

Hollow Cathodes for Low-Power Hall Effect Thrusters

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Abstract: The operation of hollow cathodes greatly impacts the overall performance of low-power Hall effect thrusters (HETs), belonging to a class of electric thrusters with an operating power lower than 500 W. This class of HETs can be installed on-board the satellites for telecommunications and Earth observation missions, being particularly suited for small satellites where power and mass budgets are inherently limited. A performance improvement of the cathode is particularly needed in such applications, since a reduction in power and propellant consumption, typically within about 10% of the respective values for the entire system, has a significant impact on the overall thruster performance. In this context, two thermionic hollow cathodes, HC1 and HC3, have been designed and tested at Sitael, to be coupled with the Sitael low-power Hall thrusters. Both cathodes feature a lanthanum hexaboride (LaB₆) emitter, and an orifice designed to extend the spot-mode operation to low values of mass flow rate. An in-house numerical model was used for the cathode design to define the geometry, in accordance with the thruster unit specifications in terms of discharge current, mass flow rate, and lifetime. HC1 is a cathode designed to provide a discharge current in the 0.3 – 1 A range, operating in steady-state conditions at mass flow rates between 0.08 and 0.5 mg/s of xenon. HC3 was designed for the range 1 - 3 A of discharge current, with 0.08 – 0.5 mg/s of mass flow rate. Both HC1 and HC3 have an expected lifetime higher than 10⁴ hours, estimated on the basis of the emitter evaporation at the operating surface temperature, computed with the aid of the numerical model. Experiments were carried out, including preliminary characterization campaigns of each of the two cathodes as well as coupling tests. The collected data are presented and discussed with reference to the model predictions, showing a good agreement between theoretical and experimental results.

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I. Introduction

SMALL satellites are becoming increasingly popular as they offer significant cost savings, higher reliability, and are generally more affordable for a wide variety of applications, including scientific near-Earth and deep space missions¹. A miniaturization of the propulsion subsystem is sought for satisfying the propulsion needs of small-scale spacecraft. Hall Effect Thrusters (HETs) are promising in light of maintaining high performance when scaled down to low-power levels. Possible maneuvers accomplished by HETs range from drag compensation in Low Earth Orbits (LEO) and Very Low Earth Orbits (VLEO), to accurate final orbit insertion, and spacecraft end-of-life disposal. The critical parameters for HETs at small scale (<500 W) are the thruster lifetime and the thrust efficiency, given the inherently higher surface-to-volume ratio². The miniaturization of hollow cathodes, which perform the propellant ionization and the ion beam neutralization, is also of primary concern, considering the impact on the overall thruster performance. As a matter of fact, the cathode mass flow rate in xenon HETs is comprised between 7 and 10% of the anode mass flow rate³, and the cathode power consumption can reach 20% of the available power⁴.

In recent years, Sitael has devoted a considerable effort in the development of low-power HETs, through the design of 100 W- and 400 W-class Hall thrusters, namely HT100 and HT400. HT100 is a permanent-magnets thruster operating in the 100 – 250 W range⁵, generating a thrust between 4 and 13 mN, and a specific impulse between 900 and 1400 s. MSHT100, a magnetically shielded version of HT100, was also designed and performed a preliminary characterization⁶. HT400 operates at 350 – 750 W of power, providing 20 – 45 mN of thrust, and 1300 – 1700 s of specific impulse⁷. In this context, two thermionic hollow cathodes have been designed and tested at Sitael, named HC1 and HC3, conceived for HT100 and HT400, respectively. Both cathodes feature a lanthanum hexaboride (LaB_6) emitter, and an orifice designed to extend the spot-mode operation to low values of mass flow rate. The cathode design includes a heater, used during the ignition phase to ease the electron emission, whereas the cathode lifetime is evaluated on the basis of the emitter evaporation at the predicted surface temperature. An in-house numerical model was used for the cathode design to define the geometry, in accordance with the thruster unit specifications in terms of discharge current, mass flow rate, and lifetime⁸. The suggested model self-consistently predicts the plasma parameters and power consumption, for fixed geometry and operating conditions. The results from the numerical model proved to be in good accordance with the experimental data collected at Sitael during the cathodes characterization.

II. Cathode Architecture

The cathode design relies upon a theoretical model previously developed at Sitael and validated against experimental data of cathodes belonging to different power classes^{8,9}. In parallel with the theoretical study, a careful evaluation of the possible materials to be used for the different cathode parts was carried out, to select the best combination for improving the thermal behavior of the cathode.

