Performance and physical characteristics of a 5 kW-class Hall effect thruster for space missions.

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Abstract
Performance characteristics of the 5 kW-class PPS®X000 Hall effect thruster, a technological demonstrator developed by Snecma, are reviewed for input electrical power ranging from 1.5 kW up to 7 kW. It is shown that the PPS®X000 thruster can be operated either in a high thrust domain (up to 350 mN) or in a high specific impulse domain (up to 3200 s). The dual-mode capability of the PPS®X000 electric thruster makes it suitable for missions like orbit topping and station keeping of heavy geostationary telecommunication satellites. Space missions like robotic exploration of outer planets of the solar system and far-off comets require thrust in excess of 1 N.

1. Introduction

The recent success of the SMART-1 lunar orbiter mission of the European Space Agency demonstrates the possibility to employ Hall Effect Thrusters (HET) as the main propulsion means for an interplanetary journey[1]. The plasma engine onboard the SMART-1 space probe was the 1.5 kW-class PPS®1350-G thruster developed and manufactured by Snecma[2]. The thuster allowed the probe to cover more than 100 millions of km consuming only 82 kg of propellant, xenon gas in that case. In spite of a long trip time - 16 months to reach the Moon - due to a weak thrust level of 70 mN constrained by the available power, the ESA mission brings to light advantages of electric propulsion over chemical propulsion: low propellant consumption and high spacecraft velocity due to a long burn time. The PPS®1350-G thruster was indeed able to operate during 4960 h in flight, a world record. In addition, Hall effect thrusters are robust and offer variable specific impulse (Isp) operation capabilities. The PPS®1350-G thruster, which is originally designed to be operated at 1.5 kW of input power, was successfully tested up to 3200 W input power with an efficiency of 60 %[2]. It could deliver a thrust in excess of 160 mN and it reached about 3000 s of specific impulse.
Currently, 1-2 kW-class HET are employed for station keeping and attitude control of geostationary communication satellites. A broad operation envelope combined with high power dual-mode capabilities open up the way for the next generation of HET to new types of space mission like trajectory correction of large geostationary telecommunication platforms, orbit topping manoeuvres and end-of-life deorbit for spacecrafts. Several types of large thrust (~ 200-400 mN) medium Isp (~ 2000 s) 5-10 kW-class Hall effect thrusters exhibit characteristics that match missions requirements. Some of them were successfully subject to extended endurance test to demonstrate the technology readiness, e.g. the NASA 173M in United-States, the SPT140 in Russia and the PPS®X000 in Europe. They all are currently under development phase and will be available for space missions in the very near future. Nowadays research activities mostly focus on higher power electric propulsion devices (> 10 kW) either in the form of single large scale HET to especially achieve very high Isp (> 3000 s) or in the form of clusters of multiple thrusters to produce very high thrust (> 1 N) with a benefit in terms of reliability. Indeed, ambitious robotic missions like exploration of outer planets of the solar system and far-off comets as well as transfer of cargo vehicle to support crewed missions require very high power electric propulsion systems. In order to achieve such missions one needs typically 1 - 50 N of thrust and 2000 - 8000 s of Isp to overcome velocity increments ?v that can be as large as several tens of km/s. Numerous projects and research programs are concerned with development of high power solar

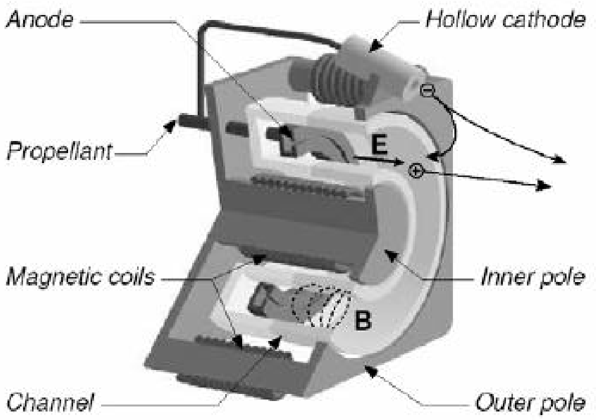

Figure 1: Simplified picture of a Hall effect thruster. Xenon is usually employed as a propellant gas.

