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DEVELOPMENT OF A 20 kW-CLASS HALL EFFECT THRUSTER

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ABSTRACT

Novel concepts for high-power electric propulsion (EP) spacecraft are being worldwide pursued to facilitate in-space transportation of large masses in support of manned space programs, orbit transfer, and exploration missions. Among the different electric propulsion systems, Hall effect thrusters (HETs) provide an optimal trade-off between specific impulse and thrust.
SITAEL is currently undertaking preparatory activities in the field of very high power Hall effect electric propulsion. In the frame of the ESA project “Very High-Power Hall-Effect Thruster for Exploration”, SITAEL is developing, designing, manufacturing and testing a new 20kW class Hall effect thruster, the HT20k, together with the associated high current hollow cathode, the HC60.
This paper provides the description of the development approach and the status of the project.

1. INTRODUCTION

Advantages offered by the high specific impulse of electric propulsion systems are well recognized and the use of EP system is growing wider for military and commercial applications as well as scientific missions. In particular, Hall effect thrusters offer a higher thrust-to-power ratio with respect to other EP technologies, allowing for acceptable missions durations. Therefore, the development of high power HETs (>10kW) represent an important step to improve the propulsion systems capabilities for space exploration. In this context, the “Very High-Power Thruster for Exploration” project aims at the identification of subsystem and unit requirements, along with the design, manufacturing and long duration testing of a 20kW-class HET and a high current hollow cathode. Specifically, a broadly validated theoretical scaling methodology has been used to size the HT20k, which is expected to provide a thrust efficiency of about 60%, thrust levels higher than 1 N and a total impulse above 30 MNs, thus enabling large Δv missions. In this paper, a non-traditional approach for the thruster design is presented, offering an alternative design option for future high power HETs. In addition, the main design features of the high current hollow cathode are described.

2. HIGH POWER HETS OVERVIEW

Hall effect thrusters are plasma propulsion devices used for spacecraft maneuvering, station keeping and orbit transfer missions. First studies about Hall thrusters began in the early ’60 independently in the URSS and USA. However, Hall thruster technology was developed to flight status in the former Soviet

Union, whereas the US research activities focused on ion thrusters [1][2]. Two types of modern Hall thrusters were developed in the URSS, the stationary plasma thruster (SPT) and the thruster with anode layer (TAL).
The first very high power SPT thruster was the Fakel SPT-290, a 25kW class HET. It operated from 5 to 30kW producing up to 1.5N of thrust [3][4]. A smaller version, the SPT-200, was tested up to 13.2kW [5].
Hall thruster technology spread in western countries after the fall of the iron curtain. First activities related to very high power applications started at NASA's Glenn Research Center (GRC) in 1998 with the 10kW class thruster NASA T-220 [6]. Most of the developments in this topic at NASA GRC took place in the last decade, especially in the 2000-2005 period, starting with the design and assembly of the NASA-457M, a 50kW class SPT type Hall Thruster. This thruster was tested up to a discharge power of 72kW, producing 2.9N of thrust [7]. It was also operated with krypton demonstrating a peak in specific impulse of 4500s at 1000V and 50kW of discharge power [8].
Further studies led to the development of the 50kW NASA-400M. Reduced channel dimensions were adopted in order to improve the thruster operation with krypton. As a result, the anodic efficiency was consistently higher than the NASA-457M when Kr was used as propellant, as well as the peak value of discharge specific impulse [9].
In addition, NASA designed, assembled and tested the NASA-300M, a 20kW class Hall thruster. The thruster demonstrated 73% of anodic efficiency with xenon at 500V and 20kW of discharge power. Furthermore, testing with krypton as propellant at 20kW and 600V demonstrated peak anodic efficiency of 68% [10].
In recent years, many western private companies also developed high power Hall thruster prototypes. In particular, Busek developed the BHT-20K. The thruster was operated from 5 to 20kW and it produced a thrust of 1N with a specific impulse of 2500 s and at a discharge power of 20kW [11]. Moreover, Aerojet Rocketdyne developed the XR-12. The thruster operated at a power level of 12kW producing a thrust of 815mN and a total specific impulse of 1961 s [12][13].
In Europe, in the frame of the HiPER project, Snecma developed the PPS-20k ML, a 20kW class Hall thruster. It was tested from 2,6kW to 23,5kW of total power with xenon as propellant. A maximum thrust of 1050 mN was obtained with anodic Isp of about 2700 s at 22.4 kW of total power [14].
To sum up, performance comparison of different high power Hall thrusters is reported in Table 1.

