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Numerical Simulations of a Plasma Thruster for CubeSats

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Abstract. *Plasma propulsion, or electric propulsion, arises from the need to explore deep space more economically and efficiently. The Cylindrical Hall Thruster (CHT) demonstrates enhanced propellant utilization and performance efficiencies within reduced dimensions and lower power thresholds when compared to conventional plasma propulsion apparatuses. The compact size and operation at lower power levels make it an interesting option to provide propulsion for CubeSats and small satellites. The CHT comprises a channel with an annular anode through which neutral gas is injected, subsequently ionized by magnetized electrons injected from an external hollow cathode. The resulting plasma ions are ejected from the device, giving thrust. This work aims to understand and study the plasma in the discharge channel of a CHT through numerical simulations. The code describes the plasma with a hybrid model in which the electrons are treated as a fluid and the ions and neutral atoms as pseudo particles. The simulations were conducted for two different potential values at the anode, namely, 150 V and 300 V, representing different modes of operation. The results obtained with this simplified model allow obtain an optimal configuration for a future prototype to be implemented at the Plasma Physics Laboratory at the University of Brasilia.*

Keywords: *CubeSats, Electric propulsion, Plasma, Ions*

1. INTRODUCTION

The search for new technologies aimed at efficiently exploring deep space has been increasingly studied. The aerospace industry has, for the most part, used chemical propulsion, which provides from a high amount of energy and a thrust sufficiently capable of overcoming the drag and weight forces, thus allowing space equipment to reach Earth orbit and even other planets (Goebel, 2008). One of the limitations of this type of propulsion has is that in order to launch a certain device, it is necessary to have a high cost of fuel and oxidizer, in addition to needing a significant storage space. These factors not only drive up expenses but also hinder the further advancement of space programs, impeding the realization of ambitious exploration objectives (Goebel, 2008).

Electric propulsion emerged as a promising alternative in the mid-1950s (Goebel, 2008). Although the concept traces back to as early as 1906 with Robert Goddard, significant research programs focused on electric propulsion began in the 1960s with the National Aeronautics and Space Administration (NASA) (Choueiri, 2003). The experimental launch of an ion thruster into Earth orbit marked a significant milestone in the early sixties, achieved through collaboration between the United States and Russia. This pioneering device utilized cesium and mercury as propellants and underwent testing until the mid-1980s (Goebel, 2008).

Hall Thrusters (HTs) are electric propulsion devices, depending on the $\mathbf{E} \times \mathbf{B}$ effect, where $\mathbf{E}$ represents the electric field and $\mathbf{B}$ the magnetic field, resulting in a current known as the Hall current. Hall thrusters are capable of accelerating ions to high speeds (Goebel, 2008).

The Cylindrical Hall Thruster (CHT) represents an alternative design that comprises a cylindrical region and a short annular channel. The CHT demonstrates improved propellant utilization and performance when compared to HTs. The magnetic field can be adjusted using electromagnet coils or permanent magnets. This device has applicability for micro and nano-satellites because this device can offer a higher ionization efficiency and silent operation, offering a better volume-to-surface ratio compared to compact HTs, potentially mitigating wall erosion (Miranda *et al.*, 2017).

2. OBJECTIVES

The operation of CHT occurs by first filling with neutral gas a cylindrical chamber, with a small ring-shaped annular region near surface of the anode. The non-magnetized ions are accelerated in the cylindrical channel by a potent electric field generated by the anode. Previous studies on the structure of this geometry assert that CHTs reduce the interaction between the plasma and the dielectric wall channel, electron transport, heat, and wall erosion, preventing power reduction (Seo *et al.*, 2013).

Our simulations start with the gas injection of xenon gas (Xe) into the cylindrical chamber, resulting in a distribution density inside the channel. The CHT boasts a well-suited design for CubeSats, as they require operation at low power levels. In this paper we examine two different values of the electric potential, namely, 150V and 300V. For this simulation, we used the Hall Ion Sources Simulation Software - HALLIS which is a hybrid code, developed at the LAPLACE laboratory in Toulouse/France (Laplace, 2018).