A. Cathode Assembly Description

Both HC1 and HC3 include the basic components of an orificed hollow cathode, as schematically shown in Fig. 1. A thin refractory metal tube, ending with an orifice, receives the propellant (usually xenon or krypton). The active element of the cathode is the electron emitter, located inside the tube and held in place by means of a spring and a spacer. The electron emitter is a hollow cylinder made of a low-work function material, providing the electrons via field-enhanced thermionic effect. Lanthanum hexaboride (LaB_6) emitters have been selected for the high robustness, high current density, and long life with respect to the traditional dispenser cathodes¹⁰. A LaB_6 emitter does not require lengthy conditioning procedures and it is less sensitive to contaminants and air exposure. The main disadvantage of LaB_6 with respect to dispenser emitters is the higher work function, namely between 2.4 and 2.7 eV for polycrystalline LaB_6 cathodes^{11,12}, as compared to about 2.1 eV for dispenser cathodes¹³. As such, a LaB_6 emitter operates at a surface temperature of about 1900 K compared to about 1300 K for a dispenser

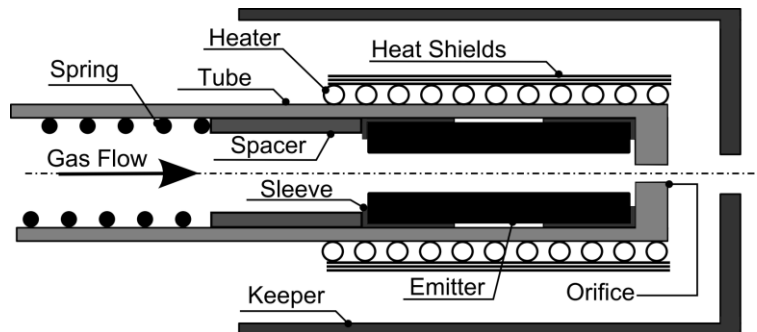


Figure 1. General schematic of an orificed hollow cathode.

emitter, to give a current density in the order of 10^5 A/m². A heater consisting of a refractory metal filament wrapped around the cathode tube and electrically insulated from the tube by means of ceramic materials is used to ease the discharge initiation, by increasing the emitter temperature to thermionic emission values. Heat shields are also included in the assembly to improve the thermal efficiency of the cathode. The heater represents a single point of failure for the cathode, if an auxiliary filament is not provided. Nevertheless, heaterless ignitions are possible, at the cost of requiring higher voltages with the risk of damaging the LaB₆ emitter due to thermal shocks. The cathode structure is enclosed by a keeper electrode, positively biased with respect to the cathode tube during the start-up phase to trigger the discharge. The keeper also protects the inner components from ion bombardment damage.

The primary drivers in determining the cathode performance are the emitter and the orifice regions, whose geometry are selected on the basis of the theoretical results of the cathode model, briefly illustrated in the following section.

B. Cathode Model

The cathode model is a volume-averaged model which considers the plasma created inside the cathode as divided in the emitter, orifice, and cathode-to-keeper gap regions^{8,9}. Systems of steady-state particle and energy balance equations are self-consistently solved for a given cathode geometry and fixed operating conditions (namely, discharge current and mass flow rate). A dedicated lumped-parameter thermal model is coupled with the plasma model, and the combined systems of equations are solved by means of an iterative procedure to compute the plasma parameters, temperature profile, and total discharge power.

The pressure model is based on a Poiseuille flow in the orifice region¹⁴, with a correction term for the transitional regime as a function of the Knudsen number. The ionization model includes the contribution of the step-wise mechanism¹⁵. The cathode lifetime is estimated according to the evaporation rate of the emitter at the computed surface temperature⁸. The lifetime computation is useful mainly to compare the theoretical results as a function of the cathode geometry, since other mechanisms such as orifice clogging and ion bombardment damage are expected to cause a performance degradation shortening the cathode lifetime. On the basis of the theoretical results, the main geometrical parameters are selected: the emitter inner and outer diameters, the emitter length, and the orifice diameter and length.

III. Experimental Setup

HC1 and HC3 were tested at Sitael in vacuum chambers of different size. The experimental campaigns included both stand-alone characterization and coupling tests with the 100 W-class Hall thrusters.

A. IV7 Vacuum Chamber

The IV7 vacuum chamber is a cylindrical vessel 0.5 m in diameter and 1 m in length, equipped with a primary scroll pump and a 500 l/s turbo molecular pump. The facility is able to reach a background pressure of 10^{-5} Pa (ultimate vacuum) when the combined pumping system is activated. The IV7 vacuum chamber was used for the preliminary characterization of the heaters. The IV7 facility is shown in Fig. 2.

B. IV1 Vacuum Chamber

The IV1 facility consists of a cylindrical stainless steel body 0.6 m in diameter and 1.6 m in length (Fig. 3a). The test bench is equipped with a primary scroll pump, a 300 l/s turbo molecular pump, and two 900 l/s cryogenic pumps. The facility is able to reach a background pressure of 1×10^{-6} Pa (ultimate vacuum) when the combined pumping system is activated. The pressure level within the chamber is continuously monitored by two Leybold-Inficom IT90 Pirani/Bayard-Alpert sensors and recorded via LabVIEW DAQ. Both HC1 and HC3 were characterized in the IV1 facility.

