Development and performance characterization of a 5 kW class Hall-Effect thruster

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Abstract: In the time frame of 2013-2015 Sitael has designed, produced and successfully tested the HT5k, a Hall-Effect thruster (HET) with nominal power level of 5 kW. The thruster can operate in two distinct modes: the high thrust mode, suitable for orbit insertion, orbit raising or repositioning, and the high specific impulse mode, typically used for station-keeping applications. High values of specific impulse are achieved by increasing the discharge voltage and, in order to obtain stable thruster operations, the intensity of the magnetic field inside the accelerating channel needs to be increased as well. For this reason, the magnetic circuit of the HT5k is designed to produce up to 50 mT of magnetic induction at the centerline of the thruster channel, near the channel exit. The thruster has been successfully operated from 2 kW to 7 kW with a discharge voltage ranging from 250 V to 600 V.

Nomenclature

V_d	=	discharge voltage
I_d	=	discharge current
P_d	=	discharge power
AMFR	=	anode mass flow rate
CMFR	=	cathode mass flow rate

I. Introduction

HALL-Effect thrusters (HET) have been successfully used in space technology during already more than 40 years. First successful flight test of HET was realized in 1972 onboard Soviet Union satellite Meteor [1]. The implementation of SPT-100 – most recognized HET in the world – started in 1995 for the final positioning and station keeping of Russian geostationary satellites. Since 2004 these systems have been successfully used onboard Western geostationary commercial spacecrafts [2]. In recent years, due to the progress in development of onboard power electronics and improvements of space solar arrays, availability of electric power onboard spacecrafts significantly increased. This made possible the use of electric propulsion (EP) devices based on HET for such missions as deep space exploration and orbit topping of satellites intended for use in geosynchronous earth orbit. These missions have higher requirements to primary propulsion system on thrust, specific impulse and lifetime.

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To date the most powerful HET, which is currently operating in space is 4.5 kW thruster produced by Aerojet Rocketdyne – XR-5 (formerly BPT-4000). The thruster has been qualified for space missions [3,4] and successfully operating for station keeping of the Advanced Extremely High Frequency (AEHF) communications spacecraft into geostationary orbit since 2010. Another 4.5 kW HET, which is currently under qualification is SPT-140 produced by Russian Experimental Design Bureau (EDB) Fakel [5]. In Europe since 1999 Snecma has been developing a 5 kW HET – the PPS5000. With the support of CNES and ESA, a technology demonstrator model – PPSX000 was manufactured and underwent several characterization and endurance testing campaigns [6]. During 2001 and 2002 laboratory model of the 5 kW thruster developed by Alta also underwent a number of experimental tests [7]. Satisfactory performance was obtained but significant improvements in prototype design needed for optimization weight-dimensions characteristics. Thus, it was decided to freeze development of that thruster.
Growing market of commercial satellites with probable soon refusal of onboard chemical propulsion and application of EP for all on-orbit propulsion needs pushed Sitael towards resumption of works on development of HET with nominal power level of 5 kW. Therefore, new 5 kW HET prototype has been developed from sketch, manufactured, assembled and tested in IV10 large vacuum facility.
This publication summarizes the main results of the thruster performance characterization and of plasma plume investigations. Furthermore, results of the thermal simulations are discussed and comparison between simulations results and experimental data, obtained from thermocouples and thermo camera acquisitions, is carried out.

II. Experimental apparatus

A. Sitael's HT5k

The Sitael's HT5k (see Figure 1) is a HET designed to work in power range 2-7 kW. Magnetic circuit of the thruster includes magnetic coils, screens, outer shell, poles and base flange. All elements of the thruster magnetic circuit are made of soft magnetic alloy and, when magnetized by coils, allow producing an almost radial magnetic field at the exit plane of the thruster accelerating channel. The maximum value of the magnetic induction, which can be reached at the channel centerline before magnetic saturation of the magnetic circuit, is 50 mT. This permits thruster operations under high discharge voltages, which usually require high values of the magnetic induction [8]. Magnetic field is mainly imposed by inner and outer coils. To increase the homogeneity of the magnetic field, only one outer magnetic coil was used.