We also employ the Element Method Magnetics software (FEMM) to generate the magnetic field needed as an input for the HALLIS software. The simulation domain defined in the FEMM software is shown in Fig. 1.

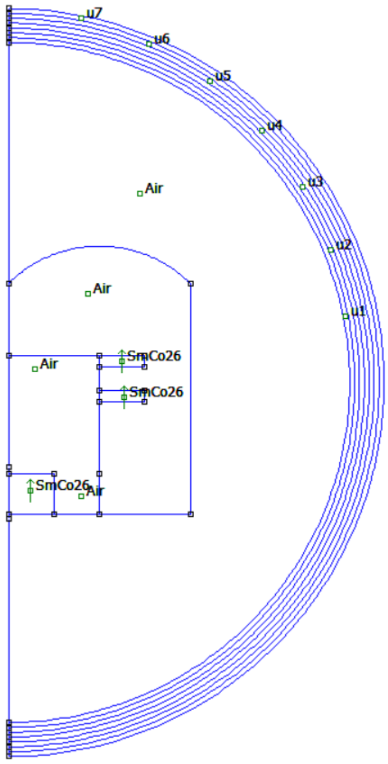

Figure 1. Simulation domain defined in the FEMM software, showing the position of the permanent magnets, marked as "SmCo36"

3. MATERIALS

The HALLIS software includes two autonomous modules for performing 1D e and 2D simulations, using a hybrid model for the plasma. In this model, electrons are treated as a fluid and neutral atoms are represented by pseudo-particles (Hagelaar *et al.*, 2002). The trajectories of positive ions and neutral atoms are computed through the integration of the equations of motion, considering collisions and interactions with walls (specular or diffusive). The transport of electrons across the magnetic barrier is described by empirical coefficients for the effective mobility and energy losses.

For each value of the anode potential, simulation results were recorded at three time, namely, $t_1 = 450\ ms$, $t_2 = 500\ ms$, $t_3 = 550\ ms$. After obtaining the analyzed data for each moment, an average was calculated to better approximate the results.

3.1 Geometry

Fig. 2 shows the results from a simulation using the FEMM software. First, the software computes the position of the finite elements needed for the calculation of the magnetic field due to the permanent magnets (fig. 2(a)). Figure 2(b) shows the results of the simulation, showing the locations of the magnetic field lines, which extend over the simulation domain.

The simulation parameters are given in table 1. In the HALLIS software, The azimuthal direction is not described and it is assumed that the plasma is axisymmetric and homogeneous in the azimuthal direction. The parameters take into account the geometry of the CHT, which removes the central part of a HT (Levchenko *et al.*, 2018).

We will focus our analysis on two quantities, namely, plasma density and electric potential. To obtain these results we used Xe with a gas flow rate $\dot{m} = 5.0\ mg/$s and Temperature $T_{gas} = 500K$.

In this simulation, the potential difference between the anode and the cathode must be provided. We use two values, namely, ΔV = 150 V and ΔV = 300 V. The magnetic field computed using the FEMM software and obtained as an input by the HALLIS is depicted in Fig. 3. The modulus of the magnetic field is represented in a color scale, and displays