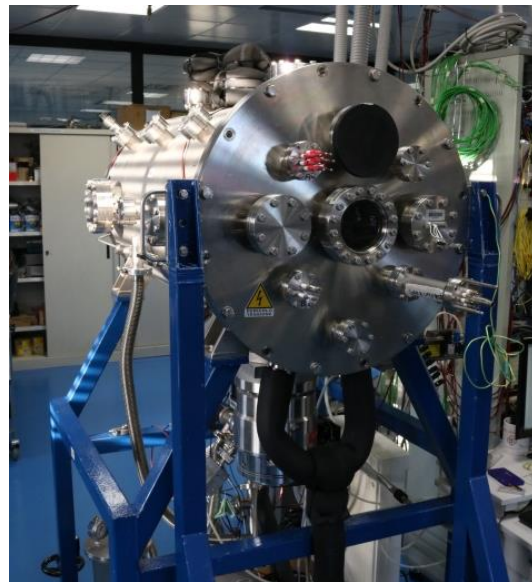
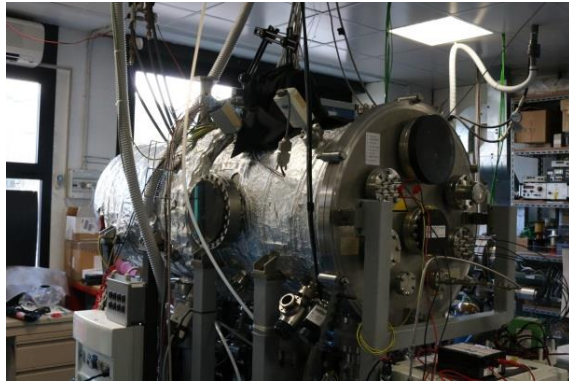


Figure 2. IV7 facility.



a)



b)

Figure 3. a) IV1 facility. b) IV4 facility.

C. IV4 Vacuum Chamber

The IV4 facility consists of two different bodies made of AISI 316L stainless steel with low magnetic relative permeability ($\mu_r < 1.06$). The main chamber has a diameter of 2 m and a length of 3.2 m, whereas the small chamber is a 1 m-diameter, 1 m-length service chamber. The two bodies are connected through a 1 m-diameter gate valve. The small chamber was used to accommodate the cathode setup, its electrical and gas-feeding systems, whereas the main chamber allowed for a free expansion of the plasma plume and it is directly connected to the main pumping system. A bi-conical, water cooled, Grafoil-lined target is installed in order to dump the beam energy down. The chamber pumping system is capable of maintaining a back pressure in the range of 10^{-5} Pa (ultimate vacuum) by using a primary stage located in the main chamber and a secondary stage located in the small chamber. The combined pumping speed of the system is approximately 1.3×10^5 l/s for xenon. The pressure level within the chamber is continuously monitored by three Leybold-Inficom IT90 Pirani/Bayard-Alpert sensors and recorded via LabVIEW. IV4 is the facility where the coupling tests of cathode and thruster were performed. The IV4 vacuum chamber is shown in Fig. 3b.

D. General Test Schematic

The general test schematic adopted for the cathodes characterization in IV1 and IV4 facilities is shown in Fig. 4. A current-limited Huttlinger PFG5000 (1000 V, 6 A) power supply controlled the cathode-to-keeper voltage during discharge initiation, and the current during operation. The cathode-to-anode current was controlled using a Sorensen DLM 300-3.5E (300 V, 3.5 A) power supply. The heater, when operated, was controlled using a Sorensen DCS 80-13E (80 V, 13 A) power supply. All the power supplies were connected to a common negative reference and the setup was electrically floating with respect to ground. The electrical parameters were measured by using current (LEM LA25-NP) and voltage probes (LEM LV25-P). K-type thermocouples were installed on the mounting flange constituting the mechanical interface, and on the backside of the anode. The error associated with the DC voltage measurements is $\pm 2\%$, whereas a relative error of $\pm 1\%$ is evaluated for the current measurements.

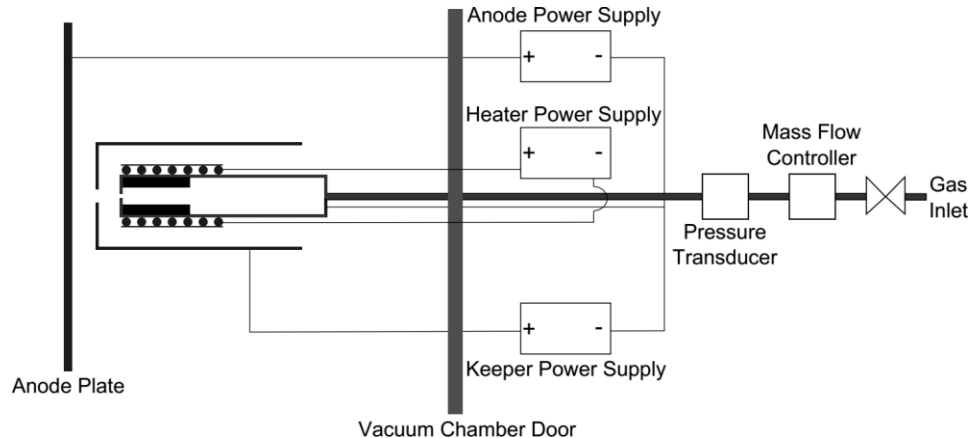


Figure 4. General test schematic for the cathode characterization.

The cathode gas feeding line was equipped with a dedicated mass flow controller (Bronkhorst F-201C-FAC-22-V), connecting the xenon tank to the test item. The tests were performed using grade 4.5 xenon. The cathode pressure was recorded by means of a Kulite (HKM-375-25A) pressure transducer located along the feeding line at a distance of about 20 cm from the cathode emitter. All the sensing probes were calibrated before the test and connected to the DAQ system controlled via LabVIEW software.