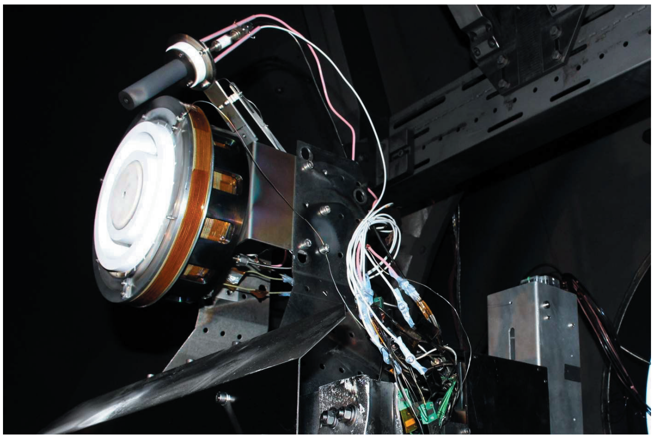

Figure 1 Sitael's HT5k mounted in IV10 vacuum facility.

The thruster is also equipped with two trim coils. First one is located behind the anode and needed to obtain a high positive axial gradient of the radial magnetic induction and to create a wide zone, near the anode, that is completely free from the magnetic field, in order to provide an unhindered electron current to the anode. Second trim coil is mounted outside thruster shell on the outer pole and when activated, permits to change the inclination of the magnetic field lines near the thruster exit plane (see Figure 2). It should be noticed that to provide symmetry of the magnetic field lines and to change their inclination, both an increase of the current in the basic inner coil and a reduction of the current in the outer one are needed.

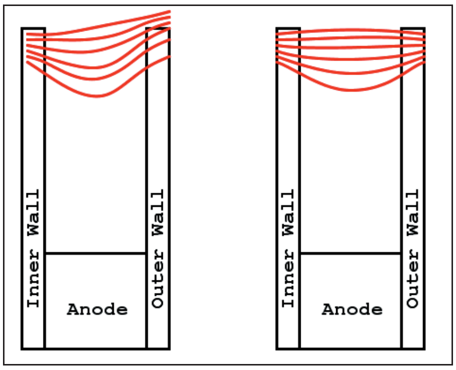

Figure 2. Distribution of the magnetic field lines inside accelerating channel of Sitael's HT5k when external trim coil is deactivated (left) and activated (right).

Significant part of the heat released from the thruster is due to radiation from its surfaces. Thereby, to make the radiative cooling more efficient, large openings were created at the back flange and outer shell of the thruster (see Figure 1). Thermal simulations showed that, when the thruster operates at the nominal operation point

(Vd=300 V and Id=16.7 A), due to these "windows", an average reduction of surface temperatures between 5-10% is obtained. Another solution used in the thruster design, which allows to reduce the thruster temperature, is the fixing of the accelerating channel support at the external magnetic pole. Such fixing avoids other conductive connections with the ceramic channel – which is the hottest part of the thruster – and establishes a short conductive way to the outer shell – which is the coolest part of the thruster and has a large radiative surface.

The anode-gas distributor of Sitael's HT5k is a hollow metallic annular assembly. It includes several parts, which create inside the anode a complex labyrinth. The anode provides a good propellant mixing and a consequently uniform distribution of the propellant inside the discharge chamber. Since the mean diameter of Sitael's HT5k accelerating channel is relatively large, in order to improve distribution of inlet propellant, three gas injectors are installed in the anode. Each injector is insulated from the gas feeding system by electrical breaks. The discharge chamber of the thruster is an annular U-shaped channel of ceramic material composed by boron nitride (BN) and silicon dioxide (SiO_2). The channel is made of three ceramic parts: the base channel section and the two exit rings, which constitute the final sections of inner and outer walls. The rings are mounted on the base channel and are retained on the outside of the channel with metallic fixtures. The sectioned channel allows to asses the influence of different channel profiles (chamfers) on both the thruster performance and the plume behavior.

B. HC20 Hollow Cathode for High-Power HET

During all tests HT5k operated with high-current hollow cathode HC20 developed by Sitael in the past few years. The cathode has lanthanum hexaboride (LaB_6) electron emitter. 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. The nominal performance of the Sitael's HC20 high-current LaB_6 cathode are listed in Table 1.

