Compact Hall Effect Assembly Propulsion subsystem PPS®X00, first test results in the range 300W-500W

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F. Marchandise[1] and N. Cornu[2]
Snecma Division Moteurs Spatiaux, Vernon, Haute-Normandie, 27200, France

and

N. Arcis[3] and D. Arrat[4]
Centre National d'Etudes Spatiales, Toulouse, Midi-Pyrénées, 31000, France

Abstract: System studies from Snecma and CNES shows interest for a system based on a Hall Effect Thruster in the range of 10mN-30mN thrust capability. Corresponding power was evaluated at 300W to 500W range at system level. Studies demonstrate that needs for missions such as low earth orbit satellites attitude control or East-West Station Keeping for geostationary satellites do not demand extremely high specific impulse. The use of a simplified electric propulsion subsystem with reduced cost is the key to implement Electric Propulsion at spacecraft level, simplifying the assembly and integration. The proposed subsystem integrates the power processing unit, the fluid management from a high pressure input, and the thrust function through a low power thruster. Thermal management is carefully designed to decrease as far as possible the heat exchange with the mechanical support and to create a limited thermal load on the spacecraft. It was decided to build a first prototype of a thruster in the typical range 300W-500W. Conception, definition, parts procurement and manufacturing of the first thruster prototype were performed between 2008 and 2010. The thruster uses innovative manufacturing processes derived from technology already developed for the PPS®X000, such as, Carbon-Carbon anode, or Carbon-Ceramic links, innovative thermal management and technical solutions. Integration was performed until beginning of 2011 and then the test characterization started. This article presents a description of the integrated subsystem with the first results of test for the thruster prototype PPS®X00.

Nomenclature

ΔV = speed increment

[1] Engineer, Electric Propulsion section, frederic.marchandise@snecma.fr
[2] Head of Electric Propulsion section, nicolas.cornu@snecma.fr
[3] Engineer, Electric Propulsion section, nicolas.arcis@cnes.fr
[4] Head of Electric Propulsion section, denis.arrat@cnes.fr

I. Introduction

SPACECRAFT missions demand various levels of total impulse for different missions. Chemical propulsion is currently still widely used for low earth orbit and geostationary orbit control. Electric propulsion offers a much better global performance at mission level, and further improvements in terms of cost reduction, heat management and system simplification of this technology will allow generalizing its use on spacecrafts.
In 2007 CNES and Snecma initiated and sponsored studies on a small propulsion subsystem. The high integration level and the simplification of the subsystem were the main design drivers. Simplification of the subsystem was done with a design that integrate only one cathode, a simple fluid line with two valves in series and a simple power electronics without power redundancies. This allows great simplifications on the spacecraft integrations side, opening the path to low cost electric propulsion. A highly integrated propulsion subsystem is proposed hereafter with a description of the system and its design driver, a description of the thruster, of the power supply and of the fluid supply.

II. The Compact Hall Effect Assembly Propulsion subsystem

Highly integrated subsystem was already explored for example in the seventies through the EOL Russian program[1] or in the nineties through the RHETT program[2] demonstration sponsored by the US.

Several missions have already been performed by small spacecraft in low earth orbit. Most of these missions are limited in ΔV to less than 200 m/s. Electric propulsion based on Hall Effect Thruster may increase the ΔV available by a factor of 5 to 10 with the same amount of propellant mass. Power is generally limited but even 500kg class spacecraft (such as Proteus[3]) can produce up to 300W payload power that can be switched temporarily for orbit control when needed. We considered a maximum available power from 300W to 500W for entire propulsion subsystem, and this lead to a thrust range typically up to 30mN. Some studies give a typical use of the thruster for less than half an hour to several hours duration dedicated to attitude control or orbit control for low earth orbit needs. For large geostationary satellites, East-West Station Keeping can be performed with the same kind of subsystem. This would be a backup solution: usually, the need (around 5m/s per year) is covered by orientation of the thrust. In case of North-South Station Keeping orientation mechanism failure, another means for the East-West correction applies, which is currently a chemical propulsion subsystem.
Also for small geostationary satellites, such propulsion subsystems could even fulfill the North-South Station Keeping needs.
Initially dimensioned for 300W power, the studies performed at CNES shows that the best interest for such a subsystem would be at 500W input power. Studies[4] from Alta shows also interest in low power propulsion subsystems for remote sensing applications that lead to a 400W thruster.

A. System architecture

The design driver was to simplify the system. One of the complexity increase driver is the redundancy at component level. To accept a propulsion subsystem without redundancy, this redundancy must be done at a higher system level by multiplying the number of simple electric propulsion assemblies in adequate positions on the spacecraft. This allows designing the thruster with a single cathode, simplifying the fluid management subsystem and electronics design accordingly. On system safety side, the only one failure that can propagate to the system is linked to the loss of pressurized gas, so the need to keep at least two tight barriers is included in the design.

