MAGNETIC CIRCUITS FOR HALL THRUSTERS:

USE OF PERMANENT MAGNETS

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Abstract

Hall thrusters are now considered as one of the most promising propulsive systems for the stationkeeping of geostationary satellites. These thrusters use the acceleration of ions by a self consistent electrostatic field. In these thrusters, the magnetic topography plays an important role to focus the electrons and to control the plasma discharge. The magnetic field is generated by a set of internal and external magnetic coils. In this paper we comment on the advantages of the use of permanent magnets instead of coils and we present the experimental results obtained with a SPT100 laboratory model tested with three coil/permanent magnet configurations.

Introduction

Several missions in space require the use of one or several propulsive systems for the following purposes: to operate a change of orbit in order to leave the initial orbit given by the launcher, to maintain a telecommunication satellite at its station on a geostationary orbit (GEO), to de-orbit a satellite at the end of its lifetime, to prevent collision with debris, to reach a specific trajectory for interplanetary missions, to obtain a precise positioning for scientific probes, to control the entry in a planetary atmosphere… The thrusters must have performances adapted for the mission. It is generally specified by a range of values of thrust, specific impulse, global efficiency, energy consumption, time of life and stability of parameters. It is obvious that other economic parameters have to be taken into account for the optimized choice, as cost, weight, reliability and possible toxicity of the ergol.

The Stationary Plasma Thrusters (SPTs) that are able to deliver a thrust of 80-100 mN with a specific impulse of 1500-2000s and a high global efficiency (around 50%) during several thousand hours is a convenient solution to perform the orbit control of the geostationary telecommunication satellites

The physical phenomena appearing in a SPT have been presented in many previous papers [see for example: 1,2,3]. The principle of SPT is shortly recalled in the chapter 1.

In the SPT, the magnetic field permits to focus the electrons emitted by an external hollow cathode in the channel and to increase the non-elastic electron-neutral collision frequency. The magnetic field contributes by different phenomena to the mobility of the electrons across the magnetic lines. This is briefly explained in the chapter 2.

In the different SPT (flight and laboratory models) the magnetic field is generated by external and internal coils. The number of coils is variable (four external and one internal coils for classical SPT and for the French SPT100-ML, 2 internal and 1 internal coils for an ATON model). The use of permanent magnets instead of coils presents several advantages. They are described in the chapter 3.

Following this idea we defined and tested three configurations using coils and magnets together or only internal and external magnets. Three systems have been designed and manufactured in order to be adapted on the SPT 100-ML. They are described in the chapter 4 with the preliminary tests performed in order to examine the thermal behaviours of the magnets and to check the magnetic field profile.

The chapter 5 presents the results of the campaigns carried out in the Pivoine ground test facility with the three configurations. These tests have permit to study the performances of the thruster (thrust, specific impulse, potential of the cathode, discharge fluctuation) as a function of the discharge voltage and mass flow rate. An electrostatic probe located at a distance of 20 cm of the axis of the plasma plume is used to obtain an information of the divergence of the propulsive jet.

1. Principle of a SPT

A schematic view of a cross section of a SPT is shown on Figure 1. In a SPT, the discharge is sustained in an insulated annular channel made of ceramic. The xenon gas - chosen for its low energy ionization level (12.1 eV) - is injected through a set of holes in an annular anode located in the bottom of the channel. An external cathode supplies an electron flow which is separated in two parts: a first flow enters the channel to ionize the neutral xenon and a second flow neutralizes the electric charge of the plasma plume.

The crossed field ExB in the channel contributes to the movement of the magnetized electrons (the Larmor radius - a few mm - is small compared to the size of the chamber).