Table 1. Comparison of thruster performance of different high power Hall thrusters operating with Xe.

	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	0.46-0.72	1741-3245	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

3. THE HT20K THRUSTER

The HT20k is a SPT type, high-power Hall effect thruster designed to operate at a nominal discharge power of 20kW.

The thruster design is based on the extensive experimental and theoretical heritage of SITAEL in the field of HETs. Specifically, a broadly validated theoretical scaling methodology (see [15]) has been used to size the HT20k and for the preliminary estimation of its performance envelope. Furthermore, thermal and mechanical analyses have been carried out.

3.1. Thruster Requirements

The HT20k has been designed in order to operate at a discharge power of 20kW with a thrust efficiency higher that 60% and producing a thrust, a specific impulse and a total impulse greater than 1N, 2500s and 30MNs respectively.

3.2. Thruster Design

The thruster design features magnetic coils, screens and polar expansions. The magnetic circuit is designed to produce an optimized radial magnetic field at the exit of the thruster accelerating channel. This design allows obtaining a highly symmetric magnetic lens that accelerates the ions axially, reducing the plume divergence. In addition, the magnetic circuit was designed and optimized in order to allow, at the channel centerline, a maximum value of the magnetic field induction of about 40 mT, before magnetic saturation occurs.

The discharge channel is an annular U-shaped channel made of boron nitride (BN) and silicon dioxide (SIO2) composite ceramic. Moreover, in order to improve the thruster-cathode coupling [16], the HT20k HET features an internally mounted hollow cathode, the HC60, Figure 1.

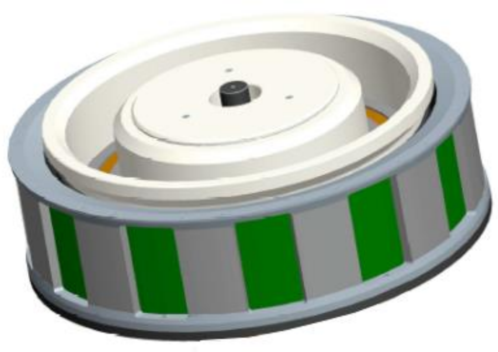

Figure 1.CAD drawing of the HT20k

In addition, in order to test the effect of different anode and cathode positioning, a set of calibrated spacing rings were designed. These rings, placed between the anode and the ceramic channel and between the cathode retaining system and the thruster back flange, allow for changing the anode and cathode position with respect to the main thruster structure.

The theoretical scaling methodology used to size the HT20k is described in details in [15].

In the scaling of a HET, a thruster of optimized performance is assumed as reference (i.e. Fakel's SPT-100) and a set of fundamental parameters is selected in order to define the thruster geometry and the nominal operating point.

In particular, the chosen parameters, which can be tailored independently in the preliminary design phase, are the following:

1. channel mean diameter d,
2. channel height h,
3. channel length L,
4. ceramic wall thickness b,
5. discharge voltage V_d,
6. discharge power P_d.

The thruster performance are then obtained as a function of the fundamental parameters through a set of scaling relations describing the acceleration processes inside a HET.

By using the scaling method, which has six degrees of freedom, the thrust (T), the anodic specific impulse (I_{sp}), the anodic thrust efficiency (η), and the total impulse (I_{Tot}) can be obtained for any given set of input parameters.

In the usual design of a Hall thruster, the channel dimensions (in terms of mean diameter and height) are scaled in order to keep the physical processes in the thruster unchanged with respect to the reference thruster, i.e. maintaining the same plasma density as in the reference case.

Therefore, the channel area, which is proportional to hd, is assumed to scale linearly with the mass flow rate. Indeed, the latter is proportional to the discharge current and thus to the discharge power. Consequently, if for the sake of simplicity, the discharge voltage is assumed to be the same of the reference thruster, the channel area scales linearly with the discharge power.

Therefore, in theory a thruster operating at any power level with the same performance parameter (specific impulse, thrust, efficiency) of the reference thruster can be obtained only by choosing the appropriate value of hd.

