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Comparative study of propellant injection modes in a low power helicon thruster

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Abstract

This paper investigates the performance of a low-power ambipolar thruster through the analysis of the molecular flux density resulting from two distinct propellant injection modes, namely, normal and vortex. Numerical simulation reveal that the vortex mode significantly enhances gas density within the thruster's discharge chamber, achieving a 43% increase compared to the normal mode. This improvement is attributed to the radial injection flow and increased gas residence time. The findings highlight the importance of injection configurations in optimizing thruster performance, contributing to advancements in propulsion technology for CubeSats and other miniaturized satellites.
Keywords: cubesats, ambipolar thruster, molecular flux density, electric propulsion

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1 Introduction

In recent years, the use of miniaturized satellites, particularly CubeSats, has grown considerably. This technology holds the potential to revolutionize the space industry by enabling individual countries, regional governments, and small companies to establish their own space missions [1].

The economic advantages of small satellites drive their growing adoption, with the development of propulsion systems being crucial for enhancing CubeSat capabilities. Complex missions demand precise orbit control and maintenance, necessitating specialized propulsion systems. Additionally, concerns over space debris have led to stringent regulations that emphasize the necessity for efficient propulsion systems[1, 2].

Electric propulsion refers to propulsion devices that employ electricity to accelerate a propellant, and it was first elucidated by Robert Goddard in 1906 and later described by Tsiolkovskiy in 1911 [3]. After that, its application was developed by Hermann Oberth in 1929 and by Sheperd and Cleaver in 1949. Since the 60's the United States and Soviet Union have made important contributions and investments in space applications for electric propulsion. Since 2004 the Plasma Physics Laboratory of University of Brasilia (LFP-UnB) is developing electric propulsion devices, including a Hall-type thruster with permanent magnets, reducing the power required for operation [4].

Integrating propulsion into CubeSats presents significant challenges due to the intricate design of space thrusters and the stringent requirements for mass, volume, power, and cost. For example, Hall thrusters can achieve higher thrust levels compared to ion thrusters, and are simpler to construct, however, their scalability to smaller dimensions compatible for micro and nano-satellites present several challenges. For example, since the surface-to volume ratio in the annular channel increases, the collisions between particles and walls increase as well, leading to heating and higher erosion rates. Moreover, the reduced thruster dimensions makes the magnetic circuit difficult to maintain. The scaling down of HTs to various power levels has been the subject of several studies [5, 6].

The cylindrical Hall thruster is an alternative concept first developed at the Princeton Plasma Physics Laboratory [7]. It consists of a cylindrical region and a short annular channel with variable depth, and presents an increased volume-to-surface ratio in comparison to compact HTs, potentially reducing wall erosion. A low-power cylindrical Hall thruster exhibited enhanced performance when subjected to a propellant inlet vortex within the discharge chamber [8]. This mode of diffuse gas injection into the propellant is achieved through the angle of the propellant supply holes, allowing for a radial injection flow that increases the residence time of the gas in the chamber, subsequently raising its density.

The aim of this work is to analyze this phenomenon through numerical simulation of the molecular flux density of neutral gas in a low-power ambipolar thruster. Two propellant injection modes are considered: the normal mode, in which the propellant is injected longitudinally in the chamber, and the vortex mode, in which the injection occurs with the angulation of the input channels to form a vortex.

This article presents a detailed model of the proposed ambipolar thruster and the methodology adopted for the numerical simulation. This paper is organized as follows. The device is described in detail in section 2. The numerical methods and numerical model are presented in section 3. The results are discussed in Section 4, and the conclusions are presented in Section 5.

2 Low power ambipolar thruster

Electric propulsion devices such as the ion thruster and the Hall thruster have achieved a high technological maturity to be employed in satellites and spacecrafts, however, their operational lifetime is limited due to several factors such as erosion of channel walls and electrodes, and loss of plasma to the internal walls. The helicon plasma thruster (HPT) is an electric propulsion device that operates without electrodes, providing durability and reliability. It uses electromagnetic radiofrequency (RF) systems to generate and accelerate the plasma, generating thrust [9]. A low-power version of the HPT, also known as the ambipolar thruster, was developed as a consequence of the miniaturization trend currently observed in the aerospace industry [10, 9].