IV. HC1: 0.3 to 1 A Hollow Cathode

A. HC1 Description and Thermal Behavior

HC1 was designed to provide a discharge current in the 0.3 - 1 A range¹⁶. The cathode operates in steady-state conditions at mass flow rates between 0.08 and 0.5 mg/s of xenon. The expected cathode lifetime, estimated on the basis of the theoretical model, is higher than 10^4 hours. The cathode mass, without cables, is about 30 grams. The cathode assembly includes a heater, used during the ignition phase to ease the discharge initiation by increasing the emitter temperature to thermionic emission values. The use of a heater allows for starting the cathode with low applied voltages between the keeper and the cathode tube. However, developing a heater to reach the emission temperatures of LaB_6 is a significant challenge for the cathode design, in particular for what concerns the materials selection. For this reason, Sitael dedicated a significant internal effort to the execution of an extensive experimental campaign to test different material couplings and to improve the heater and overall cathode configuration.

The preliminary characterization of the heaters was carried out in the IV7 vacuum chamber, being the test item represented by the heater only. For each heater, the voltage drop across the filament was recorded as a function of the supplied current, and the corresponding values were used to predict the filament temperature, by means of a semi-empirical formula. Such empirical formula holds for a particular filament material and correlates the temperature and the electrical resistances (both in cold conditions and during operation) of the filament. Representative results of the tests are reported in Fig. 5, in terms of the filament temperature computed on the basis of the electrical parameters measured, as a function of the heater power. A performance improvement was obtained during the development activities, as shown for three different heaters: as a matter of fact, the temperature of the filament at about 29 W was more than 250 K higher for the third heater with respect to the first. This improvement was tied both with the filament geometry and also with the selection of materials for the different parts of the heater. After the heater development phase, the final configuration was selected and included in the cathode assembly to perform a dedicated thermal test in the IV1 facility.

The results are summarized in Fig. 6a, where five temperatures are reported as a function of the heater power. The heater filament temperature was computed with the aforementioned semi-empirical formula, though based on experimental data. The other four temperatures were measured by means of K-type thermocouples located in reference points of the cathode assembly, namely at the rear flange constituting the mechanical interface, at the keeper front and side surfaces, and at the emitter surface. With a heater power of about 20 W, the emitter temperature increased up to about 1250 K, after which the test was stopped due to the temperature operating range of the thermocouples. Correspondingly to a heater power of about 20 W, the cathode interface reached a temperature of about 500 K, whereas the highest temperature recorded at the keeper was about 600 K.

Another test was dedicated to assess the heating transient, by varying the heater power and monitoring the emitter temperature. The results are shown in Fig. 6b, where the emitter temperature is reported as a function of time. With a heater power of about 45 W (which is the value assumed during a 120-cycles ignition test, as described in Section IV.B), an emitter temperature of about 1460 K was reached in about 600 s. When the heater power was increased up to 60 W, the heating time interval to reach the same emitter temperature was lowered down to about 200 s. The maximum value of temperature at the emitter surface was limited by the integrity of the K-type thermocouple.

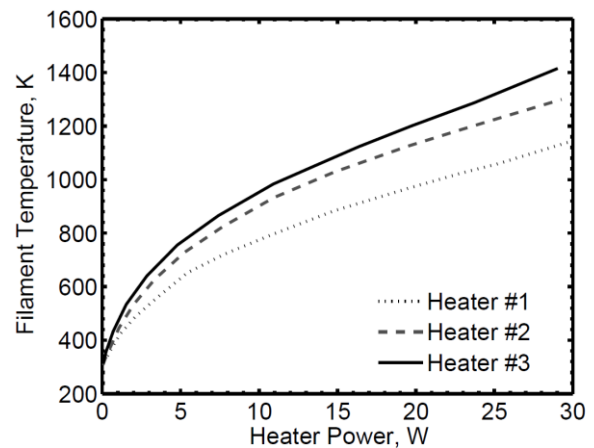


Figure 5. Heater filament temperature computed as a function of the heater power, for three different heaters.