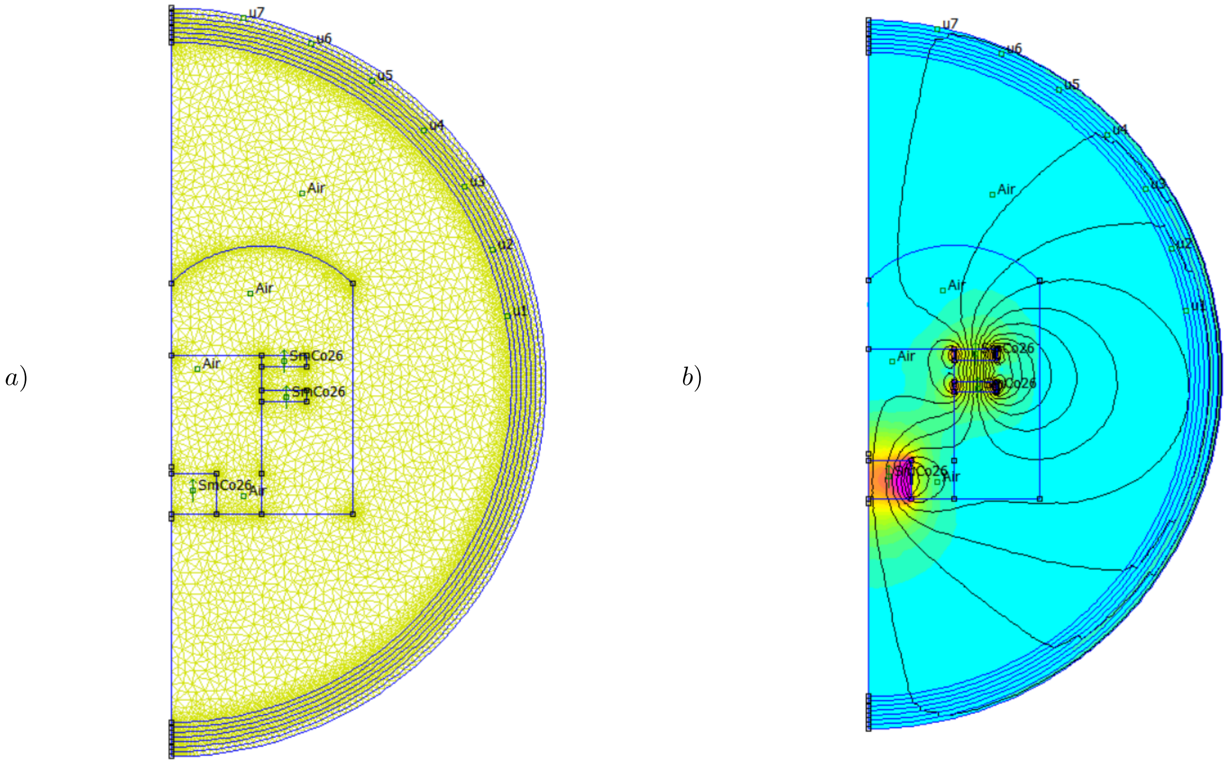

Figure 2. (a) Mesh used by FEMM with 11814 nodes (b) FEMM magnetic density flux lines

Table 1. Numerical values of the simulation parameters with the HALLIS software

Parameters	**Values (cm)**
Axial domain	5.00
Radial domain	2.50
Channel Lenght	2.50
Inner Radius	0.00
Outer Radius	2.00
Cathode position	(2.50, 1.00)
Anode	(0.00 , 1.50)
Gas inlet	(1.25, 1.75)
FEMM offset	1.20

variations in the axial (X) and radial (Y) directions of the channel. Note that the field lines concentrate closer to the region of the higher magnetic field.

4. RESULTS

4.1 Potential and Plasma density

Fig. 4 shows the results for an anode potential of $\Delta V = 150V$, with a xenon gas mass flow rate $\dot{m} = 5.0\ mg/$s and temperature $T_{gas} = 500K$. The electrostatic potential displays a maximum value near the anode, and decreases rapidly in the axial direction, towards the channel exit region. The plasma density displays large values near the $Y = 0$ central axis of the channel, however, a localized maximum can be also distinguished towards the anode. This isolated maximum is due to a population of electrons, trapped by the magnetic field, that collide with the neutral gas.

Next, we change the anode potential to a value of 300V, keeping the gas mass flow rate and temperature the same. Fig. 5(a) shows that the electrostatic potential displays a similar pattern, however, a narrow strip of low values extending from the anode to the channel exit can be observed. The plasma density also shows that a narrow strip connects the anode region with the central region at the channel exit with the highest values. Evidently, the higher potential value at the anode has an impact on the plasma particles inside the thruster channel.