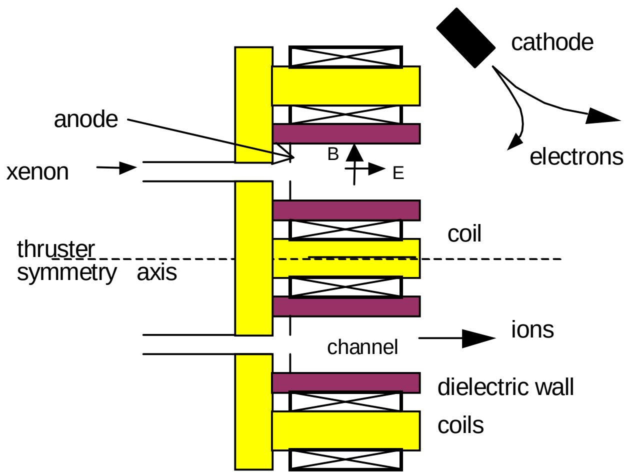

Fig.1 Schematic view of a Stationary Plasma Thruster

Ions of xenon (mainly Xe^+) are created in the channel and they are accelerated by an axial electric field (maximum value around 400 V/cm) appearing to compensate the decrease of the electron mobility. The non magnetized ions gain a large part of the discharge potential due to the separation of the ionization and acceleration zones with an efficiency around 80% [4].

2. Importance of the magnetic field in a SPT

The magnetic field is one of the most important parameters in Hall thrusters. Its 2D topography and the optimization of its value are necessary for a satisfactory functioning. However, one can note that all the couplings between the magnetic field and the properties of the discharge are not yet completely explained. Nevertheless, the magnetic field appears to be active in the following different effects:

- It contributes by its value to generate a plasma where only the electrons are magnetized. The electrons move around the magnetic lines and they have an electron drift velocity in the azimuthal direction (velocity around 10^6m/s).
- The electron mobility is different along and across magnetic lines (more important along B lines).
- This electron normal mobility can be assumed to be dependent on B^{-2} near the anode (neutral-electron collisions are preponderant)
- The usual electron mobility is small near the channel exit where the gas density is very low, due to the ionization process. Wall mobility (by B^{-2}) is suggested in the inner acceleration zone and Bohm effect due to plasma fluctuations (by B^{-1}) is proposed in the plume just after the exhaust [4].
- An optimization of the magnetic field value, all the other operating parameters being fixed, is obtained when the discharge current is minimum. This B value gives the maximum efficiency of the thruster.
- The magnetic map and especially the gradient along the channel axis of the radial component of B influences the oscillations of the plasma discharge. A negative gradient of Br in the channel provokes plasma instabilities.
- The divergence of the plasma plume is imposed by the map of the electric potential, which is close to the magnetic lines if the electron diffusion is small. This divergence induces negative effects: interactions with the solar panels, decrease of the thrust efficiency (thrust efficiency of 80%-90%) and increase of sputtering effect on the channel wall..

In a SPT the magnetic field is obtained until now by a set of magnetizing coils which produce, through a magnetic core, a magnetic field mostly radial in the channel, with a maximum value near the channel exit. For experimental reasons this value is measured without the plasma discharge. Anyway the magnetic field is assumed to be unaffected by the discharge. In the SPT 100 ML we used for our experiments, the magnetic field is produced by 4 external coils and 1 central coil. It must be pointed out that in such types of thruster the size of the internal coil affects the design of the channel.

3. Interest of the use of permanent magnets

The magnetic circuit of a Stationary Plasma Thruster (SPT) is generally defined and manufactured as a function of different criteria such as:

- defined magnetic topography in the annular channel,
- limit for the temperature of the coils during the operating processes,
- minimization of the weight and the size of the thruster,
- accessibility for a set of diagnostics for laboratory models.

The present work concerns the possibility of replacing the magnetizing coils by permanent magnets. Such a solution seems to present numerous advantages, such as a) reducing the electrical power consumed, which results in an increase of the total efficiency, b) reducing the mass and the size of the thruster, c) reducing the temperature, due to the absence of Joule effect, d) increasing the reliability, since the length of the high temperature wire is reduced as well as the complexity of the dc current power supplies, e) finally, reducing the cost of the thruster. These solutions have been covered by a patent.

