Preliminary Experimental Results of the PHALL II-C with Improved Magnetic Circuit Design and Hollow Cathode

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Abstract. We are going to present preliminary experimental results for our latest PHALL thruster of the annular type, which has been greatly improved with a new magnetic circuit design that allows operation with the magnetic field perpendicular (normal configuration) or parallel (magnetic shielding) to the thruster walls; where the benefit of this last magnetic field configuration is an improvement of three orders of magnitude on the thruster’s lifetime. For the first time, we will report on PHALL II-C operation up to 620 W with the generation of up to 41.39 mN of force and 2286.22 s of specific impulse, using a hollow cathode. These tests elevate the TRL of our thruster to TRL 4, with more realistic tests planned in our near future. We will also detail current work on the control and dissipation of thermal energy which will allow our thrusters to operate for long periods of time in space.

1. Introduction

Hall thrusters are one of the most successful electric thrusters for space application that has been made until now. The Plasma Physics Laboratory of the University of Brasília (UnB) has been developing a Permanent Magnet Hall Thruster (PHALL) for the Brazilian Space Program since 2004 [1-6], with the support of the UNIESPACO Program from AEB and from other agencies like FAP-DF, CNPq, CAPES, FINEP and FINATEC.

The purpose of our research group is the development, test and application in space missions of plasma thrusters of the Hall type (PHALL) of innovative character using permanent magnets to produce the magnetic field responsible for the formation of the plasma in a more efficient way. Hall thrusters generally use an annular channel with an anode at the bottom and a hollow cathode placed at the exit of the channel that emits electrons. Plasma is formed from the acceleration of these electrons towards the anode and collisions with the propellant gas. There are magnets at the exit of the channel whose magnetic field magnetizes or traps only the electrons in a circular orbit of the ExB type around the channel, generating a closed Hall Effect current, whence the name closed drift thruster. This current generates a virtual cathode cloud that forms an electric field towards the anode and in the opposite direction towards the exit, which accelerates heavy positive ions in the desired direction, thereby generating significant thrust reaction forces.

The PHALL project has developed until now four thruster prototypes. PHALL I (Figure 1.a)) used long ferrite magnets with an average magnetic field inside the 3 cm channel on the order of 260 Gauss. PHALL II-A (Figure 1.b)) used long (35 mm) Neodymium magnets with a magnetic field at the center of the 2 cm channel of around 1100 Gauss which caused magnetization of both ions and electrons as seen by the plasma torus in Figure 1.b).
For this propulsion system to work we have to use conditions where the Larmor radius of the electrons \( r_e \) is substantially smaller than the dimensions of the annular channel \( L \), which itself has to be substantially smaller than the Larmor radius of the ions \( r_i \) in such a way that the ions are not magnetized and can be ejected from the thruster in order to generate a useful propulsive force [7]. These relations are explicit in Equation 1 (where \( v_e \) and \( v_i \) is the electron and ion velocity respectively, \( e \) is the electron elemental charge and \( B \) is the magnetic field magnitude) and Table 1. Since the plasma channel dimensions are generally between 1 to 3 cm length, the proper magnitude of magnetic fields to use with Hall thrusters is between 100 to 300 Gauss.

\[
r_e = \frac{m_e v_e}{eB} < L < r_i = \frac{m_i v_i}{eB}.
\] (1)

### Table 1. Magnetic field intensity and Larmor radius for ions and electrons depending on applied magnetic field.

| Magnetic Field Strength (Gauss) | \( r_i \) (mm) \( (1000 \text{ K}) \) | \( r_e \) (mm) \( (1 \text{ eV}) \) | \( r_e \) (mm) \( (10 \text{ eV}) \) |
|--------------------------------|--------------------------------------|---------------------------------|----------------------------------|
| 1                              | 5500                                 | 40                              | 120                              |
| 100                             | 55                                   | 0.4                             | 1.2                              |
| 1000                            | 5.5                                  | 0.04                            | 0.12                             |

Using these concepts we later improved to PHALL II-B (Figure 2.a)) by decreasing the channel magnetic field strength to around 100 Gauss using short (10x10x10 mm square) magnets together with a properly designed ferromagnetic material, providing in this way only magnetization to electrons (that form the circular plasma current seen in these thrusters) as desired for propulsion purposes [6]. We have also increased the size of the anode to occupy most of the space inside the channel, increasing in this way the plasma uniformity and volume (Figure 2.b)). The dielectric thermal and dielectric protection of the thruster was also changed from a dielectric paint on aluminum substrate (Figure 2.a)) to a single piece of MACOR (Figure 2.b)), improving significantly the thermal resistance of the thruster.