Figure 2: PPS®1350-G thrusters used on board the SMART-1 lunar orbiter (credit: ESA).

and nuclear electric propulsion means; however, present state of the art thruster concepts are still far from being able to achieve the necessary performance level.

In this contribution, after a brief review of Hall effect thruster history and basic physical principles, the performance characteristics of the 5 kW-class PPS®X000 Hall effect thruster developed by Snecma are presented for input electrical power ranging from 1.5 kW up to 7 kW. The PPS®X000 is a dual-mode capability HET able to meet the needs in terms of station keeping and orbit transfer manoeuvres for the next-generation of heavy geostationary space platforms. Though initially designed to operate at 5 kW input power, recent test campaigns carried out in the PIVOINE-2G ground-test facility reveal that the PPS®X000 thruster architecture, specifically designed to handle high thermal loads, is promising to allow building of a 10 kW Hall thruster that would provide 500 mN of thrust with ~ 2500 s of Isp. Notwithstanding numerous improvements in the design of large scale very high power HETs over the last few years, scientists and engineers still encounter troubles especially when running thrusters under high voltages in order to achieve Isp > 3000 s. Among other, problems include erosion of dielectric channel walls, stability of the discharge and evacuation of large heat loads with radiators.

2. Hall effect thrusters: history, principles and features

2.1 A bit of history

In comparison with chemical rocket jets, electric propulsion devices offer an attractive way to save propellant mass thanks to a much faster propellant ejection speed. Electric propulsion is nowadays considered as a very promising concept for space applications[3, 4]. Among all proposed electric propulsive devices such as arcjets, magneto plasma dynamics thrusters, gridded ion engines and Hall effect thrusters to only name a few, the latter is currently recognized as an attractive system in terms of performance level and flexibility. A Hall effect thruster, also called Stationary Plasma Thruster or closed electron drift thruster, is an advanced propulsion device that uses an electric discharge to ionize and accelerate a propellant gas[5, 6, 7]. The basic concept of a Hall effect thruster was suggested in the early 60s almost simultaneously in the former USSR and in the USA[8, 9]. However, it is only in 1972 that the first demonstration was given in flight by the soviet satellite Meteor. Since the time of pioneer works, several hundreds of spacecrafts have flown with Hall thrusters, which represents a significant heritage in terms of science and technology. Nowadays, HET are often used onboard geostationary communications satellites for attitude control and station keeping. The recent development of 5 kW-class thrusters will offer possibility to employ electric propulsion for orbit topping and trajectory correction of prospective heavy communication platforms.
The first scientific space mission to rely on electric propulsion was the Deep Space 1 mission from NASA in 1998[10]. The ultimate goal of the mission was the flyby of Comet Borrelly. The DS1 spacecraft was equipped with the 30 cm in diameter NSTAR gridded ion engine developed by NASA, which delivers 92 mN of thrust and 3100 s of Isp. The

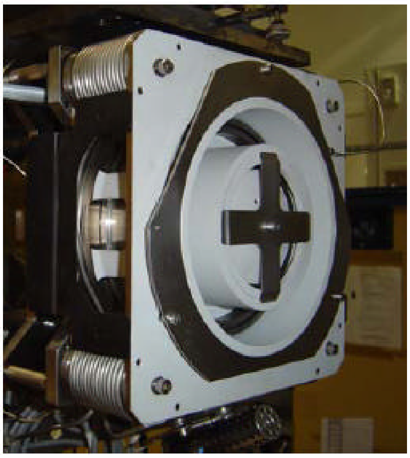

Figure 3: Photograph of the PPS®X000 Hall effect thruster before insertion into the lock chamber of the PIVOINE-2G facility.