However, when scaling up to very high power levels the application of this scaling approach leads to very heavy and large devices. Hence, in the frame of the present project, with the purpose of increasing the

thrust to mass ratio of the thruster, we decided to use a design approach different from the traditional one and to design a thruster that operates with a density higher than the SPT-100.
This increase of the plasma density implies an increase of the wall losses [15]. However, the effect of wall losses on thruster performance becomes less relevant for increasing discharge power.
Thus, using this approach a very compact high power HET can be obtained, maintaining at the same time a high thrust efficiency.
Furthermore, an HET designed following this approach is expected to operate better with alternative propellants as krypton, which have higher ionization energy than xenon.
Indeed, due to its higher ionization energy with respect to Xe, the thrust efficiency is typically reduced when Kr is used as propellant. However, the design of the HT20k should improve the ionization processes inside the thruster and thus increase the overall thruster efficiency with respect to “traditional” HETs when Kr is used as propellant.
In order to properly size the ceramic wall thickness, a relation between the erosion rate and the thruster operational parameters was derived.
The erosion rate at the exit plane of the thruster (ε_{ex}) can be expressed as a function of the thruster operating parameters

$$\varepsilon_{ex} = Y J_{iw(ex)}, \tag{1}$$

where $J_{iw(ex)}$ is the ion current to the wall per unit surface at the exit of the channel and Y is the sputtering yield. The latter can be considered proportional to ion kinetic energy E_i [17]

$$Y \propto \frac{E_i}{E_{th}} \propto \frac{u_{i(ex)}^2 m_i}{E_{th}}, \tag{2}$$

where E_{th} is the threshold energy, $u_{i(ex)}$ is the ion velocity at the channel exit and m_i is the propellant mass. Furthermore, we have that,

$$J_{iw(ex)} \propto u_B n_{ex}, \tag{3}$$

where u_B and n_{ex} represent respectively the Bohm velocity and the plasma density at the exit of the channel. In particular, n_{ex}, u_B and $u_{i(ex)}$ are related to the density at the entrance of the channel (n_{in}) and to the discharge voltage (V_d) as follows,

$$n_{ex} \propto \frac{n_{in}}{\sqrt{V_d}}, \tag{4}$$

$$u_{i(ex)} \propto \sqrt{\frac{V_d}{m_i}}, \tag{5}$$

$$u_B \propto \sqrt{\frac{T_e}{m_i}} \propto \frac{1}{\sqrt{m_i}}. \tag{6}$$

In addition, n_{in} can be written as,

$$n_{in} \propto \frac{\dot{m}}{A\sqrt{m_i}}, \tag{7}$$

where $\dot{m}$ and A represent the thruster mass flow rate and channel area respectively.
Therefore, the erosion rate can be computed as,

$$\varepsilon_{ex} \propto \frac{n_{in}\sqrt{V_d}}{E_{th}} \propto \frac{\dot{m}\sqrt{V_d}}{E_{th} A m_i}. \tag{8}$$

The ratio of the erosion rate of the scaled thruster with respect to the SPT-100 is

$$\frac{\varepsilon_{ex}}{\varepsilon_{SPT}} = \frac{n_{in}}{n_{SPT}}\sqrt{\frac{V_d}{V_{SPT}}} \tag{9}$$

where V_{SPT}, n_{SPT} and ε_{SPT} represents the discharge voltage, the plasma density and the erosion rate of the SPT-100 operating at the nominal power level of 1350 W.
Finally, the total impulse produced by the thruster is

$$I_{TOT} \propto T\Delta t \propto T\frac{b}{\varepsilon_{ex}} \propto Tb\frac{n_{in}}{n_{SPT}}\sqrt{\frac{V_d}{V_{SPT}}}\,\varepsilon_{SPT}, \tag{10}$$

where Δt represent the scaled thruster lifetime and b is the ceramic wall thickness. This simplified relation was used to define the ceramic wall thickness needed to achieve the total impulse required.
Given a fixed discharge power of 20kW, a wide range of thruster configurations (defined in terms of geometric parameters and discharge voltage) were analyzed by means of the scaling methodology, thus estimating the thruster performance.
Moreover, for each analyzed configuration the generation of the magnetic field was investigated. The optimization of the magnetic field is one of the fundamental aspects in the design of a HET. The magnetic field topology is the primary responsible for the resultant electric field, which in turns governs the ion acceleration [18].
Finally, among all the analyzed configurations, we selected those compliant with the thruster requirements in terms of performance (i.e. minimum