**Figure 1.** a) PHALL I at 50 W and b) PHALL II-A also at 50 W total power.

All these initial thruster versions used a coiled tungsten wire doped with barium as a source of electrons (Figures 1 and 2). The last version, the PHALL II-C used for the first time a hollow cathode as electron source, together with Samarium-Cobalt magnets with a higher working and Curie temperature as needed (Figure 3).
2. PHALL II-C Experimental Results
The first PHALL version demonstrated its purpose in 2004 (Figure 1.a)) by showing how it was possible to achieve good results with this type of thruster with the proper magnetic fields generated by permanent magnets, culminating in the last PHALL II-C thruster developed by our laboratory. We have performed several plasma measurements (including with Langmuir probe and Faraday cup) on our thruster in order to determine the developed plasma potential, plasma density, ion energy among other diagnostics. These results are compressed into useful data in Table 2 for two different total applied powers.

| Total Power (W) | Anode Power (W) | Cathode Power (W) | Force (mN) | Power / Force (W/mN) | Specific Impulse (s) | Electric Efficiency (%) |
|----------------|-----------------|-------------------|------------|----------------------|---------------------|------------------------|
| 350.4 W        | 200.4           | 150               | 24.92      | 14.60                | 1979.88             | 57.19                  |
| 620.6 W        | 470.6           | 150               | 41.39      | 14.99                | 2286.22             | 75.83                  |

These results are extremely relevant and show an important PHALL technology maturation by achieving for the first time our proposed goal of generating a thrust force above 40 mN at 620 W with a very good specific impulse of 2286 s, as desired for the expected application in space missions or in small satellites.

Figure 2. a) PHALL II-B at 50 W and b) PHALL II-B with improved anode.

Figure 3. a) PHALL II-C at 620 W and b) zoom of the cathode.
3. PHALL Temperature Decrease and Control by Proper Heat Dissipation

In order for the PHALL thruster to be able to operate for long periods of time in a space environment, proper care and attention has to be directed towards the heat dissipation on the structure of the thruster due to electron and ion impact mainly on the channel walls and anode, which will be thermally propagated also to the magnets which must remain at a working temperature below 350 °C in order not to start losing their magnetization, which is vital for the thruster to work. The steady-state power balance equation for the total power dissipated in the thruster is given by [7]:

\[ P_{\text{discharge}} = P_{\text{beam}} + P_{\text{radiation}} + P_{\text{wall}} + P_{\text{ionization}} + P_{\text{anode}} \]  

(2)

where \( P_{\text{discharge}} \) is the total discharge power applied, \( P_{\text{beam}} \) is the kinetic beam energy, \( P_{\text{radiation}} \) is the radiated heat, \( P_{\text{wall}} \) is the heat dissipated in the channel walls, \( P_{\text{ionization}} \) is the power required to ionize the propellant, and \( P_{\text{anode}} \) is the power to the anode due to electron collection and collision. More specifically [7]:

\[ P_{\text{beam}} = V_{\text{beam}} I_{\text{beam}}, \]  

(3)

Where \( V_{\text{beam}} \) is the plasma potential in the beam and \( I_{\text{beam}} \) is the current in the plasma beam.

\[ P_{\text{radiation}} = n_0 n_e < \sigma_e v_e > V, \]  

(4)

Where \( n_0 \) is the ion density at the sheath edge, \( n_e \) is the electron density, \( \sigma_e \) is the excitation reaction rate coefficient, \( v_e \) is the electron velocity and \( V \) is the volume of the high temperature plasma region in the channel.

\[ P_{\text{ionization}} = (I_b + I_{\text{iw}}) U^+, \]  