Table 1. HC20 Technical Specifications

Discharge Current	5 – 25 A
Keeper Current	< 5 A
Operating Voltage	10 – 30 V range (typical, 15 V)
Ignition Voltage	< 1000 V
Mass Flow Rate (steady state)	0.5 – 2 mg/s
Mass Flow Rate (ignition)	< 5 mg/s

C. Testing Facility

The Sitael IV10 vacuum facility is the largest vacuum chamber currently available in Europe for EP testing. Vacuum vessel has total length 9.4 m, inner diameter 5.7 m and free internal volume of 160 m^3. The large size and the large volume available for the free expansion of the ion beam allows to reduce the contamination of the thruster due to back-sputtering from the facility's walls during endurance tests.

Figure 3 Sitael's IV10 vacuum facility.

Chamber is equipped with LN_2 cooled bi-conical beam target which is accommodated on the opening cap of the facility in front of the thruster in order to damp the energy beam. The particular shape preferentially diverts the sputtered atoms directly towards the side walls instead of heading them back to the thruster. Moreover, all the critical surfaces undergoing significant bombardment from the thruster will also be lined up with Grafoil (purity > 99.9 %) in order to reduce the back-sputtering effects.

The vessel is equipped with a large number of ISO standard flanges in order to provide the maximum flexibility when connecting pumping system, pressure sensors, residual gas analyzers, power / signal / gas feedthroughs, LN_2 pipes for thermal control, windows for optical observation.

D. Pumping system

The pumping system currently installed in IV10 permits to maintain completely oil free vacuum. The process of pumping down includes four main stages:

- Stage 1 (pressure $10^3 \times 10^{-2}$ mbar) 1 screw @ 630 m^3/hr (N_2); 1 roots (N_2)
- Stage 2 (pressure $10^{-2} \times 10^{-5}$ mbar) 2 turbo @ 2000 l/s (N_2); 2 scroll @ 25 m^3/hr (N_2)
- Stage 3 (pressure $10^{-5} \times 10^{-9}$ mbar) 2 cryo @ 5000 l/s (N_2)
- Stage 4 (pressure $10^{-5} \times 10^{-6}$ mbar) 5 cold panels @ 60000 l/s (Xe)

The total pumping speed is therefore in the order of 300000 l/s which ensured an ultimate pressure $< 1\times10^{-9}$ mbar and a chamber pressure in the order of $< 1\times10^{-5}$ mbar (Xe) during the test campaign.

E. Thrust Stand

The thrust stand which has been used in all tests is a single axis stand with a double pendulum configuration, capable of sustaining the thruster weight with a degree of freedom along the principal direction. The sensing element is based on high precision strain gages measuring the strain on the flexural elements. The calibration procedure allows to measure the applied force versus strain required to post-process the data.

The thrust stand is mounted on a tilting platform actuated by a stepper motor. This system allows to level the thrust stand during the calibration and before the thruster operations in order to eliminate the drift due to the chamber warping occurring during the pump down procedure. The thrust stand is also equipped with an electromagnetic calibrator, generating a reference force when requested. The calibrator is added to check the proper functioning of the stand during the test.

It must be noted that the characteristics of accuracy, repeatability and sensitivity, drift are not an absolute property of the thrust stand alone, but they strongly depend on the thruster under test since thruster mass, moment of inertia, thruster thermal behavior and number of power and diagnostic harness and propellant feeding lines may have some non negligible impact on the performance of the thrust stand.

III. Test Results and Discussion

F. Thruster performance

In 2014 experimental investigation of the performance of Sitael's HT5k operating with Xenon has been performed. Thruster was characterized at discharge voltages from 250 V up to 600 V for mass flow rates through the anode between 5 mg/s and 20 mg/s (see the Performance Map in Figure 4). In order to optimize specific impulse (calculated for AMFR and CMFR) and to provide stable thruster operation CMFR=1 mg/s had been used for all tested points.

Magnetic field was optimized by means of all four available magnetic coils, which provide fine-tuning of the magnetic field. During the optimization of magnetic field notable effect on the thruster performance due to activation of behind anode trim coil was not observed. Whereas effect from outer trim coil was significant and following acquired data allowed to increase thruster performance up to 10% depended on operational regime. Only one optimized configuration of the magnetic field in terms of field lines distribution was applied for all studied operation points without exceptions. It should be noticed that this magnetic field configuration is corresponded to B-field topology simulated during thruster design phase.