The main components of the device are displayed in Fig. 1, and its operation can be described as follows. Neutral gas is injected into the discharge chamber via distributor holes, which are responsible for the homogeneous distribution of the gas inside the chamber. A radiofrequency antenna surrounds the discharge chamber, and is responsible for ionization. The resulting plasma is radially confined by magnetic fields, provided by two rings of permanent magnets. The use of permanent magnets can help reduce the power requirements of the device. The magnetic field is directed toward the axial direction at the center of the rings. The strenght of the magnetic field due to the ring that is close to the physical nozzle is weaker, resulting in a magnetic nozzle configuration that directs the plasma outside the discharge chamber. Since the mass of the electrons is smaller than the mass of the ions, the electrons are ejected first, creating an electric field that accelerates ions.

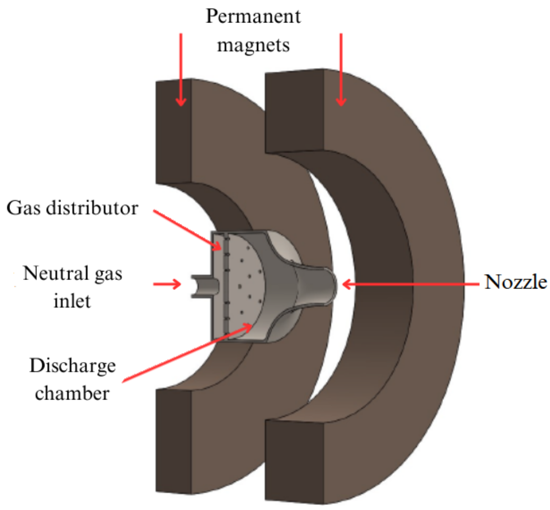

Figure 1: Schematic diagram of the low-power helicon thruster, showing its main components, namely, the permanent magnets, the discharge chamber, physical nozzle, the neutral gas inlet, and the gas distributor plate with the injection holes. The helicon antenna, described in the text, is not shown here.

3 Methodology

We employ the molecular flow model of the COMSOL Multiphysics software [11] to perform numerical simulations of the neutral gas density inside the discharge chamber. We compute two different configurations for the distributor holes, namely, the "normal mode" in which the holes are aligned with the normal of the gas injection plate, and the "vortex" mode, in which the holes describe an angle with respect to the normal of the injection plate, resulting in a circulation vortex inside the chamber.

The first configuration, designated the "normal mode," involves the direct injection of propellant perpendicular to the axial axis. In the second configuration, designated the "vortex mode", the propellant supply channels are angled in relation to the walls of the injector plate, generating an entry vortex. In this section we describe the molecular flow model employed in this paper, and the normal and vortex modes.

COMSOL Multiphysics

The COMSOL Multiphysics software is a finite element simulation software widely utilized across various physical and engineering domains, particularly in scenarios involving coupled and multiphysics phenomena. The molecular flow module stands out for its capability to simulate free molecular flows within intricate geometries.

This module computes crucial parameters such as molecular flow, pressure, and density not only at the surface of the model but also at any specified point within the flow domain. The core methodology employed is the angular coefficient method of interactions, a specialized variant of the radiation method tailored specifically for vacuum applications. This approach involves aggregating the incoming molecular flux to a surface element with the outflow from all other visible areas.

For internal density calculations within the domain, the Molecular Flow module leverages Numerical Density Reconstruction. This technique derives the numerical density n at a surface which is given by

$$n = J\sqrt{\frac{\pi m}{2k_B T}} \qquad (1)$$

where J is the outgoing flux, m is the molecular mass, k_B is Boltzmann's constant, and T is the temperature. In this simulation, the initial conditions were set as follows: a mass flow rate of $12sccm$ of argon (with a molecular weight of $0.4\ kg/mol$), a surface temperature of $293.15\ K$, and a pressure of $0.00133\ Pa$ (approximately $10^{-5}Torr$).

