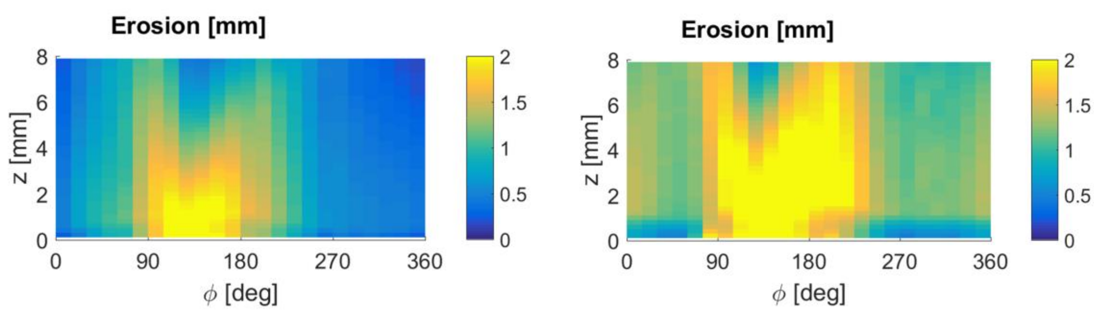

Figure 10 Erosion of the inner (left) and outer (right) ceramic for the HT20k after 150 hours at 300 V and 15 kW with external cathode.

Thruster operating parameter and performance	
Voltage [V]	300-1000
Power [kW]	10-20
Efficiency	Up to ~ 70%
Thrust [mN]	300-1100
Specific Impulse [s]	2000-3800

Table 4 HT20k Operating parameters and performance.

After this second characterization, the HT20k was fired for 150 hours at 15 kW and 300 V using the external cathode. An AED measurement was performed at time intervals of about 40 hours. As presented in Figure 10, the inner wall shows lower erosion with respect to the outer. In particular, a non-symmetric behaviour with respect to the azimuthal angle was identified. For the inner channel, the maximum erosion of the outer wall is found approximately in a region 105° to 165° from the cathode position in the azimuthal direction. The maximum erosion rates on the outer and inner walls were, respectively, ~8 µm/h and ~5 µm/h.

All in all, the two characterization campaigns permitted to extensively study the thruster behavior in various operating regimes. The HT20k operating parameters and performance can be thus summarized according to Table 4.

V. Conclusion

The HT20k was characterized up to 1 kV of discharge voltage with xenon propellant, highlighting the versatility for 10-20 kW power range applications. The thruster design was based on the scaling methodology developed in SITAEL during the past years. In the final scaling iterations, an alternative thruster configuration with a reduced size was selected. This approach was adopted due to the lower influence that the wall losses have at higher power levels on the overall performance and according to the greater influence of thruster dimensions and weight on the product competitiveness.

Once the thruster dimensions have been fixed, the optimization of the magnetic circuit was carried out. A proper magnetic field topology was designed to obtain an effective acceleration of the ions near the exit of the channel. In addition, the circuit was designed to withstand magnetic induction peaks of 40 mT on the channel centerline. The characterization, however, showed that a peak of 40 mT was not needed. Thus, the magnetic circuit can become less heavy in view of a future thruster design optimization.

The reduced thruster dimensions requires a careful thermal analysis during the design phase. However, during 30 hours of wear test at 400 V and 20 kW, the thruster did not show any thermal issue and the back plate reached slightly more than 400 °C of steady-state temperature.

After the two test campaigns, the HT20k accumulated 250 hours of firing, a significant result for a thruster in this power class. Nevertheless, in order to exploit this high-power thruster in missions that require long operational lifetimes (e.g. cislunar, Earth-Moon cargo missions), the thruster channel erosion should be reduced.

As a matter of fact, a magnetically-shielded version of the thruster is under development. Lessons learned from the development of the HT5k LL [27] thruster will be implemented in the new design. In particular, to account for the different emerging scenarios and the near-term perspectives in which the adoption of high-power EPS may play a strategic role, there is a need to further optimize the HT20k operation, at high voltages and high specific impulse levels as well as at low voltages and high thrust levels.

The data collected from the two campaigns, the parallel activities currently ongoing on the HT5k LL thruster and the expected improvements in SITAEL's high current hollow cathode, the HC60, will greatly contribute to the development of the new HT20k.

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