Figure 6 and Figure 7 show thruster performance obtained during test campaign. Maximum value of thrust 396 mN was demonstrated at power level of 7245 W with V_d=350 V and AMFR=20 mg/s. Whereas highest specific impulse was obtained at power level of 5850 W with V_d=600 V and AMFR=10 mg/s. Apparently, judging on the thruster thermal behavior, trend of the discharge current and plume character, further increasing of discharge voltage and mass flow rate through the anode may update maximum values of thrust and specific impulse. However, power supplies used in test campaign did not allow reaching higher values because of current/voltage limitations. Behavior of basic thruster characteristics with changing of V_d and AMFR is corresponded to general trends [9] without notable anomalous. Thrust efficiency is growing with increasing of V_d (see Figure 7 on the right).

Unclear tendency can be noted in Figure 7(on the left). For discharge voltages higher than 450 V step of increasing of specific impulse with increase of V_d on 50 V is approximately equal 100 s, whereas for discharge voltages 250-400 V this step is in order of 200 s.

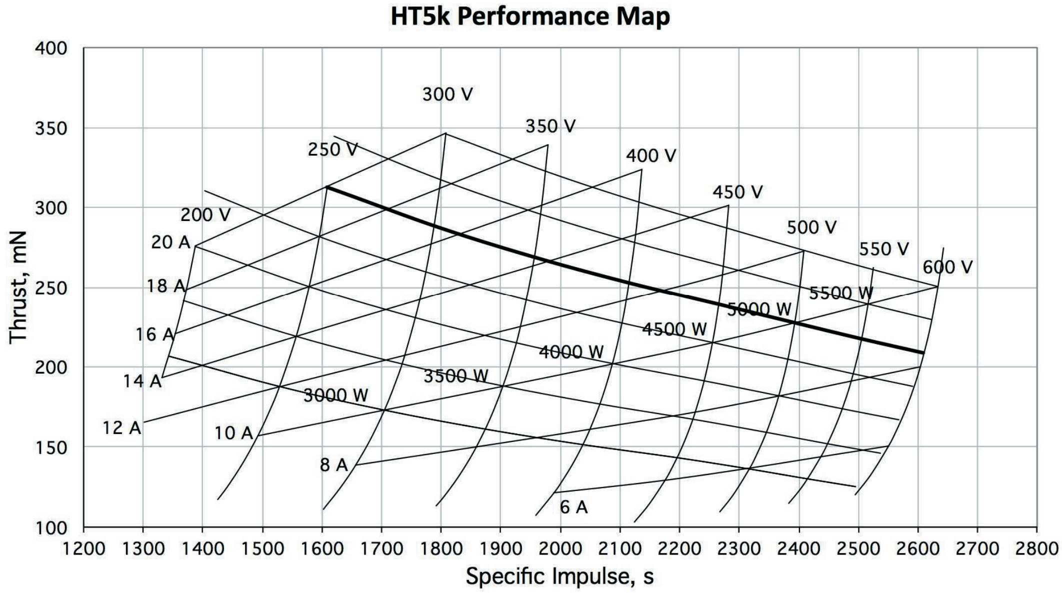

Figure 4 HT5k Performance Map

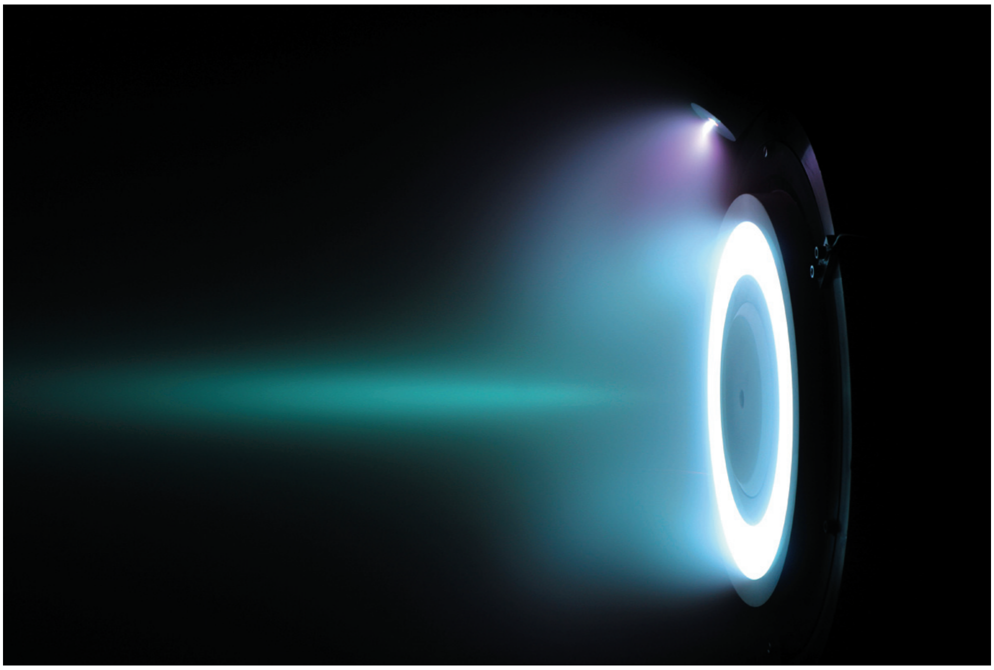

Figure 5 Sitael's HT5k plume during firing at Vd=600 V and AMFR=10 mg/s.

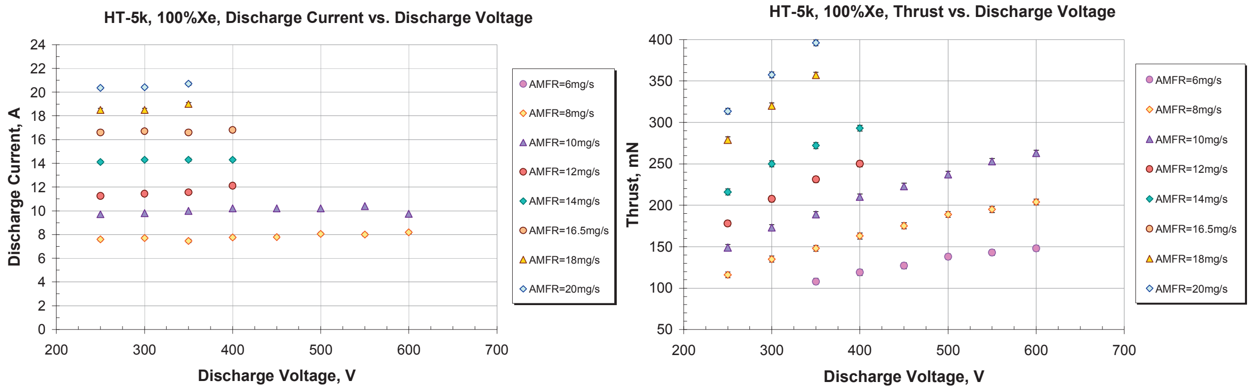

Figure 6 Discharge current(on the left) and Thrust(on the right) as function of discharge voltage for different mass flow rates.

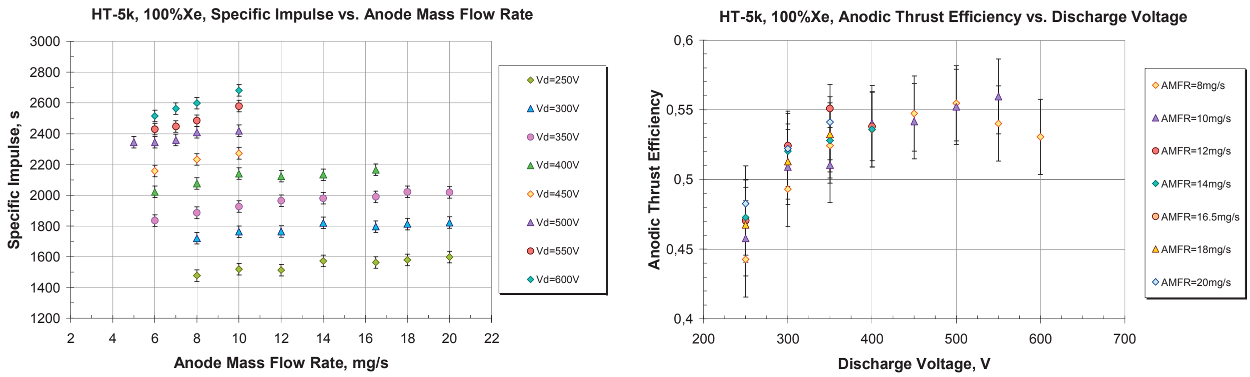

Figure 7 Specific Impulse as function of anode mass flow rate for different voltage(on the left) and Anodic Thrust Efficiency as function of discharge voltage for different mass flow rates.