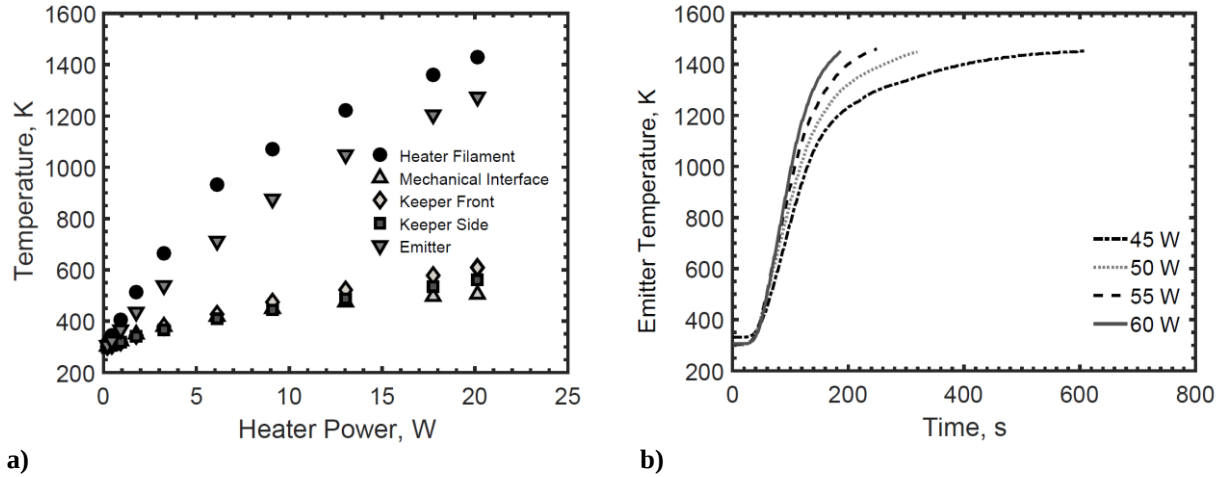


Figure 6. a) Temperatures of the heater filament (computed) and at the reference points (measured) as a function of the heater power. b) Emitter temperature measured as a function of time, at four values of heater power.

B. HC1 Characterization Results

HC1 operated with xenon for more than 550 hours and cumulated more than 350 ignitions, both with and without the use of an in-house-made heater. In the case of a heaterless ignition, keeper voltages as high as 800 V were required to start the discharge, whereas a heater power of about 45 W allowed for ignitions with keeper voltages as low as 45 – 50 V.

The effect of a heater on the cathode ignition parameters was studied during a dedicated test¹⁷, where 120 ignitions were performed by applying a heater power of about 45 W. The cathode was started with a xenon mass flow rate of 0.6 mg/s, and with a keeper voltage of about 45 V. The heater power was decreased to assess the dependence of the keeper voltage at ignition on the heater power, as shown in Fig. 7a at 0.6 mg/s and 0.1 mg/s (the latter value demonstrated that the cathode could be ignited at a mass flow rate compatible with a steady-state operation). As expected, the keeper voltage required for the discharge initiation increases if the heater power decreases, due to a lower emitter surface temperature entailing a lower electron emission. In addition, the keeper voltage at ignition increases if the mass flow rate decreases, at a fixed heater power. The heating transient was also studied during the test. As such, the heating time was varied, maintaining 45 W of heater power and a mass flow rate of 0.1 mg/s, to obtain the dependence of the keeper voltage at ignition on the heating phase duration. The corresponding results are shown in Fig. 7b, which reports a keeper voltage up to about 150 V for a heating time of about 330 seconds. The keeper voltage decreased to about 50 V if the heating time was extended to about 450

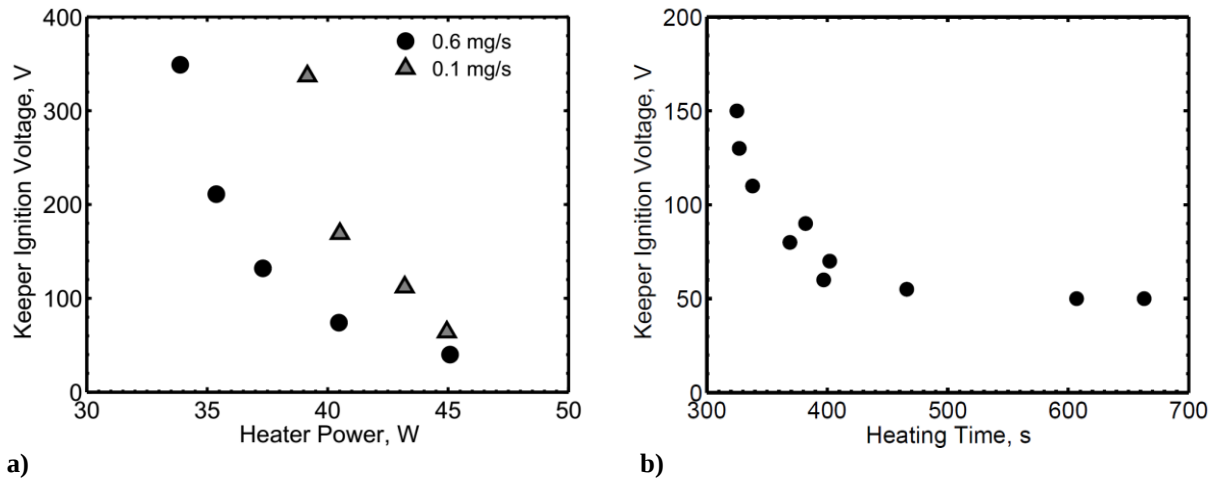


Figure 7. a) Keeper voltage at ignition as a function of heater power, at two mass flow rates. b) Keeper voltage at ignition as a function of the heating time, at 0.1 mg/s and about 45 W heater power.