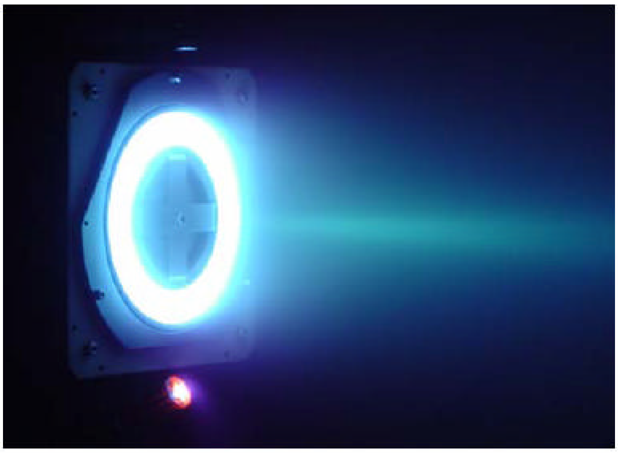

Figure 4: PPSX®000 firing in the PIVOINE-2G facility. The plasma inside the annular channel as well as the plume are clearly visible.

engine fired for 678 total days and consumed 72 kg of xenon. The Japanese Hayabusa (Muses-C) space probe, which was launch in 2003, uses four microwave gridded ion thrusters. It is the first mission to attempt to land on an asteroid (Itokawa), collect samples, and return them to Earth. After successfully picking up a soil sample in winter 2005, the probe is schedule to go back home in 2010. The third mission to use solar electric propulsion was the SMART-1 mission to the Moon from ESA in 2006[1]. The probe was equipped with the 1.5 kW-class PPS®1350-G Hall effect thruster from Snecma. It covered more than 100 millions of km with the thruster firing 207 total days and consuming 82 kg of xenon. These missions demonstrate that electric propulsion is from now on a mature technology for outer space trips. The development of high power HET will soon permit to enter the era of ambitious exploration missions.

2.2 HET basic principles and characteristics

Hall effect thrusters offer interesting features in terms of thrust, specific impulse, efficiency and lifetime. In a Hall thruster, acceleration of heavy atomic ions to high velocity occurs within the core of the plasma where ions are produced, which implies the use of a magnetized plasma enable to sustain internal electric fields[5, 6, 7]. The general structure of a Hall thruster is shown in Fig. 1. The basic physics of a HET consists of a magnetic barrier in a low pressure DC discharge generated between an external hollow cathode and an anode. The anode, which also serves as gas injector, is located at the upstream end of a coaxial annular dielectric channel that confines the discharge. Xenon is generally used as a propellant gas for its specific properties in terms of high atomic mass and low ionization energy. A set of solenoids provides a radially directed magnetic field **B** whose strength is maximum in the vicinity of the channel exhaust. The magnetic field is chosen strong enough to make the electron Larmor radius much smaller than the discharge chamber length, but weak enough not to affect ion trajectories. The electric potential drop is mostly concentrated in the final section of the channel owing to the low electron axial mobility in this restricted area. The corresponding induced local axial electric field **E** has two main effects. First it drives a high electron azimuthal drift - the so-called Hall current - that is responsible for the efficient ionization of the supplied gas. Second, it accelerates the ions to very high speed, which generates thrust and creates a plasma plume. The ion beam is neutralized by a fraction of electrons emitted from the hollow cathode. When operating near 1.3 kW, a HET ejects ions at 20 km/s and generates 80 mN of thrust with an overall efficiency in excess of 50 %. A 3D picture of the PPS®1350-G thruster is shown in Fig. 2. The thrust of such a device is 88 mN at 1.5 kW input electrical power with 1650 s of Isp. So far its qualification lifetime is above 10500 hours. For moderate input power, typical HET parameters are: 4.5 A discharge current for a seeded xenon mass flow rate of 5 mg/s and 300 V applied voltage; 19 km/s mean Xe^+ ion axial velocity beyond the channel exhaust. Note that at 300 V the maximum speed is 21 km/s. Several physical quantities have been measured or derived from simulations. The electron temperature is 20 eV at the channel exhaust. Atom density is 10^{20} m^{-3} in the anode vicinity and the electron density is around 10^{18} m^{-3} inside the channel. The electron drift current, which is driven by an axial electric field of a few 10^4 V/m is close to 25 A. The HET discharge displays various type of oscillations[5, 11], which weakly influence performances.