The performance of plasma thrusters can be evaluated by operational parameters such as thrust, specific impulse (I_{sp}),

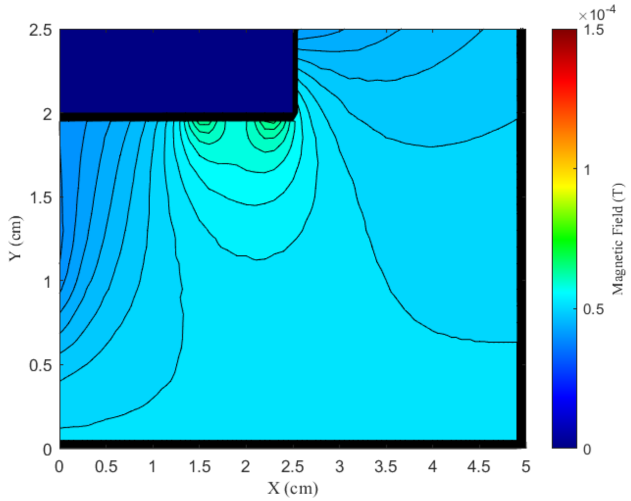

Figure 3. The magnetic field lines, and the modulus of the magnetic field in color scale

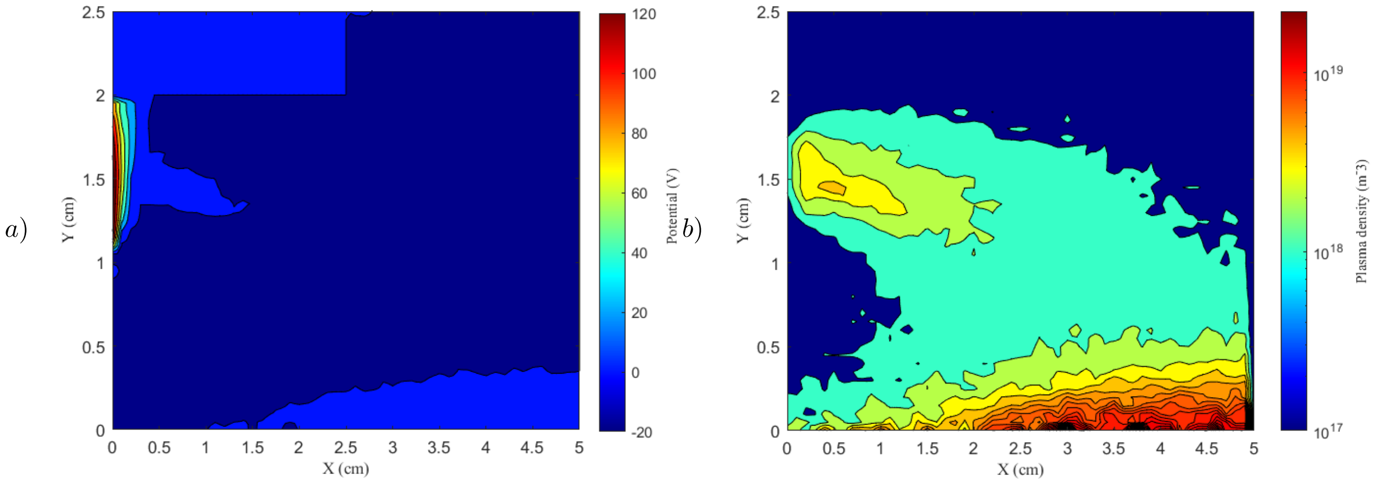

Figure 4. Contour plots of (a) the electrostatic potential, and (b) plasma density, for $\Delta V = 150V$