T, I_{sp}, η and I_{TOT}), magnetic circuit requirements (i.e. magnetic induction peak of 40 mT without magnetic saturation) and mechanical requirements (i.e. allow the integration of the central cathode). The most compact configuration, with a channel outer diameter of 254 mm, was then chosen as the final HT20k configuration.
The predicted thruster performance are briefly summarized in Table 2.

Table 2 HT20k predicted operating parameters and performance

Thruster operating parameters and performance [Xe]	
Voltage [V]	550
Power [kW]	20
Efficiency	0.63
Thrust [N]	~1
Specific Impulse [s]	2520

In Table 3 and Figure 2 the channel outer diameter of the HT20k is compared to the one of different 20 kW class Hall thrusters.

Table 3. Outer channel diameter comparison of various 20 kW-class Hall effect thrusters.

Thruster	Outer Channel Diameter [mm]
HT20k	254
SPT-290	290
NASA-300M	300
Snecma PPS–20k ML	320

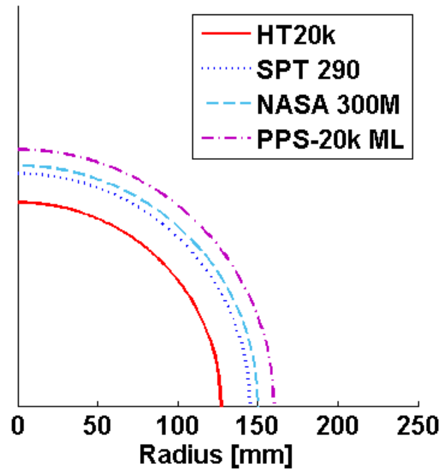

Figure 2. Outer channel radius comparison of various 20 kW-class Hall effect thrusters

When considering the design of a high power HET one of the main issues is represented by the thermal design of the thruster.
Indeed, power deposition to the chamber walls and to the anode heats up the thruster.
A proper thermal design become even more relevant when the high power HET is designed following a non-traditional approach. Thus, the reduced dimensions of the HT20k could negatively influence the thermal behavior of the thruster leading to very high temperature of the various thruster components.
For these reasons, thermal simulations were performed in order to evaluate the overall thermal stresses of the HT20k design.
All the dominant power losses of the thruster were included in the simulations, i.e. the power deposition to the walls and to the anode and the power dissipated by the coils, together with the heat loads coming from the centrally mounted cathode. All the steady state simulations were executed using the actual 3D geometry of the thruster and estimating the power dissipated inside the coils using a conservative approach (i.e. considering a magnetic induction of 40 mT at the channel centerline). The thermal simulations did not highlight the need of thermal screen or radiators in order to manage thruster temperatures.
The only issue was related with the high temperature reached inside the coils (up to 500 °C), outlining the need of a high temperature cable. Thus, a very high temperature mineral insulated wire (capable of withstanding a temperature of 700°C) was selected for producing the coils.
Moreover, with the purpose of investigating the structural integrity of the HT20k design, thermo-mechanical analyses were carried out. Critical areas of the design were identified in the regions at the boundary between the inner and outer coils and the magnetic circuit.
Therefore, the presence of a gap between the ferromagnetic circuit and the coils was prescribed in order to avoid pressure actions due to the thermal expansion.

4. HIGH CURRENT CATHODE - HC60

An orificed, thermionic hollow cathode has been developed to be used for the propellant ionization and the ion beam neutralization of the HT20k. The cathode was designed to deliver a maximum current of 60A, hence the name HC60. The design relies upon a theoretical model previously developed at SITAEL [19], describing the performance of a hollow cathode and used as a quick numerical tool for the geometry selection for a given current class. Thermal and mechanical analyses have been carried out to verify the structural integrity of the cathode in the predicted operating environment.