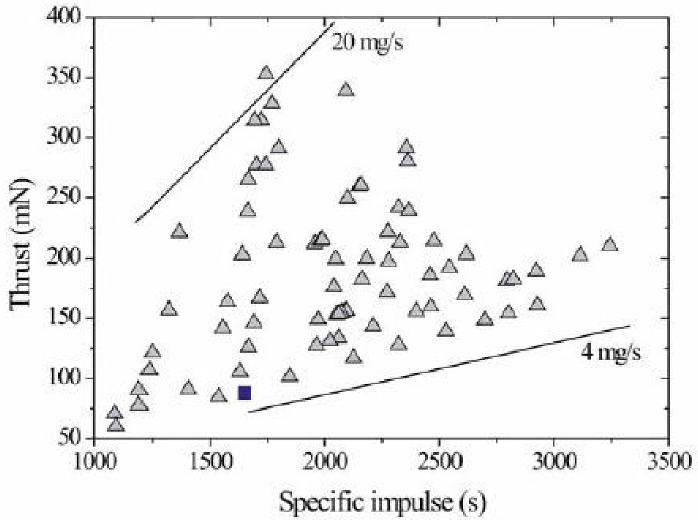

Figure 5: Operation envelope – thrust versus Isp plot – of the laboratory model PPS®X000 Hall effect thruster. The thrusters can be operatec either in large thrust mode or in high Isp mode. The lines are computed assuming a thrust efficiency of 1, a full ionization of the gas injected through the anode and a beam solely composed of singly-charged xenon ions. The square corresponds to Snecma-built PPS®1350 at normal operating conditions (350 V, 1.5 kW).

3. The 5 kW-class PPS®X000 thruster

3.1 A PPS®X000 thruster features and operation envelope

The PPS®X000, a technological demonstrator for the PPS®5000, is a high power Hall effect thrusters developed by Snecma to offer dual mode capability[12, 13, 14]. It has a nominal power rating of 5 kW. The magnetic circuit design incorporates one internal magnetic coil and four external coils. The thruster used in this work is a laboratory model. It is equipped with dielectric BN-SiO_2 channel walls and with a carbon anode. Outer solenoids are wired in series. The external hollow cathode was manufactured at the MIREA institute in Moscow and positioned below the thruster. A photograph of the PPSX000-LM is shown in Fig. 3, and in Fig. 4 the thruster is fired at 4.8 kW input power in PIVOINE-2G.

In Fig. 5 we present the operation envelope - thrust versus Isp plot - of the laboratory model PPS®X000-LM thruster, referred to as PPS®X000 in this paper for simplicity sake. The magnet current is adjusted depending on firing conditions. As can be seen in Fig. 5, it appears that the PPS®X000 thruster is robust and versatile as it offers dual-mode capabilities with steady-state operation over a broad range of power from 1 kW to 7 kW[13]. The demonstrated performances included a maximum thrust of 353 mN and a maximum Isp of 3240 s. In addition to the *F* vs Isp data of the PPS®X000, the normal operating point of the Snecma-built PPS®1350 is also shown in Fig. 5 for reference (88 mN, 1.5 kW, 350V, 4.28 A and 1650 s). Lines drawn in Fig. 5 correspond to calculation outcomes. They simulate the behavior of an "ideal" HET with a thrust efficiency of 1, a full ionization of the xenon gas injected through the anode and a monoenergetic beam solely composed of singly-charged xenon ions.

3.2 Thrust and specific impulse

In Fig. 6, the PPS®X000 thrust is plotted as a function of the applied voltage for various anode mass flow rates $\dot{m}_a$. For a fixed flow rate, the thrust increases with the discharge voltage U_d. Similarly, the thrust increases with $\dot{m}_a$ for a constant voltage. The magnetic field is optimized for each operating condition in order to minimize the discharge current. For a given applied power, the best way to achieve a high thrust level is to use a large flow rate with a

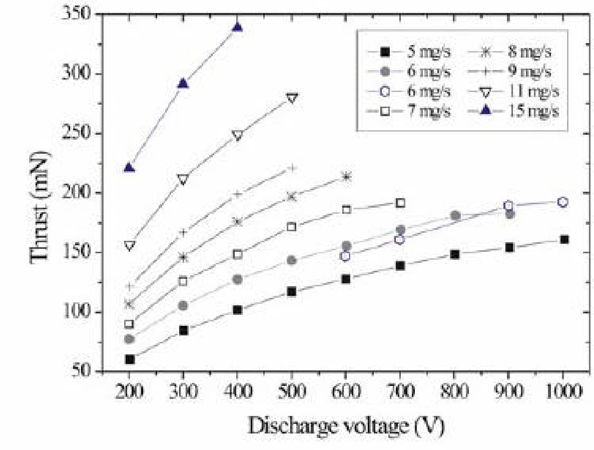

Figure 6: PPS®X000 thrust measurements at various anode flow rates as a function of discharge voltage.