G. Plume measurements

Figure 5 illustrates typical character of plasma plume exhausted from Sitael's HT5k during operation with optimized magnetic field. For the fast plume characterization IV10 vacuum facility is equipped with a diagnostic system consisted of rotary circular rake of 2 m in diameter with mounted on it of 18 electrostatic collimated Faraday cup probes pointing at the center of the thruster exit plane [10]. Distributions of ion current density measured by means of a probe pointed to the center of thruster are shown in Figure 8 and in Figure 9. In general, obtained trends correlate well with results presented, for instance, in [11] and [12], namely: ion current density is increasing with increase of AMFR and Vd as well. It should be noticed that a deviation of plume was observed when thruster was firing at regime with AMFR=8 mg/s and Vd=600 V (see Figure 9). Likely, this deviation was caused by setting up not optimal magnetic field with not enough intensity for the operation with increased Vd.

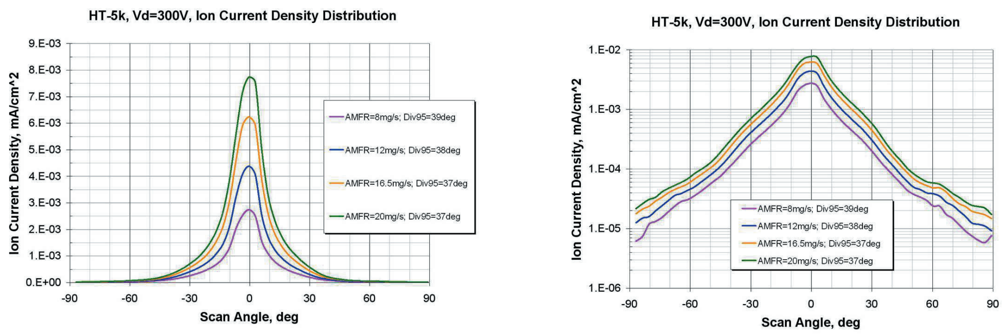

Figure 8 Distribution of Ion Current Density of Sitael's HT5k operating with pure Xe at Vd=300 V and different AMFRs with fixed magnetic field (logarithmic scale).

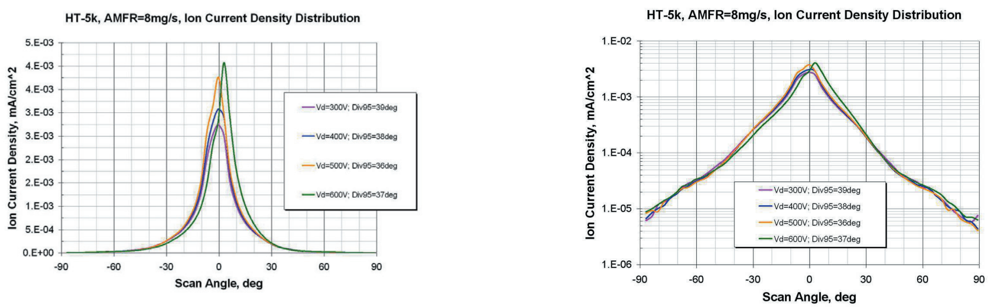

Figure 9 Distribution of Ion Current Density of Sitael's HT5k operating with pure Xe at AMFR=8mg/s and different Vd with fixed magnetic field (logarithmic scale).

H. Thermal behavior

Thermal behavior of the thruster has essential influence on thruster performance. Local overheating of the discharge chamber or hot spots on the anode surface may be reasons of significant plume deviation, what increases power losses and reduces performance. In order to assess surface temperature of HT5k thermo camera (FLIR A-600) and thermocouples (K type) were used during 10 hours continuous firing test at discharge power of 4500 W and discharge voltage of 350 V. Thermo camera was mounted in viewport on the opposite end of vacuum chamber with respect to thruster location that way to measure temperature of thruster face.