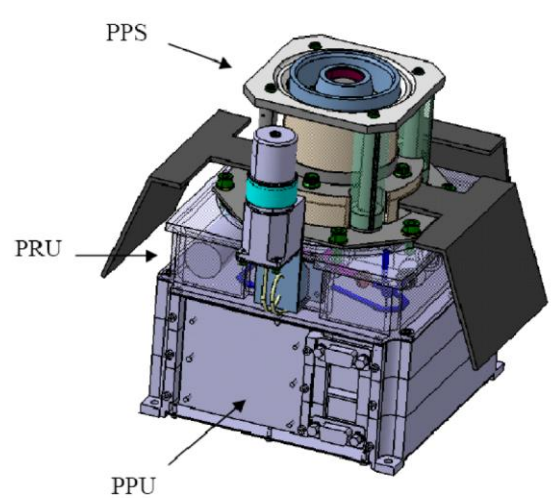

Figure 1. Compact Hall Effect Assembly Propulsion subsystem. *Overall dimensions are 150x150x220 without radiation panels and cathode.*

The thruster PPS®X00 is designed with a single cathode and special radiation panels to extract the heat from the inner ceramics towards external space. Interface between the PPS and the fluid management subsystem (PRU X00) is thermally dimensioned to avoid the heat conductive transfer. This allows keeping a correct temperature at PRU level.

Usual fluid management system separates pressure regulation function and flow rate regulation function (Smart-1[5], DS-1[6], Eurostar[7 8], Alphabus[9]…). We choose to integrate the two functions in order to minimize the components number for one fluid system. The consequence is to have a small change in the flow rate at thruster level which creates a non linear impulse with time of firing. This stays in an acceptable range through an adequate behavior modeling of the thrust.

The electronics driver (PPU X00) manages the fluid subsystem, the thruster supplies, the starting sequence, and the operational firing sequence. It has interfaces that are linked to the spacecraft power bus and signal bus. We currently design this interface for the classical CNES power and signal bus but the concept authorizes different bus interfaces if needed. The electronic contains some intelligence to manage the thruster operation; especially during short firings and it has the capability of self diagnostics in order to allow the spacecraft to stop the hardware if there is any functional issue.

Another challenge is to deal with the thermal loads on the subsystem that comes from thruster firing (or not), electronics Joule effect, and from valve heat losses. The PRU thermal design is done to avoid cold levels at the depressurization device. The thermal design of the electronics is done to minimize the temperature rise, increasing the efficiency of the electronics, with the benefits that it creates less heating from Joule effect losses.

Two options coexist for the fixation brackets, it can be put at the bottom of the subsystem (fig. 1) or it can be put at the PPS-PRU interface. In this case, the radiation panels are displayed in a different way. These two cases are thermally different and may need some accurate thermal management.

The overall mass of the entire propulsion subsystem described is expected to be less than 4kg, with 1.5kg for the electronics, 1.5kg for the thruster and 1kg for the pressure regulation unit with its structural frame.

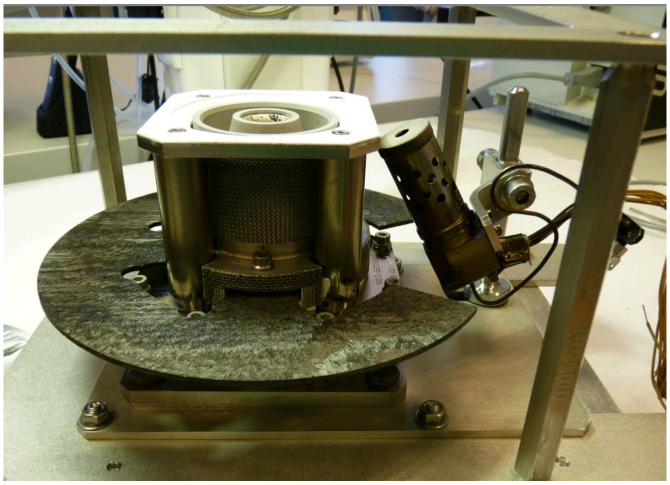

Figure 2. PPS®X00 prototype n°1. *The thruster is mounted in its handling tooling, we can see the radiation device (in carbon-carbon) specific to the test bench, the cathode is not in its definitive place.*

B. Thruster Unit

HET thrusters are characterized by their large power and thrust range for a single geometry. As an example, even if not optimized, the PPS®1350-G allows a large range of power, specific impulse and thrust. Thrusters in the range of 10 mN to 30 mN with Xenon has dimensions with external channel diameters of around 45-50 mm and the decision to use a diameter of 52 mm was done. The magnetic design is kept similar to PPS®1350 with 4 external coils and one internal coil to create the necessary magnetic field at the outlet of the channel. The anode-channel assembly has been drastically simplified with only 4 pieces (two parts with ceramics and two parts with carbon-carbon) that creates the gas distribution, the current feeding, the electrical insulation and the thruster channel confinement for the plasma.