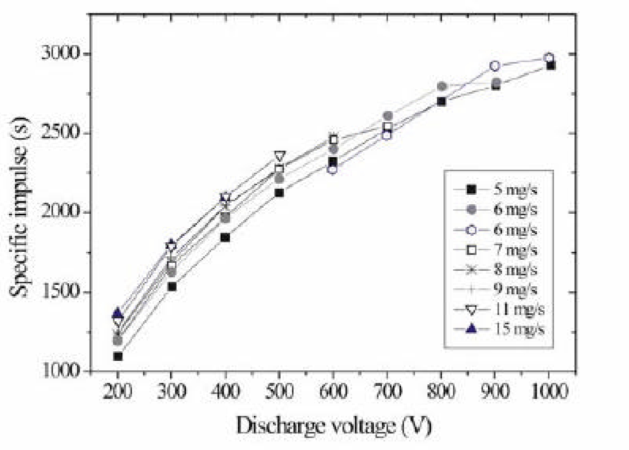

Figure 7: PPS®X000 specific impulse at various anode flow rates as a function of discharge voltage.

moderate voltage. Graph in Fig. 7 shows the specific impulse of the PPS®X000 thruster versus discharge voltage for various anode mass flow rates. The Isp also increases with U_d, as expected in view of Eq. 1:

$$Isp = \frac{F}{\dot{m} \cdot g} \tag{1}$$

where g is the Earth standard gravity (~ 9.81 m/s^2) and $\dot{m}$ is the total gas flow rate, i.e. $\dot{m} = \dot{m}_a + \dot{m}_c$ where subscript a, respectively c, refers to anode, respectively cathode. The thrust F is given by:

$$F = \dot{m}_i \cdot \bar{v}_i \tag{2}$$

where $\dot{m}_i$ is the ion mass flow rate (only singly-charged ions are considered here) and $\bar{v}_i$ the average ion velocity. Naturally, $\dot{m}_i$ is a fraction of $\dot{m}$ ($\dot{m}_i \approx 0.9 \cdot \dot{m}_a$).

Combining Eq. 1 and 2 and neglecting $\dot{m}_c$, one finds $Isp \propto \bar{v}_i$. Taking into account energy conservation throughout the potential fall, one can show that Isp is roughly proportional to $U_d^{1/2}$, which is the trend observed in Fig. 7. A more rigorous treatment of the link between Isp and U_d must account for energy losses and multiply charged ions[15]. A high Isp level requires to operate a HET at high voltage. For an available electrical power, a high specific impulse value is always obtained with a low flow - high voltage couple. Efficiency, thermal load, Isp and thrust level must then be considered all together to select the best option.

The operation domain of the PPS®X000 HET is wide enough to propose high specific impulse for platform station keeping manoeuvres and high thrust for orbit raising manoeuvres. The dual mode capabilities of the PPS®X000 are well illustrated with the following numbers: at 5.1 kW input power the thruster provides with either both 180 mN and 2790 s (800 V, 6 mg/s) or both 265 mN and 1670 s (300 V, 15.6 mg/s). In terms of electric power-to-thrust ratio p_e, or specific power, in kW/N, which is a measure of the cost of generating the desired thrust, the two preceding working conditions give 28.3 kW/N and 19.2 kW/N respectively. The specific power p_e reads:

$$p_e = \frac{P_{elec}}{F} = \frac{g}{2 \cdot h} \cdot Isp \approx g \cdot Isp \tag{3}$$

where ? is the thrust efficiency given by:

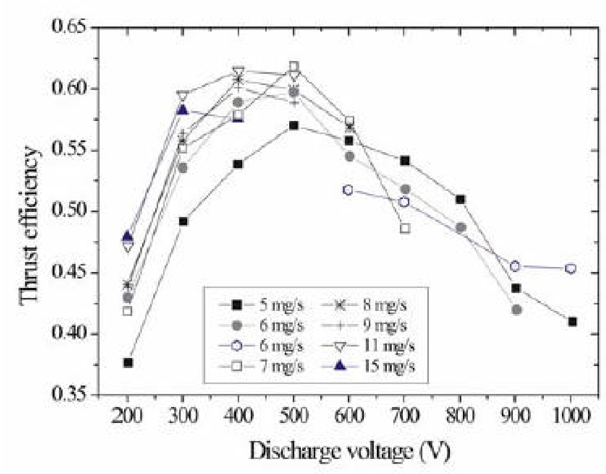

Figure 8: PPS®X000 thrust efficiency versus discharge voltage for various anode flow rates.

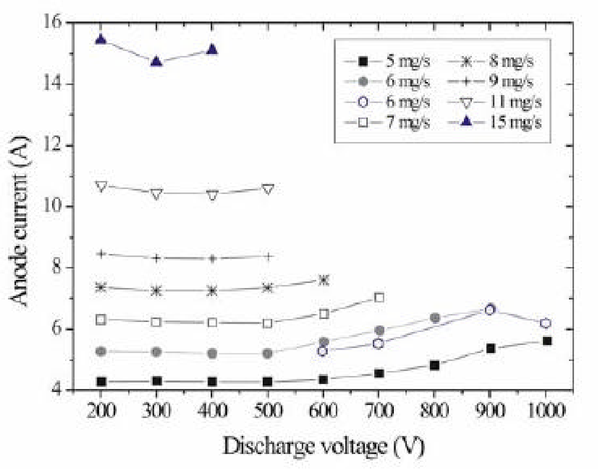

Figure 9: PPS®X000 anode current versus discharge voltage for various anode flow rates.

$$h = \frac{F^2}{2 \cdot \dot{m} \cdot U_d \cdot I_d} \tag{4}$$

where I_d is the discharge current.

A glance at Eq. 3 indicates that a high thrust requires a high input electric power even at moderate Isp. In like manner, maintaining a low thrust level at very high Isp value, in order to minimize propellant consumption, comes at the cost of a high power level. To sum up: for a given space mission, i.e. a given velocity increment ? v and trip time, there exists an optimal value for the specific impulse.

3.3 Thrust efficiency

Another key parameter to be considered when analysing thruster performances is the thrust efficiency ? defined by Eq. 4. Figure 8 displays ? versus U_d for the PPS®X000 thruster for a large set of anode flow rate. At a fixed voltage, ? improves at each higher anode flow due to a better mass utilization. However, Fig. 8 reveals the existence of an optimum anode flow. The evolution of ? with U_d results from a balance between ionization, losses at wall, current generation and beam divergence. At low voltages, ? drops due to a decrease in plasma density, hence discharge instability. As can be seen in Fig. 8, the efficiency reaches a peak around ~ 550 V depending on the mass flow. The peak efficiency corresponds to Isp in the order of 2200 s and an anode specific impulse of about 2500 s. The anode specific impulse Isp_a solely accounts for the anode mass flow rate. It reads:

$$Isp_a = \frac{F}{\dot{m}_a \cdot g} \tag{5}$$

Such a behavior is also observed with low-power thrusters like the Fakel-built SPT100 and the SPT115 from RIAME-MAI[16, 17], the Snecma-buit PPS®1350[2,18] and with high-power (~ 5 kW) thrusters like the SPT140 laboratory model[17], the P5 from the University of Michigan[19, 20], the Busek BHT-1000[21] and the 173Mv1 from NASA[22]. The existence of a peak in the ? -U_d curve is linked both to production of multiply-charged ions and to the magnetic field topography.
Another interesting feature is the increase of the discharge current with the discharge voltage, as can be seen in Fig. 9. Whatever is the mass flow rate, the discharge current increases when U_d is above 500 V, i.e. when ? drops. The current build-up is explained by the increase in electron current and/or by the production of multiply-charged ion species at high voltage, as was shown by means of RPA and E×B probe measurements[23, 24, 25] and by a detailed