Before chamber close out calibration test of thermo camera was performed by means of additional thermocouples mounted on anode and discharge chamber surfaces. Changing of temperature was provided by variation of currents in the magnetic coils. During tests two thermocouples were used for assessment of thruster surface temperature with accuracy of 3%. First thermocouple (TC1) was placed at the front part of the thruster on outer pole and second one (TC2) – on the thruster back flange near thruster centerline. Measured data shows that stabilization of thruster thermal behavior at chosen operation regime has been reached after approximately 5 hours of continuous operation (see Figure 11), whereas TC1 indicates temperature of 350 degreeC and TC2 – 365 degreeC.

Obtained experimental data were used for validation of HT5k thermal model, which was performed in 3D time-depended statement in Comsol Multiphysics environment. Thermal properties of used materials were taken from available open sources. Thermal loads to the chamber walls coming from plasma discharge have been determined by means of balance equation presented in [13]:

$$P_{\Sigma} = P_{e\_a} + P_{R\_a} + P_{i1\_w} + P_{i2\_w} + P_{R\_w} + P_{i\_amb} + P_{R\_amb} \quad (1)$$

where:

P_{e_a} – power got by electrons in the discharge and "coming" to the anode surface boundary,

P_{R_a} – power of plasma radiation goes to the anode surface boundary,

P_{i_amb} – power for producing ions which go outside channel into an ambient,

P_{R_amb} – power of plasma radiation goes into an ambient,

P_{R_w} – power of plasma radiation goes to chamber walls surfaces,

P_{i2_w} – power released from chamber walls surfaces after neutralization of ions on these walls,

P_{i1_w} – power released from chamber walls surfaces after interacting with accelerating ions.

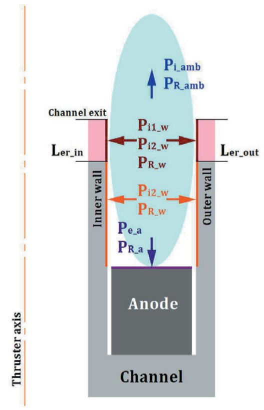

Figure 10 Scheme of thermal loads in the discharge channel of Hall thruster [13].

Figure 12 shows qualitative comparison of surface temperature distributions derived from simulation and experimental measurement made by means of thermo camera. Quantifiable comparison with simulation results is reasonable to perform for thermocouple data or local measurements of temperature by 'virtual probes' (crosses on b indicated as 'Sp'), which may be set up manually using graphical user interface (GUI) of managing software of thermo camera. It should be noticed that to get correct value of temperature by 'virtual probe' in certain point, magnitude of emissivity in this point should be defined. Even though this definition is difficult due to lack of information about material properties and weak resolution of thermo camera it provides important information about thermal behavior of thruster during its operation.

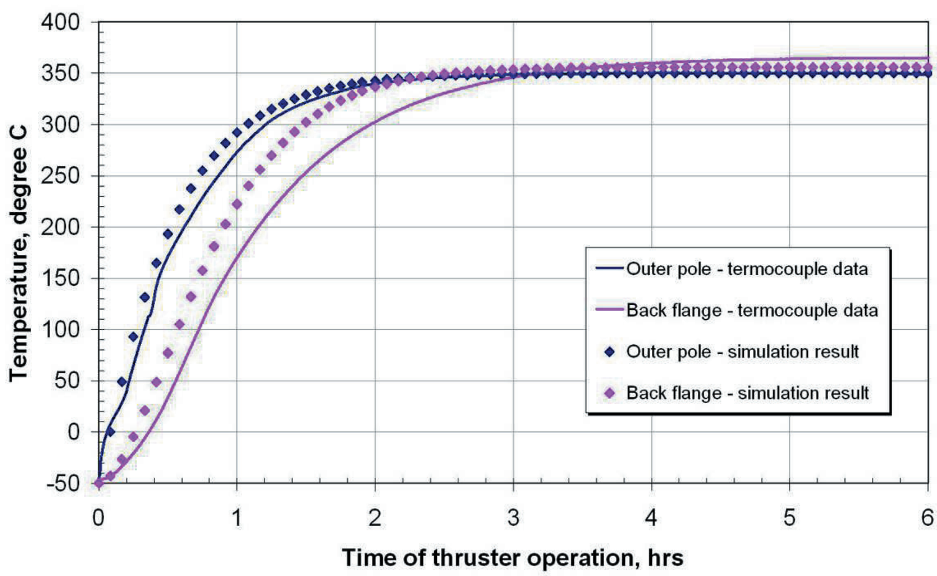

Figure 11 Temperatures of outer pole and back flange of Sitael's HT5k during continuous 10 hours firing test at P_d=4500 W and V_d=350 V.