We have verified the applicability of the molecular flow model by computing the Knudsen number K_n, which characterizes the degree of gas rarefaction, and is defined as the ratio of the equivalent molecular free path to a representative physical length scale

$$K_n = \frac{l}{a},$$

where l is the equivalent molecular free path, and a is the representative physical length scale. The equivalent molecular free path is given by

$$l = \frac{\mu \nu_m}{P},$$

where ν_m is the most probable molecular velocity, which can be obtained as follows

$$\nu_m = \sqrt{\frac{2K_B T}{m}},$$

P represents the gas pressure, and μ is the gaseous viscosity. The Knudsen number K_n within the simulation domain obtained is larger than 1, therefore, intermolecular collisions can be neglected, and the molecular flow model is valid.

Normal Mode

The configuration in question is illustrated in Figure 2. In this configuration, the propellant enters the system through a main channel, where it meets a pre-mixing chamber and finally passes through the injector plate to the discharge chamber.

The injector plate will serve as the focus of our analysis. It is $1mm$ thick and comprises 25 cylindrical-shaped input holes with a radius of $0.25mm$. However, for the numerical simulation, the study is based on the internal gas flow. Therefore, it was necessary to model the gas path inside the propellant, as illustrated in Figure 3. In this model, the cylindrical inlet channels gave way to two-dimensional circular surfaces.

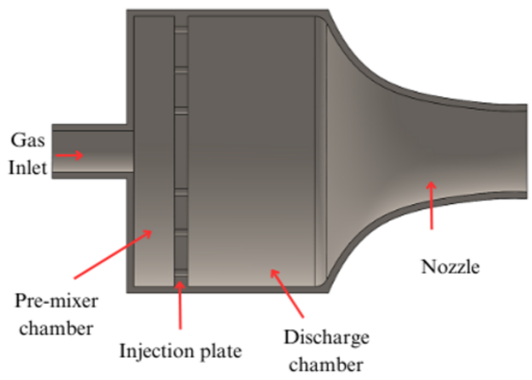

Figure 2: Site view of the low-power helicon thruster showing its main components. The version shown here corresponds to the "normal mode" prototype.

Vortex Mode

In vortex mode, the neutral gas follows the same path described in normal mode, but its injection into the chamber occurs radially, resulting in the formation of a vortex throughout the thruster. This effect provides an increase in the residence time of the gas as well as its density, which in turn favors its propulsive characteristics [8].

This phenomenon is a consequence of the angle applied to the holes in the plate, which describe an angle of $30ř$ with the wall and its associated with the direction of rotation of the holes, as illustrated in Figure 3 (b). This figure represents the flow inside the discharge chamber for purposes of simulation. Consequently, the injection channels are reduced to ellipses with a larger radius of $0.5mm$ and a smaller radius of $0.25mm$.

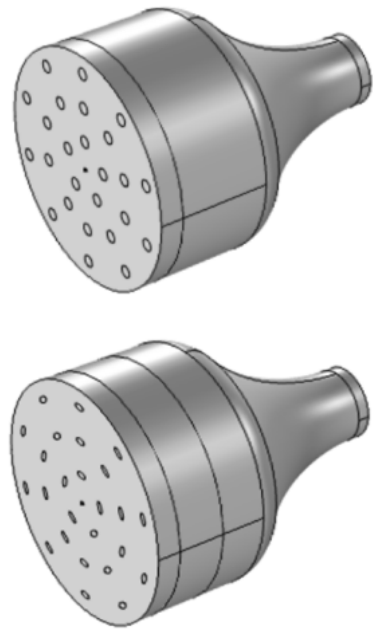

Figure 3: Perspective view of the simulation domain, showing the gas distributor plate in the normal mode (top panel), and the vortex mode (bottom panel).