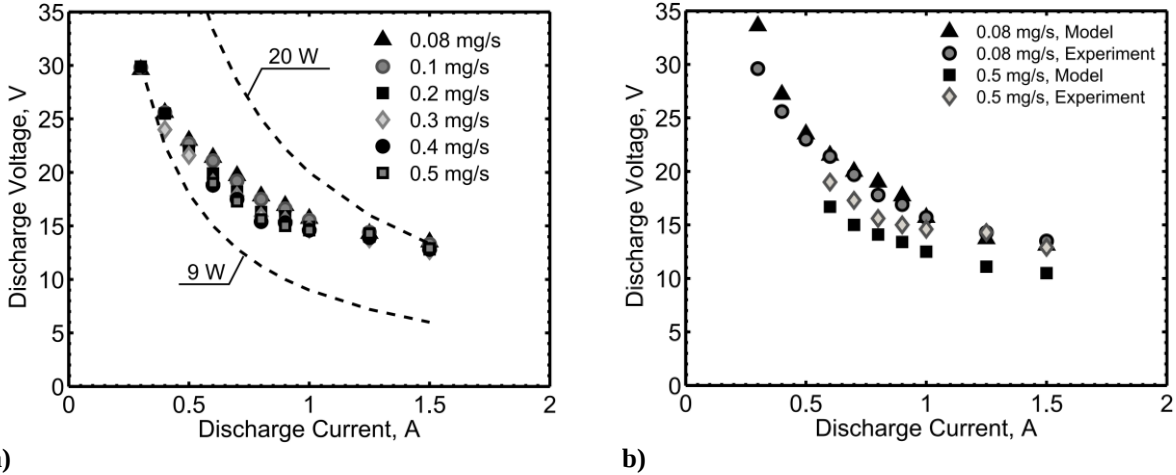


Figure 8. a) Electrical characteristics with the keeper, at different Xe mass flow rates. b) Comparison between experimental and theoretical electrical characteristics, at two Xe mass flow rates.

seconds, whereas a further increase in the heating duration did not entail any significant decrease in the keeper voltage at ignition. The effect of the heater on the ignition parameters is evident, considering that heaterless ignitions required a keeper voltage up to 800 V and a mass flow rate of 1 mg/s.

Fig. 8a shows the electrical characteristics of HC1 operated with keeper only, at different mass flow rates. The curves follow the typical trend found in orificed hollow cathodes, namely higher discharge voltage at low discharge current and a weak dependence of the discharge voltage on the mass flow rate. The discharge voltage decreases from about 30 to 15 V, for an increase in the current from 0.3 to 1.5 A. The power consumption of HC1 settles in the range from 9 to 20 W, depending on the operating conditions. The electrical characteristics reported in Fig. 8b at two mass flow rates show that the model results are in good agreement with the experimental data. As a matter of fact, the worst prediction of the discharge voltage showed a discrepancy of about 20% with respect to the measured values.

HC1 operated in diode mode with an auxiliary anode plate located about 15 mm downstream of the keeper exit section. With the keeper left floating and a cathode mass flow rate of 0.8 mg/s Xe, the anode voltage was about 40 V for an anode current between 1.25 and 1.5 A, as shown in Fig. 9a. Correspondingly, the cathode reference potential (CRP) settled in the range from about -5.0 and -6.5 V, with a general increasing trend as a function of the anode current (Fig. 9b). At mass flow rates lower than 0.8 mg/s, the cathode transitioned to the noisy plume mode, characterized by high voltages and a luminous discharge around the cathode tip¹⁸. HC1 was coupled with HT100, the Sitael 100 W-class Hall thruster⁵, operating in the 100 - 250 W range, for a thrust level between 4 and 13 mN

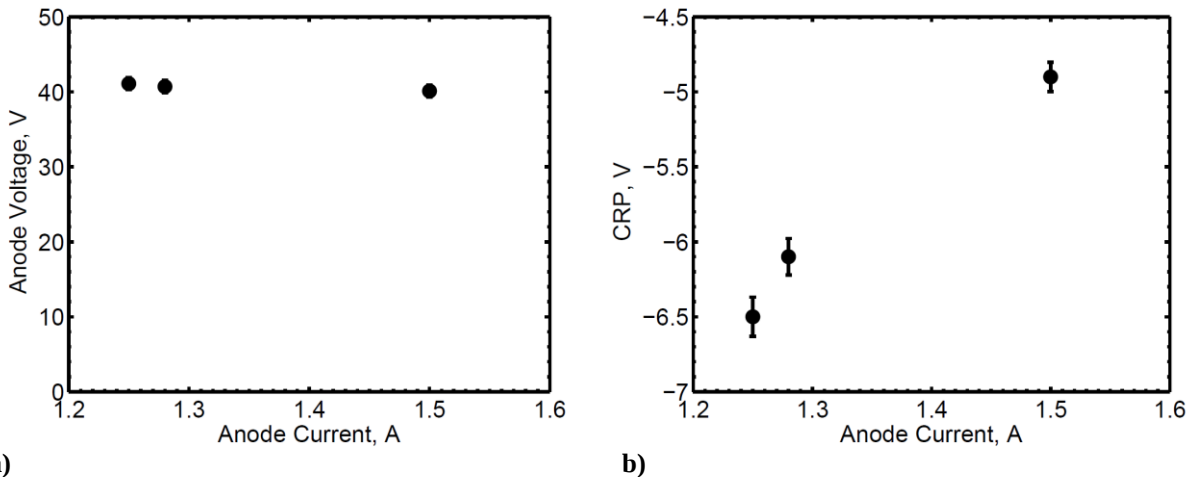
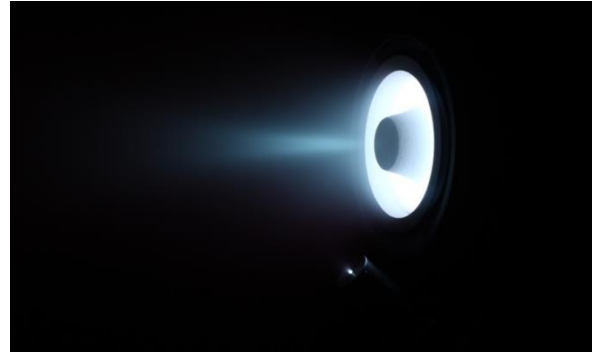
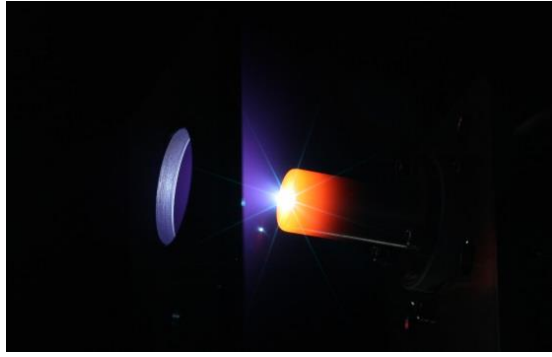