4.1. Cathode Requirements

The HC60 cathode has been designed to operate at mass flow rates between 2 and 6 mg/s of xenon propellant, at discharge currents between 30 and 60 A. The cathode predicted lifetime should be higher than 8000 hours

4.2. Cathode Design

According to the architecture sketched in Figure 3, the cathode is made of the following basic components: an active electron emitter, or insert, is placed inside a refractory metal tube surrounded by a heater and heat shields. The gas is injected through the tube and is ionized by the electrons emitted via thermionic effect from the insert. The tube ends with an orifice plate, which increases the internal pressure enhancing the propellant ionization. The tube is enclosed in an electrode, called keeper, whose main function is to help the cathode ignition with an applied positive potential with respect to the inner tube. The keeper also protects the internal parts, such as the orifice plate and the heater, from the damage due to ion bombardment.
Among the materials which can be used for the thermionic emission process, the most common in hollow cathode applications are the so-called dispenser emitter and the lanthanum hexaboride (LaB_6) compound. The dispenser emitter consists of a porous tungsten matrix impregnated with BaO-CaO-Al_2O_3 in various molar ratios (4:1:1 for the S-type, 5:3:2 for the B-type). The work function of such impregnated emitters is about 2.1 eV, obtained in a superficial layer established by means of chemical reactions between the impregnants and the matrix. The chemical processes require the diffusion of the compounds toward the emitter surface, which is achieved with the use of a heater. The activation is a time-consuming process which can last several hours, and is performed before the first cathode ignition and after each atmospheric exposure. On the other hand, the LaB_6 compound does not require any lengthy activation procedure, since the bulk material is characterized by a relatively low work function, i.e. 2.4 – 2.7 eV [20]. An insert temperature of about 1800 K can emit over 10 A/cm^2 of thermionic current. In addition, LaB_6 is definitely less sensitive to gas impurities and air exposure with respect to dispenser emitters, and the lower evaporation rate at the typical current densities allows for a longer cathode lifetime [21]. LaB_6 has been used as the electron emitter in hollow cathodes since 1970s. For this reason, the space heritage of this technology is considerable: over 200 SPT Hall thrusters have flown in telecommunications satellite applications using LaB_6 cathodes [22]. LaB_6 was thus selected as the emitter material, since the advantages compared to dispenser cathodes overcome the drawback in the value of the work function.
The design features a LaB_6 cylindrical insert in a molybdenum-rhenium tube with a titanium-alloy keeper. The LaB_6 insert is protected from direct contact with the refractory metal tube by a thin graphite sleeve, to avoid chemical compatibility problems at high temperatures. The insert is held in place with a tungsten spring placed inside the tube. The tube is sufficiently long and thin to minimize heat conduction from the insert to the base plate according to the results of the thermal simulations. A heater was included to reduce the emitter thermal stress during the cathode ignition and to ease the discharge initiation. The estimated overall mass of the cathode is about 505 g without harnesses. The maximum dimensions are 160 mm length and 80 mm diameter. A CAD drawing of the hollow cathode is shown in Figure 4.

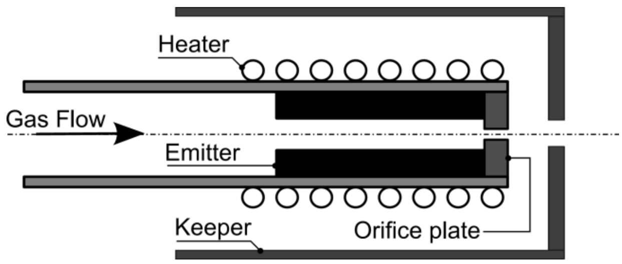

Figure 3. General schematic of an orificed hollow cathode.

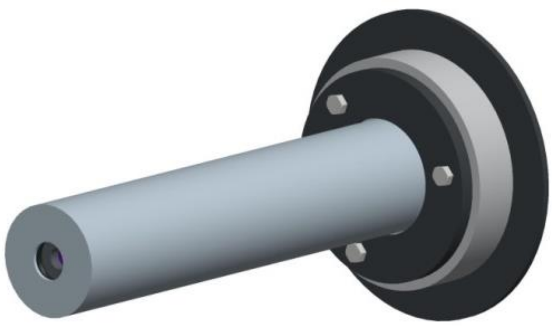

Figure 4. CAD drawing of the HC60 cathode.