4 Results

Figure 4(a) shows a cross-section of the resulting neutral gas density for the "normal" mode, whereas Fig. 4(b) shows the neutral density for the "vortex" mode. The cross section is defined as a surface at an axial distance of 1 mm from the injection plate. The injection holes are represented by continuous thin lines, superposed to each figure as a reference. This figure shows that the neutral density increases around the injection holes as expected, and is highest in a region surrounding the central area of the discharge chamber. Note that the color scales in Figs. 4(a) and 4(b) are different. For the normal mode, the maximum value of the neutral density is 1.51×10^{21} m^{-3}, whereas the vortex mode has a maximum value of 2×10^{21} m^{-3}. This indicates that the vortex mode results in an increase of the neutral gas density, close to the injection plate.

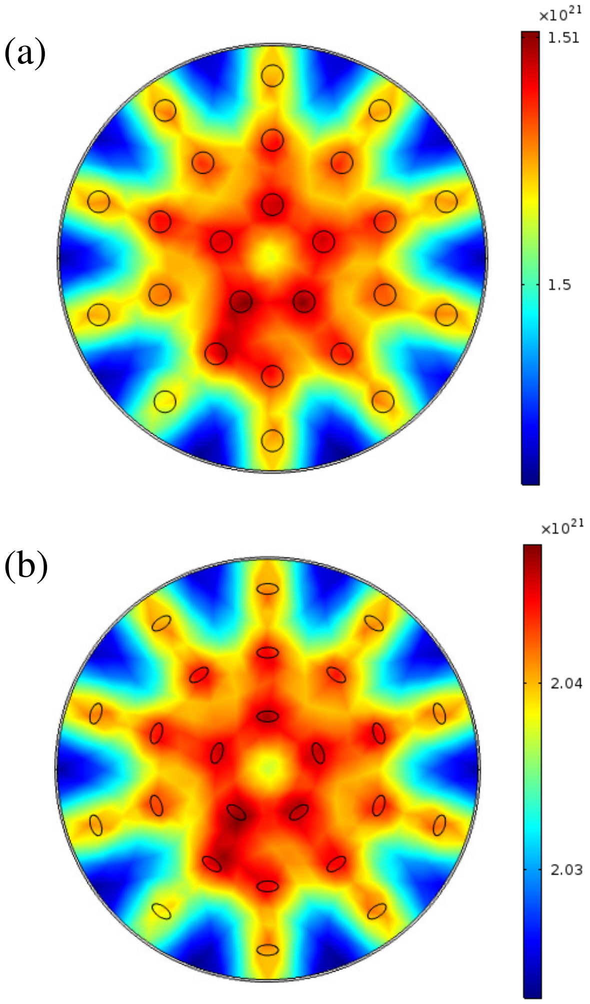

Figure 4: Density distribution of neutral gas in a cross-section plane for (a) the normal mode, and (b) the vortex mode. Thin lines indicate the contour of the distributor holes. Color scales are indicated for each panel.

Figure 5 shows the neutral gas density as a function of the axial distance from the injection plate, obtained at the center of the discharge chamber. The normal mode is shown in blue, while the vortex mode is shown in red. Both curves display similar shapes, with a maximum value near the injection plate, and decreasing values as the distance increases. The density decreases at a faster rate at a distance around 15 mm, which is close to the physical nozzle near the exit region. From this figure it is clear that the neutral gas density of the vortex mode is higher than the normal mode for all values of the axial distance, demonstrating that the vortex mode leads to an increase of the gas density inside the discharge chamber. Close to the injection plate, the vortex mode results in a 43 % increase with respect to the normal mode.