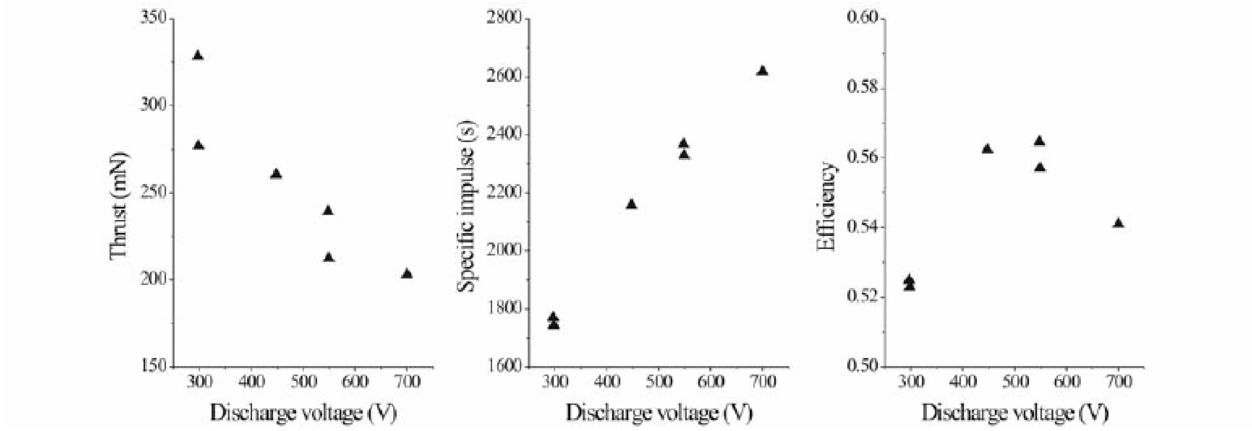

Figure 10: Thrust, Isp and efficiency of the PPS®X000 thruster as a function of the applied voltage for anode gas flow ranging from 7.3 mg/s to 18.3 mg/s. The magnetic field is kept constant.

analysis of discharge current contents[17]. In Fig. 10, we present another set of measurements of thrust, Isp and efficiency of the PPS®X000 thruster as a function of the applied voltage. The anode gas flow ranges from 7.3 mg/s to 18.3 mg/s. The magnetic field is kept constant. The measurement series has been carried out in the PIVOINE-2G ground-test facility. The thrust efficiency reaches 56 % at 550 V for 4.9 kW input power; the specific power p_e is equal to 20.5 kW/N.

The critical analysis of performance characteristics of the PPS®X000 thruster reveals that the latter is perfectly suited for operation at power below 6 kW and that it can deliver thrust of ~ 250 mN and Isp ~ 2500 s, necessary performances to meet the needs in terms of actual space market demands. A short-duration (slightly over 300 hours) endurance test at 700 V was carried out in the year 2004, and was followed in the year 2005 by a successful 1000-hour endurance test at a discharge voltage of 550 V, a world-record discharge voltage for an endurance test on a Hall effect thruster, and a power level of 4.5 kW[14].

4. Conclusion

The critical analysis of the performance characteristics of the 5 kW-class PPS®X000 Hall effect thruster for input electrical power ranging from 1.5 kW up to 7 kW reveals the dual-mode capability of such a HET. At 5 kW input power, the PPS®X000 truster delivers either 260 mN of thrust or 2800 s of specific impulse. Therefore the latter is perfectly able to meet the needs in terms of station keeping and orbit transfer manoeuvres for the next generation of large geostationary communication platforms. As was shown, the HET technology is nowadays mature for high thrust operation ~ 250-300 mN. Conversely, the actual design of HET is not optimum when running thrusters under high voltages in order to achieve Isp > 3000 s. Indeed, above ~ 600 V depending on the thruster design, the thrust efficiency decreases, as does the thruster lifetime. Today state of the art HET technology is still far from being able to provide the necessary performance level to accomplish ambitious robotic exploration missions, however, work is in progress and the next decade could see the first long-distance interplanetary trip of a solar electric-propelled space probe.

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