The distribution chambers are partly done with carbon-carbon anode and partly with the ceramics. The link between these parts is done through a specific brazing process already developed for the PPS®X000 thruster. A special machining of the anode allows a good gas distribution in the channel that gives an initial inlet with a radial velocity of Xenon.

The thermal load on a small thruster is high on the inside ceramics and a special part evacuates the temperature from that area to the radiation panel. The thermal effect modeled shows that a decrease of the inside temperature is obtained by this way and can reach 100°C. The corresponding part has been implemented on the inside ceramics of the PPS®X00 prototype n°1. The radiation panels were also implemented in a mechanical configuration specific to the test bench.

The well known PPS®1350-G cathode design is currently implemented. This is over dimensioned for the thruster need (between 0.7A and 2A) and for low level of current, it needs a keeper current to keep the LaB_6 emitter at the right temperature. As far as this cathode has a wide heritage at higher power, development effort is restrained and reliability is at high level. This cathode is derived from the Russian KN3H cathode design, and was developed together with Snecma and Fakel in the nineties to be mounted together on Russian and French PPS®1350. On the PPS®X00 prototype n°1, a similar Fakel cathode is implemented (fig.2).

C. Fluid management Unit

The fluid management unit is a very simple one, decreasing the number of valves needed down to only two. The pressure inlet is supposed to be in the expected operating range of 5bar to 150bar as classical for such a propulsion subsystem. Effort can be done to decrease acceptable pressure of the lower level down to 2bar or even less, but only if the thruster performances can be degraded. This can be accepted for a typical end of mission when the spacecraft will become debris and when it has to be removed from the orbit.

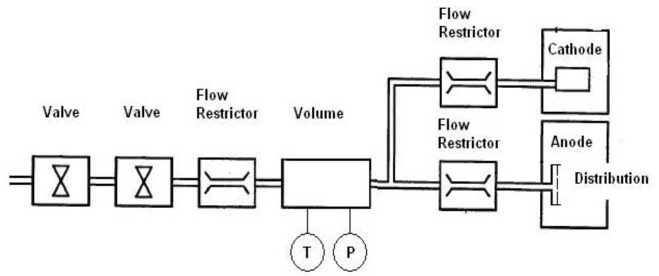

Figure 3. Fluid management sketch. *The fluid management device dispatch with only three restrictors, two on-off valves, one pressure transducer, one temperature probe, volumes and tubing the gas from the main tank to the thruster.*

The fluid management subsystem has an inlet valve with the function of opening or closing the gas flow to the subsystem as On-Off element. This valve is then followed by a secondary valve that is opened and closed to fill, through a restrictor, a small volume (fig.3). This volume is equipped with one pressure transducer and one temperature measurement. The volume (typically 20 cm3) dispatches the gas through two feed lines with restrictors to the anode and to the cathode. The working pressure of the intermediate volume is typically 1 bar.

The great simplification of this device has some cost: the Xenon gas filled in the intermediate volume would be lost at each thruster stop. This could be bypassed using a new method to operate the thruster even with decreasing flow rate, called blow-down. The thruster performance is characterized continuously during this flow rate decrease. Such a scheme uses most of the gas delivered to the propulsion subsystem with high specific impulse and high efficiency. Another cost of such a system is the ripple of the pressure of the volume and as a consequence on the flow rate during firing. Because of the still low level of ripple, this has no real impact on the thruster behaviors such as lifetime or firing stability except that a small performance ripple occurs. This has to be characterized to give at upper level the right total impulse delivered during firing. The other way to overcome this disturbance would be to manage the firing time by the subsystem but the necessary intelligence associated would be too complex to implement in the propulsion subsystem. This work will have to be done by Attitude and Orbit Control system at spacecraft level.

D. Power Processing Unit

The power processing unit manages all electrical functions of the propulsion subsystem. It also has a role of health monitoring and it has its own intelligence for all the sequences foreseen for the propulsion. There is also an operating mode with low intelligence where the spacecraft could give direct orders to some components (typically, to order a thruster stop or a valve off in case of subsystem malfunction). Usually in a hall effect propulsion subsystem, there is a filter unit added for each thruster, this function is now integrated into the power processing unit as far as the distance between the thruster and the electronic is small. This allows a very low electromagnetic conducted noise perturbation, especially with a good management of the grounding of all the subsystem parts involved in the last electrical loop.