4. Description of the used magnet devices and preliminary tests

Preliminary tests have been performed by using only the magnetic core of a SPT 100. In our tests, a given coil is replaced by a “magnetizer”, i.e. a circular cylindrical device composed of a magnet and some pieces of soft iron, placed inside a non magnetic metallic tube. The magnetizer takes exactly the room of the corresponding coil.

First, the capability of obtaining the convenient magnetic field profile by using magnetizers instead of coils has been checked for the three following configurations: a) 4 external magnetizers and a central coil, b) 4 external coils and a central magnetizer, c) 5 magnetizers, then no coil at all. In these preliminary tests, we had mostly in mind to reproduce only the Br(z) field profile along the mean channel radius. Since the magnets we used were only SmCo cylinders of a commercially available size, reproducing precisely the whole field configuration given by the coils was then difficult, due to the fixed size of the magnets. Fig. 2 shows, as an example, a comparison between to the 5 coil configuration and the a) configuration. It can be seen that the central curve (5 coils at the nominal 4.5 A dc current value) can be approached by the two curves corresponding to 0 A and 1 A respectively in the central coil. Adjusting the current in the central coil allows the field profile to be close to the convenient value. Same types of curves have been obtained for the b) configurations. In the c) configuration, it is obvious that approaching the right profile can be achieved only by playing with the magnets inside the magnetizers.

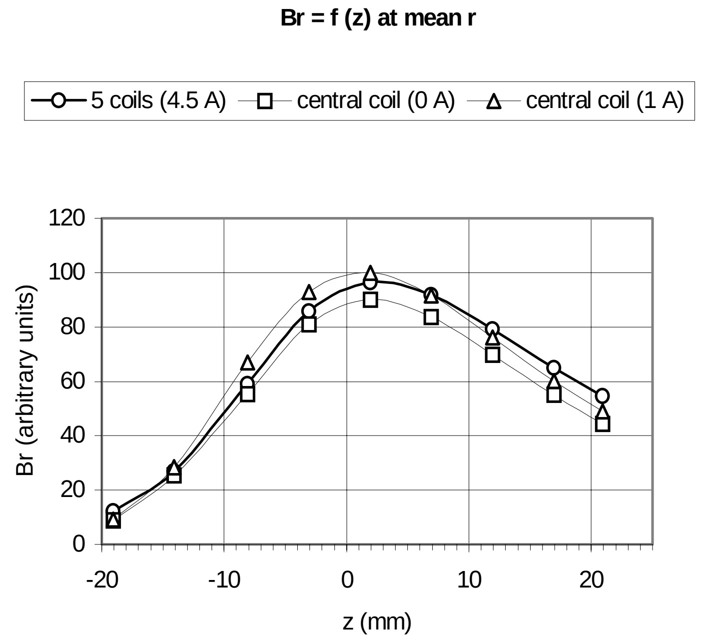

Fig. 2 Comparison between the 5 coil configuration and the a) configuration, for two different dc current values in the central coil. Number of z points has been reduced for clearness.

Second, the thermal behaviour of a magnet sample has been tested. Indeed, the thermal evolution [5] of the sub-elements of a Hall thruster is a critical point during the operation In the SPT 100 ML which is tested, the temperature is only around 490 K in the inner coil and around 470 K in the external coils, measured in the nominal running conditions. This level of temperature results from the energy coming from the plasma (evaluated at 300 W) and from the Joule effect in the coils and from different radiative/conductive heat flux. Consequently, its appears that the thermal behaviour of the magnets should be considered as a critical point.

The remanence Br of a small magnet sample was measured along several temperature cycles from 90 to 470 K by using a Vibrating Sample Magnetometer, equipped with a convenient dewar. The remanence increases by 6 % from RT down to 90 K and decreases by 14 % from RT up to 470 K. It has been verified that for at least 10 temperature cycles such variations are reversible. Since the temperature of a magnetizer should be lower than that of a coil, it was expected that such magnets will be suitable for running the thruster. Experiments have been indeed successful as shown below. In addition, the running temperatures of the magnet have been approximatively measured during the tests by using a thermocouple introduced in the magnetizer close to the magnet: the recorded values are lower compared to the coils.