Figure 9. a) Anode voltage as a function of anode current with floating keeper, at 0.8 mg/s Xe. b) CRP as a function of anode current with floating keeper, at 0.8 mg/s Xe.



a)

b)

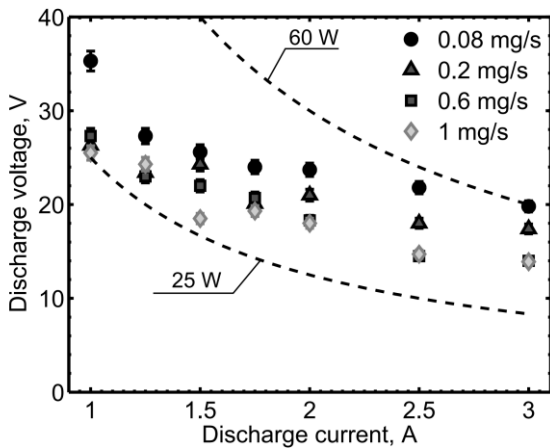
Figure 10. a) HC1 in triode mode with keeper and anode during the stand-alone test campaign. b) HC1 during operation with HT100D.

and a specific impulse between 900 and 1400 s. The thruster was successfully operated with HC1 with the keeper left floating. Coupling tests were also carried out with MSHT100, the magnetically shielded version of HT100, with both xenon and krypton propellants⁶. HC1 operated with MSHT100 during a 350-hour endurance test on xenon, with a keeper current of 0.5 A. The cathode behaved successfully in the operating envelope tested. A heaterless version of HC1 performed a 200-hour endurance test with an anode plate, at 1.25 A and 0.8 mg/s Xe. Fig. 10 shows HC1 during the stand-alone test campaign, and coupled with HT100.

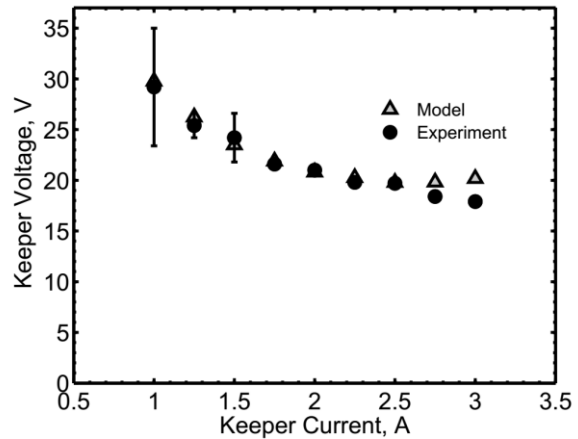
V. HC3: 1 to 3 A Hollow Cathode

HC3 was conceived to operate at a discharge current in the range 1 – 3 A, with a mass flow rate between 0.08 and 1 mg/s¹⁶. The cathode has a predicted lifetime higher than 10^4 hours, as computed from the theoretical model. The cathode mass, without cables, is about 50 grams.

The cathode was provided with a heater, belonging to the first-generation design. As a matter of fact, the development efforts in the heaters were focused on HC1. Nevertheless, the improvements obtained in the heaters for HC1 will be implemented in the future activities related to HC3. The heaterless ignitions of HC3 required up to 700 V of keeper voltage and a mass flow rate between 1 and 2 mg/s, whereas a heater power of about 60 W allowed for ignitions at keeper voltages lower than 300 V and 0.4 – 0.8 mg/s Xe. HC3 cumulated about 150 hours of operation with xenon, and more than 60 ignitions. Representative electrical characteristics in the presence of a discharge between keeper and cathode are shown in Fig. 11a, at different xenon mass flow rates, showing that the discharge power ranges from about 25 to 60 W, corresponding to a discharge voltage settling in the range 14 – 35 V. The electrical characteristics computed with the aid of the numerical model are in good agreement with the experimental results, as shown in Fig. 11b at a fixed mass flow rate. The cathode was also able to sustain a current of 0.7 A (thus



a)



b)

Figure 11. a) Electrical characteristics with the keeper, at different Xe mass flow rates. b) Comparison between experimental and theoretical electrical characteristics, at 0.1 mg/s Xe.