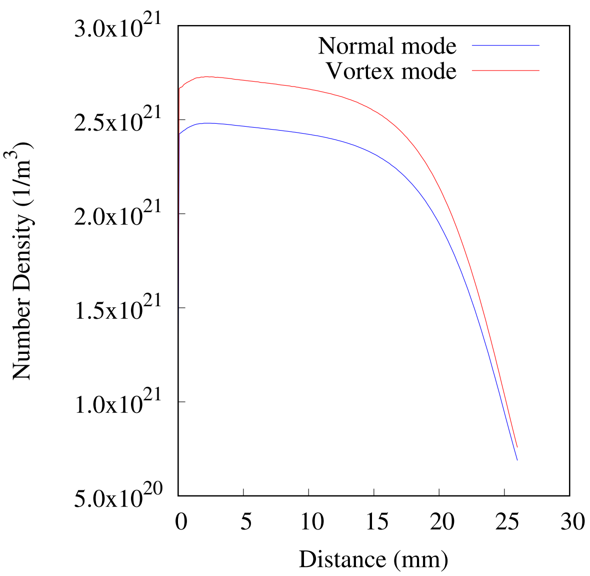

Figure 5: The neutral gas density distribution as a function of the distance (in mm) from the injection plate, computed at the center of the discharge chamber, for the normal mode (blue line) and vortex mode (red line).

5 Conclusion

In this study, we examined the behavior of neutral gas injection in a low-power ambipolar thruster under two distinct propellant injection modes, namely, the normal mode and the vortex mode. The numerical simulations performed using the COMSOL Multiphysics software have yielded results that highlight the impact of injection configurations on the gas density distribution and molecular flux density within the thruster.

The findings indicate that the vortex mode significantly enhances the gas density within the discharge chamber, achieving a 43% increase compared to the normal mode. This enhancement can be attributed to the increased residence time of the gas due to the radial injection flow by the angled propellant supply holes. This study highlights the significance of neutral gas injection configuration in optimizing the performance of ambipolar thrusters and potentially other analogous propulsion systems.

The results obtained provide a solid foundation for future experimental validations and further exploration of neutral gas injection techniques to improve the efficiency and performance of low-power thrusters for CubeSats and other miniaturized satellites. The findings of this study contribute to the advancement of propulsion technology, paving the way for more efficient and sustainable space missions.

The neutral gas density profiles obtained in this paper can be employed in numerical simulations of plasma particles in electric propulsion devices. The particle-in-cell (PIC) approach is a common technique to perform numerical simulations of astrophysical, space and laboratory plasmas [12, 13]. In this approach plasma particles are represented as computer particles with positions, velocities, and electromagnetic fields self-consistently solved from the equations of motion and Maxwell's equations. The Plasma Physics Laboratory at the University of Brasilia have implemented PIC models of propulsion devices, for example, Miranda et al. [14] applied the PIC approach to a model of a cylindrical Hall thruster, and described a number of techniques that can help reduce the execution time of the numerical simulations. The specific impulse and thrust computed from their simulations are in agreement with laboratory experiments. Braga and Miranda [15]compared the performance of two types of Hall thrusters, namely, the SPT-100 and the PHall-IIc, the latter being developed by the Plasma Physics Laboratory at the University of Brasilia. This comparison was carried out by performing PIC simulations. Their results indicate that the thrust and the specific impulse of the PHall-IIc attain lower values than the SPT-100, which is expected since the PHall-IIc operates at a lower power in comparison with the SPT-100. Miranda et al. [16] described a numerical model of a helicon plasma thruster device currently under development at the University of Brasilia. The two-dimensional model is obtained by representing the device using a cylindrical geometry, and neglecting variations in the azimuthal direction. The computational code solves the electrostatic equations and the equations of motion of charged particles self-consistently using the PIC approach. Their model predicts the emergence of a structure similar to a current-free double-layer in the plasma, which has been detected in similar experiments. Most of the works cited above employ simplified models for the spatial distribution of the neutral gas, which is an important input that can influence the density of the plasma from the numerical results. The neutral gas distribution obtained using the molecular flow model presented in this paper will allow for more realistic numerical simulations of the plasma particles and accurate results, and will be used in future works.

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