4.3. Cathode Predicted Performance

The cathode electrical characteristic computed with the theoretical model is shown in Figure 5, considering 5 mg/s xenon mass flow rate. For the operating point of 60 A discharge current and 5 mg/s

Xe mass flow rate, a discharge voltage of 12.2 V was numerically computed, along with an emitter temperature of about 1700 K, an orifice temperature of about 1920 K, and a total power consumption of 730 W. The electron temperature is estimated to be about 1.18 eV in the emitter region, and 1.88 eV in the orifice.

The theoretical model has been used to predict the cathode operation with krypton propellant. The results showed a discharge voltage up to about 3 V higher using krypton with respect to xenon, along with higher temperatures, i.e. a difference of about 30 K for the emitter temperature, and up to 70 K for the orifice temperature, considering krypton in place of xenon.

The thermal analysis of the cathode showed that the cathode structure is able to withstand the high temperature gradients tied to the thermionic electron emission. The predicted thermal deformation is expected not to compromise the cathode operation, since the displacement is mainly directed along the cathode axis.

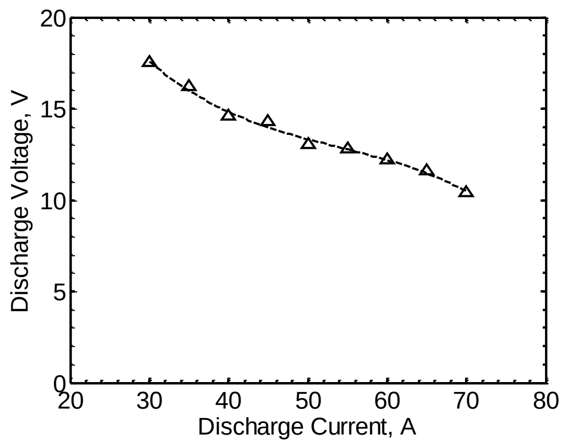

Figure 5. Theoretical electrical characteristic of the HC60 (5 mg/s Xe).

5. FUTURE WORK

The activities foreseen for the near future include the manufacturing and assembly of the HT20k prototype, a functional test campaign of the thruster coupled with the associated high current cathode HC60 and a long duration test campaign of 150 hours during which thrust and erosion measurements will be performed. The thruster will be tested using both Xe and Kr as propellants.

6. CONCLUSIONS

In the frame of the ESA TRP project "Very High-Power Hall-Effect Thruster for Exploration, SITAEL is developing a 20kW class Hall thruster, the HT20k, together with the associated high current hollow cathode, the HC60.

The HT20k is a Morozov type, high-power Hall Effect thruster designed to operate at a nominal discharge power of 20kW.

A broadly validated theoretical scaling methodology has been used to size the HT20k following an alternative design approach. As a matter of fact, the HT20k is expected to operate with a density higher than the SPT-100. This design approach allowed reducing the overall dimensions and mass of the thruster by about 20% with respect to a "traditionally" designed thruster of the same power level. Furthermore, the HT20k is expected to operate better with alternative propellants as krypton, which have higher ionization energy than xenon. At a discharge power of 20kW the thruster is supposed to produce a thrust greater than 1N and a specific impulse higher than 2500s and to provide a thrust efficiency higher than 60%.

In order to improve thruster performance, the thruster design envisages a centrally mounted cathode. In addition, using a set of calibrated rings the anode and cathode position with respect to the other thruster elements can be changed.

This solution, together with the wide range of attainable levels of magnetic induction, makes the HT20k suitable for systematic performance investigations with the aim of performance optimization in an extended operating envelope.

The orificed, thermionic hollow cathode configuration with a lanthanum hexaboride (LaB_6) emitter was selected as the baseline configuration of the HT20k.

The HC60 cathode was designed to operate at mass flow rates between 2 and 6 mg/s of xenon propellant and at discharge currents between 50 and 60 A.

The hollow cathode design was carried out through a dedicated numerical model previously developed at SITAEL. The theoretical model was also used to predict the cathode electrical characteristic with both Xe and Kr as propellants. In particular, the results showed a discharge voltage up to about 3 V higher using krypton with respect to xenon, along with higher temperatures, i.e. a difference of about 30 K for the emitter temperature, and up to 70 K for the orifice temperature, considering krypton in place of xenon.

7. ACKNOWLEDGMENTS

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