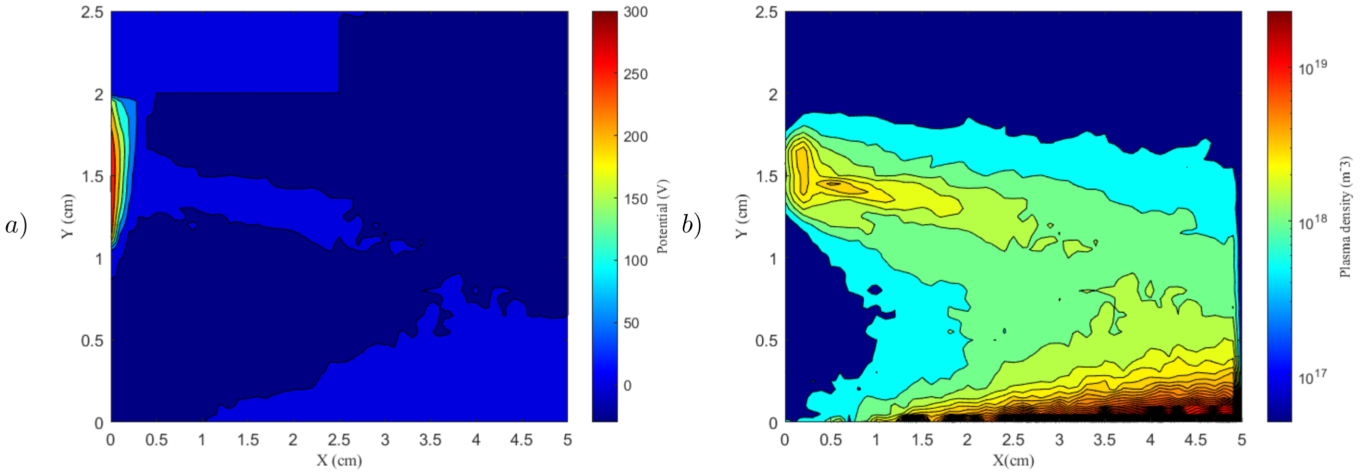

Figure 5. Contour plots of (a) the electrostatic potential, and (b) plasma density, for $\Delta V = 300V$

and efficiency (η). The thrust in this type of propulsion systems has units of millinewtons, and can be written by

$$T = -v_{ex}\dot{m}_p \tag{1}$$

where m_p is the mass of propellant, $\dot{m}_p$ represents the mass variation in time, and v_{ex} is the exhaust velocity.

Table 2. Performance parameteres for 150 V

Performance at $\Delta V = 150V$	
Parameters	**CHT Values**
Thrust (mN)	21.250
Specific Impulse (s)	433.23
Power (W)	254.768
Efficiency (%)	23.8

Table 3. Performance parameteres for 300 V

Performance at $\Delta V = 300V$	
Parameters	**CHT Values**
Thrust (mN)	46.012
Specific Impulse (s)	938.07
Power (W)	715.616
Efficiency (%)	32.7

The specific impulse is defined as Eq. 2, which represents the xenon mass flow rate and is provided in the Isp field. (Boeuf, 2017).

The specific impulse is defined by

$$Isp = \frac{T}{\dot{m}g} \tag{2}$$

where $\dot{m}$ is the xenon mass flow rate. Tables 2 and 3 shows the values of these parameters for $\Delta V = 150$ V, and $\Delta V = 300$ V.

5. CONCLUSIONS

The Cylindrical Hall Thruster is an electric propulsion device for CubeSats, when compared to traditional Hall Thrusters, due to its smaller dimensions, it facilitates operation at low power levels. Its geometry reduces susceptibility to channel wall erosion and makes it particularly suitable for low-power operations (<200 W) (Garrigues *et al.*, 2008). In this work we performed numerical simulation for two different values of the electrostatic potential at the anode, namely, ΔV = 150 V and ΔV = 300 V.

The potential drop is primarily concentrated in the cylindrical section of the channel and into the plume. Two peaks in plasma density were observed: one in the annular region and the other at the axis further to the exit thruster $(x > 2.5cm)$, which is attributed to the converging ion flux.

Future work involves conducting other simulations using a high-performance computer from the Plasma Physics Laboratory at the University of Brasilia to obtain more accurate results. These results will be valuable for designing alternative prototypes of CHTs for application in CubeSats.

6. ACKNOWLEDGMENTS

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