(5)

Where \( I_b \) is the beam current, \( I_{\text{iw}} \) is the ion current to the wall and \( U^+ \) is the ionization potential of the propellant gas.

\[ P_{\text{anode}} = 2T_e v_I d \approx 2T_e v_d. \]  

(6)

Where \( 2T_e v \) is the energy deposited from the plasma to the anode by the electrons, \( I_a \) is the electron current to the anode and \( I_d \) is the discharge current.

\[ P_{\text{wall}} = n_e e A_w \left[ \frac{kT_e e}{\epsilon} \right]^{3/2} \left( \frac{2e}{\pi m} \right)^{1/2} e^{e\Phi_s/M} \left( e - \Phi_s \right) \]  

(7)

Where \( e \) is the electric charge of an electron, \( A_w \) is the area of the wall, \( k \) is the Boltzmann constant, \( m \) is the mass of propellant mass in kg, \( M \) is the ion mass in atomic mass units, \( \Phi_s \) is the sheath potential and \( \epsilon \) is the ion energy.

If we consider a total discharge power of 390 W, the total power will be dissipated has follows:

1) Beam Power (Used for Propulsion): 245 W (62.82 % Efficiency)
2) Total Dissipated Power: 145 W
   A) Power used in gas Ionization: 13 W
   B) Heat Power Dissipated in Thruster: 132 W (Heats the Thruster)
      - Wall Heating by electron collision: 115 W
      - Wall Heating by ion collision: 4 W
      - Anode Heating by electron collision: 10.5 W
      - Plasma Radiative Power Loss: 2.5 W
Using these parameters on a Hall thruster with length of 5.4 cm and external diameter 6.4 cm (Figure 4), we obtain a maximum temperature of 369 ºC on the thruster and 299 ºC in the area of the magnets. The working temperature of the Samarium Cobalt magnets is 250 ºC for SmCo5 and 350 ºC for Sm2Co17, where both have a Curie temperature of around 800 ºC. The working temperature is the temperature above which the magnets start to become increasingly depolarized with temperature but can return to normal magnetization if the maximum temperature is below the Curie temperature, above which the magnets become irreversibly depolarized. In the case of the present simulation results we could use Sm2Co17 magnets but not SmCo5 magnets, due to the smaller working temperature of 250 ºC.

Figure 4. a) Hall thruster with length of 5.4 cm and external diameter 6.4 cm subjected to a total of 425 W and b) expanded view of the thruster.
If we add a disc dissipater of thickness 2 mm and 10 cm diameter (Figure 5.a)) we manage to dissipate enough thermal energy in vacuum by radiation alone that it is capable to reduce the maximum temperature in the thruster to 346 °C in general and 266 °C in the magnets area. However, if we use two similar dissipater discs separated by 2.5 cm, then the total maximum temperature reduces to 337 °C and in the magnets area we obtain a temperature of 249 °C (Figure 5.b)).

This last temperature is perfectly safe to use both types of Samarium Cobalt magnets, and these simulations have allowed us to design a heat resilient space capable engineering model for a Hall thruster with a long lifetime.

Figure 5. a) Hall thruster with one 10 cm diameter / 2 mm thickness dissipater and b) same Hall thruster with two similar disc dissipaters separated by 2.5 cm.
4. Conclusions
After these encouraging results, both in the force generating magnitude and in the heat resilience capability, we intend to further develop the PHALL thruster to a technology maturation level compatible with the necessary levels for space qualification. For that, we will have to develop more advanced and compact thrusters in cooperation with the industry so that they can be perfected and used in future space vehicles of the Brazilian Space Program.

5. References
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Acknowledgments
The authors acknowledge support from the UNIESPAÇO program of the Brazilian Space Agency (AEB), FAPDF, CNPq, IF/UnB, DPP/UnB and CAPES. A.A.M. gratefully acknowledges the Brazilian Space Agency (AEB), the National Institute for Space Research (INPE) and the National Council of Technological and Scientific Development (CNPq) for the attribution of a Post-Doc Scholarship for the development of electric propulsion systems of the Hall plasma type to use in satellites.