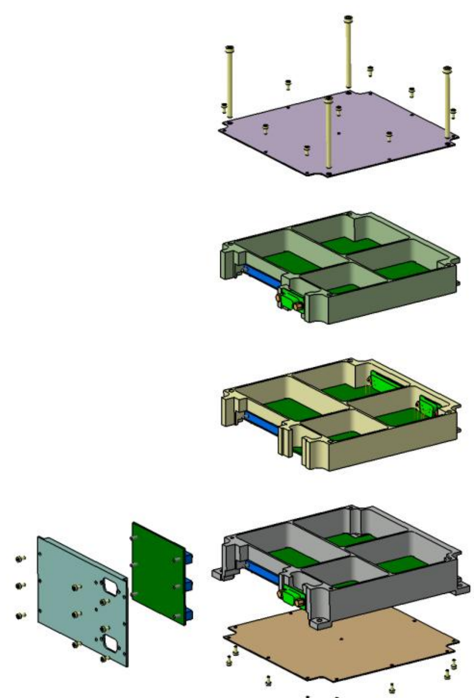

Figure 4. Power Processing Unit. *View of the inside of the PPU able of 500W management.*

The power processing unit transfers and controls the power mainly to the cathode heater, to the thruster discharge, to the valves opening and closing. The power processing unit also supplies the pressure transducer, the temperature measurement, and all internal devices for the management of power and low power devices. Software is also implemented to drive the sequence according to orders from the spacecraft, and to monitor the health of the subsystem and reports to the spacecraft.

The overall efficiency of the electronics is particularly important to decrease the thermal load during firing. In this way, the power dedicated to the thruster can be adjusted to a higher level. A typical efficiency of 85% to 90% can be managed and for 500W device, it means still 50W to 75W losses converted into heat.

E. First test results

The PPS®X00 prototype n°1 performed firing sequences in the Snecma Vernon test bench LIB. This test bench was dedicated to PPS®1350 firing (endurance of the qualification model was performed, as has some Alphasat thrusters). So, its diagnostics system is made for a 70mN-100mN thrust. The extension of use downsize to 10mN-30mN lead to more uncertainties on the data.

The test campaign begins with a research of the best practice for the thruster start. Good results were obtained with the initial start of the cathode with keeper current, rapidly followed by a high voltage (above 380V) directly on the anode. It gives repetitive starts, then the setting points were explored and other points were also explored with a modification of magnetic field (internal or external) and with modification of flow rate. The surprise was that the thruster functioned in a stable manner in a very large domain from 55W to 870W.

The initial objective of the subsystem was at 300W and the test plan explored the setting points, with the previsions in fig.6. The results observed were lower than the predicted value (see fig.7), but the magnet optimization was not performed in this test campaign where the main objective was still to start the thruster and to have a look at the operating domain performance. Prediction and observed thrust are consistent with the thrust balance uncertainties of +/-2mN. Nevertheless, the performances of the thruster are interesting and an optimization campaign has to be programmed.

The thruster fired a cumulated time of 10h51mn during 15 cycles. The other characteristics of the thruster such as divergence or efficiency are not given in this paper because of the uncertainties that exist on the data. Divergence measurement was done with too low beam current for the probes inside the test bench and adaptation of the probes and conditioning has to be done. Efficiency is a computation from the electrical power, the thrust and the anode mass flow rate. It gives results with large uncertainties and even if we are confident with value such as 36% to 48%, the wider range of computed data observed (from 28% to 73%) shows that they need confirmations.

Figure 5. PPS®X00 prototype N°1 firing. *Firing performed on the LIB Snecma test bench.*

Setting point - predictions	1	2	3	4
Discharge voltage	220V	250V	290V	330V
Discharge current	0.62A	0.86A	1.07A	0.75A
Flow rate	0.72mg/s	1.00mg/s	1.25mg/s	0.88mg/s
Predicted thrust	10mN	15mN	20mN	15mN
Predicted specific impulse	1300s	1400s	1500s	1600s

Figure 6. PPS®X00 prototype N°1 setting points. *4 setting point at respectively 136W, 215W, 310W, 248W power level.*

Setting point - observations	1	2	3	4
Discharge voltage	220V	250V	290V	330V
Discharge current	0.55A	0.81A	1.05A	0.70A
Flow rate	0.72mg/s	1.00mg/s	1.25mg/s	0.88mg/s
Observed thrust	8mN	14mN	18mN	13mN
Observed specific impulse	1150s	1420s	1470s	1510s

Figure 7. PPS®X00 prototype N°1 points results. *Power tested at respectively 121W, 203W, 305W, 231W.*

III. Conclusion

The Compact Hall Effect Assembly Propulsion subsystem principle is a promising concept for the use of low cost electric propulsion at spacecraft level. The development effort has still to be decided but the initial results of the thruster PPS®X00 prototype n°1 are in accordance with prediction with regards to the uncertainties of the test diagnostics used. Magnet optimization, setting point optimization, test diagnostics optimization (such as thrust balance and beam divergence) are still to be done.

Acknowledgments

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