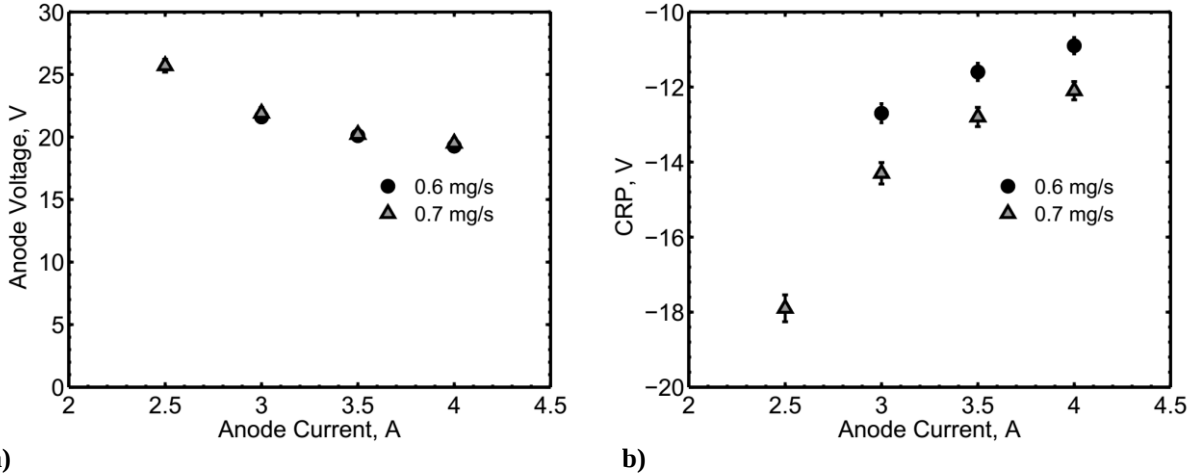


Figure 12. a) Anode voltage as a function of anode current, with floating keeper, at two Xe mass flow rates. b) CRP as a function of anode current, with floating keeper, at two Xe mass flow rates.

lower than the minimum expected value of 1 A) with a mass flow rate of 0.4 mg/s, operating with the keeper only.

HC3 was tested in diode mode with an external anode plate located about 20 mm downstream of the keeper exit section. A minimum mass flow rate of 0.6 mg/s Xe was needed to operate the cathode in the range of discharge current 2.5 – 4 A in spot mode, with floating keeper¹⁷. The anode voltage and CRP are shown in Fig. 12 as a function of the anode current, at two mass flow rates. An additional HC3 cathode was assembled to carry out a 150-hour endurance test with an anode plate, performed at 4 A and 0.5 mg/s Xe. Although designed to be coupled with HT400, HC3 was operated with HT100, by maintaining the keeper on during the characterization of the thruster. HC3 is shown in Fig. 13a during the stand-alone test campaign, and coupled with HT100 in Fig. 13b.

VI. Conclusion

Sitael has devoted a considerable effort in the development of two hollow cathodes, HC1 and HC3, for low-power Hall effect thrusters. The cathodes were characterized both in stand-alone test campaigns and during coupling tests with the HT100 Hall effect thruster. The experimental results are in good agreement with the theoretical predictions from an in-house model describing the operation of orificed hollow cathodes. Future developments will include the design of the second-generation heaters for HC3, along with an improvement of the mechanical design of the cathodes. Endurance tests of both HC1 and HC3 will be also carried out, as well as extended coupling tests with HT100 and HT400, respectively. A more extensive comparison between theoretical and experimental data will also allow for a deeper validation of the numerical model.

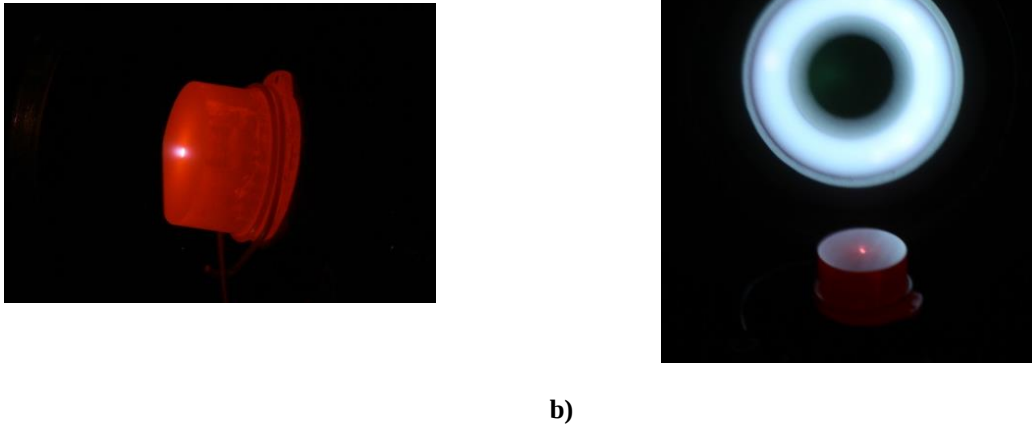


Figure 13. a) HC3 in diode mode with the keeper. b) HC3 coupled with the HT100 Hall thruster.

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