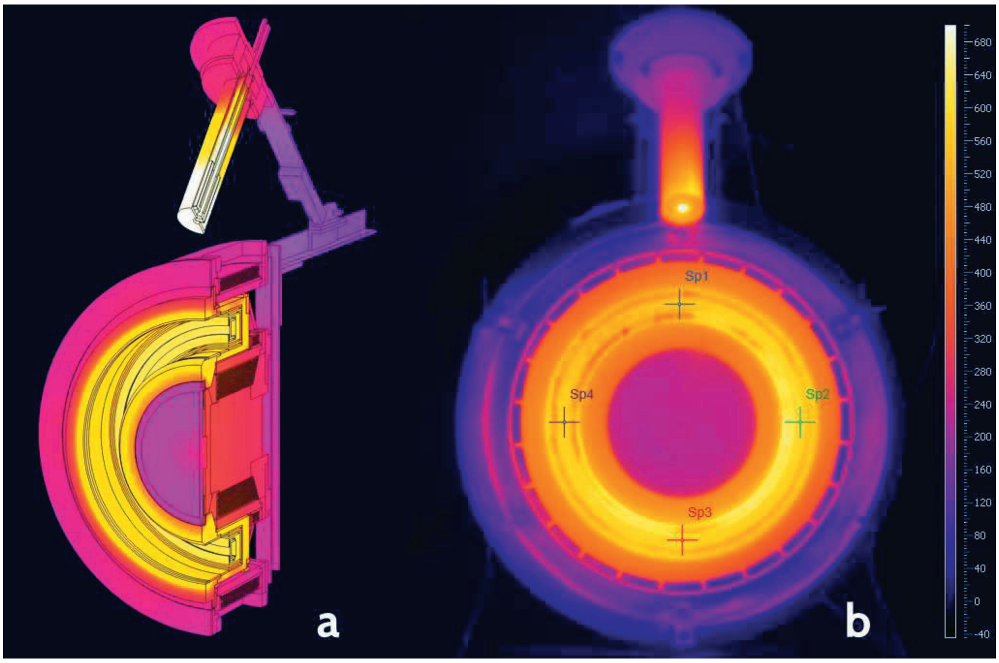

Figure 12 Qualitative comparison of simulation (a) and experimental measurements (b) of temperature distribution in Sitael's HT5k after thermal stabilization during continuous 10 hours firing test at P_d=4500 W and V_d=350 V.

Generally, results of simulations match well with experimental data as it is indicated in Figure 11 and in Figure 12. Therefore, developed thermal model might be used for prediction of thruster thermal behavior during operation at regimes interested for engineers and researchers. In addition, 3D statement of the thermal model permits to take into account such elements of thruster design as openings on back flange and outer shell of the thruster, which are crucial for thruster cooling and allow increasing radiation efficiency and reducing surface temperature of some components on 5-10%.

IV. Conclusions

Engineering model of 5kW-class Hall-Effect thruster – HT5k has been designed, fabricated and assembled by Sitael. Thruster has been successfully characterized with pure Xenon as propellant in wide range of anode mass flow rates (from 6 mg/s to 20 mg/s) and applied discharge voltages (from 250 V to 600 V). During all tests thruster operated with HC20 Hollow Cathode for High-Power HET also developed by Sitael. Except of operation at discharge voltage of 250 V and at low AMFR (<8 mg/s) thruster demonstrated anodic thrust efficiency higher than 50%. Plume measurements indicated that beam divergence calculated for 95% of registered ion current density is in a range of 35-40 degrees for all measured operation points.

Thermal model of Sitael HT5k was developed within Comsol Multyphysics environment and successfully validated with experimental data obtained during 10 hours continuous firing test.

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