5. Test with the SPT100-ML in Pivoine facility

The tests of the SPT100-ML equipped with magnetizers have been carried out in the vacuum facility PIVOINE in the Laboratoire d'Aérothermique at Orléans (France).

The picture below shows the thruster – in the 5 magnetizer configuration – fixed on its running bench before to be introduced in the vacuum chamber.

Fig. 3 Picture of the SPT 100 ML in the 5 magnetizer configuration at its place on the test bench. The front side of the magnetic core has been removed for better view.

PIVOINE facilities (70 000 l/s cryogenic pumping speed - 2.5 10^{-5} mbar with a xenon mass flow rate of 5 mg/s) and the SPT100-ML have been previously described in detail in [6]. SPT100-ML operates at the following conditions:

- anode flow: 5 mg/s
- discharge current: 4.6 – 4.9 A
- discharge voltage: 100 – 400 V
- magnetizing dc current in the full coil configuration: 4.5 A

The main results of the tests are reported in Fig.4, which shows the thrust for the three magnetizer configurations, compared to the thrust given by the full coil thruster.

When examining such curves, it must be kept in mind that all the magnetizer configurations were not at all optimized, as above mentioned. The flux lines in the channel are not so orthogonal to the axis as for a 5 coil configuration. This could explain why the performances of our magnetizer configurations are more or less lower than those of the 5 coil configuration. This point is confirmed by the following: it can be seen that the higher thrust values are obtained in the b) configuration, i.e. a central magnetizer and 4 external coils; we know that in our experiments the b) configuration presents the better field profile in the channel.

Conclusion

This paper presents experimental results obtained with a Hall thruster equipped with permanent magnets. It must be pointed out that the aim of this study was mainly to show that a Hall thruster can operate by using permanent magnets instead of coils. In a first step we have verified that a convenient magnetic profile can be obtained, not too far from the profile given by coils, by using only magnets of the commercially available size. Although this profile was not yet optimized, we succeeded in running the thruster and obtaining performances close to those of a full coil thruster. Further experiments will consist in optimizing the magnet configuration to get the optimal performances for the SPT 100 geometry. Another way will be to study the application of magnets to more powerful types of thruster and look at the corresponding possible improvements of the magnetic core.

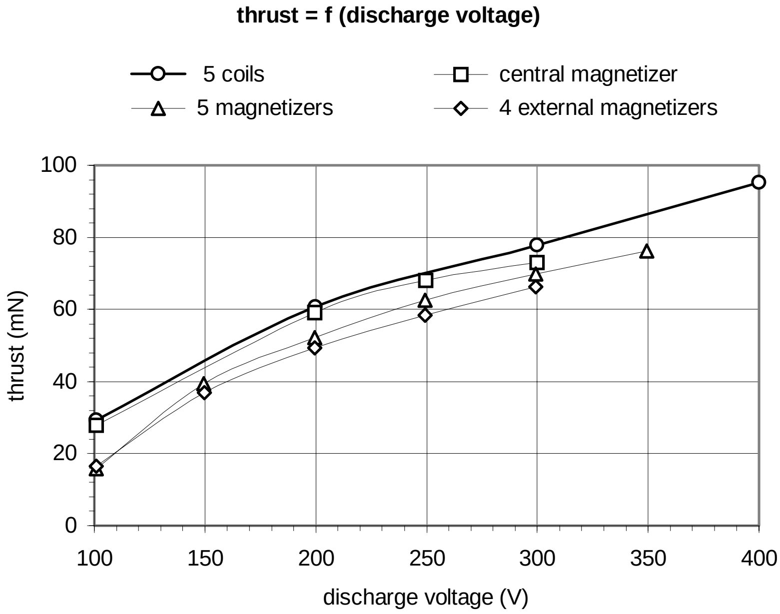

Fig. 4 Thrust for the magnetizer configurations compared to the full coil configuration

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