Radio Frequency Excited Plasma Discharge Simulation for Potential Helicon Plasma Thruster

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Abstract. The development of advanced propulsion is the key element in the implementation of a robust space exploration program. Advance thruster concepts such as the development of electrodeless Plasma thrusters with high-density helicon plasma sources expected to mitigate the existing problems of the finite lifetimes inherent in electric propulsion. Electrodeless plasma thrusters are potentially more durable than conventional thrusters that use electrodes such as a gridded ion, Hall thrusters, arcjets, and resistojets. The goal of the research is to simulate a compact high-power-density helicon plasma source operating, which is under examination for a potential electric propulsion application. Plasma modeling is performed in COMSOL Multiphysics plasma module. A Nagoya type III antenna is placed on the surround of a dielectric tube and electrically excited at 13.56 MHz. Plasma is formed in the ionization chamber, which contains argon gas at low pressure. The plasma is sustained utilizing electromagnetic induction.

1. Introduction

Electric propulsion is capable of achieving high specific impulse, and the ability to control thrust levels makes it suitable substitute to the conventional chemical thruster for in-space propulsion application. The recent improvement will enable the electric thrusters to be used as a primary propulsion systems for future spacecraft. Variable specific impulse thruster with multiple in-space refuelling capabilities will permit successful asteroid redirect mission [1].

Electric propulsion applies electrical energy to the propellant from an external power source. Electric thrusters divided into two broad categories: use the electricity to heat the propellant, which emerges as a neutral gas, and those use the electric or magnetic field to accelerate ions. Since the beginning of space era, chemical rockets dominated due to the high thrust to mass ratio. However, chemical rockets have limited lifetime.

Electric propulsion has a wide range of thruster based on the mechanism through which electric power is utilized to accelerate the flow. Characteristic specific impulse ranges of different space propulsion is shown in Table 1. Currently, electrothermal, electrostatic, or electromagnetic thrusters are used in space application. Electrothermal thruster’s works on the principle of using electricity to heat the propellant at high temperature which creates the driving force by acceleration through the nozzle. Thermal energy of the propellant fluid is transformed to kinetic energy. Electrostatic thrusters make use of a static electric field to produce thrust by accelerating charged plasma. The electromagnetic field can be generated externally or self-induced [2].
Table 1. Specific impulses, thrust efficiency’s and thrusts of electric thrusters, deployed and experimental.[3]

| Thruster type                  | $I_{sp}$ (s) | Efficiency ($\eta_t$) | Thrust          |
|--------------------------------|--------------|----------------------|-----------------|
| Plused Plasma                  | 240-760      | 20% - 30%            | $1 \times 10^{-4}$ Ns |
| Gridded ion                    | 7650         | 77%                  | 0.43N           |
| Hall                           | 1600         | 50% - 60%            | $(2.5 - 12) \times 10^{-3}$ N |
| Magneto-Plasma-dynamic         | 3670         | 38.8%                | ~ $250 \times 10^{-3}$ N |
| Mini helicon                   | 1000-4000    | ~ 20%                | $10 \times 10^{-3}$ Ns |
| Electron cyclotron resonance   | 429 (Xe)     | 3.5%                 | $0.86 \times 10^{-3}$ N |
| Electrodeless Lorentz force (ELF)| 1000-6000   | 50%                  | 1.0 N (average) |
| Hybrid (VASIMR)                | 3400         | 56%                  | $3.6 \pm 0.2$ N |

Until now, all operating electric thruster uses electrodeless to ionize the propellant, for acceleration of the ions and electrons. The increasing of input power for ionization causes erosion, mainly by sputtering degrades lifetime limit on such devices. To address the point, the development of electrodeless thruster, such use electric or magnetic body forces to ionized gases to produce a propellant stream with directional velocity [3]. In the development of electrodeless plasma thruster, Helicon plasma sources are useful in various condition. They can create high density ~ $10^{13}$ cm$^{-3}$ helicon plasma with a spacious range of operating parameters. The experimental and theoretical approach of helicon plasma production and its acceleration schemes with described and characterized [4].

2. Helicon Plasma thruster
To realize a long lifetime of an electric propulsion system, we have been investigating various electrodeless electric propulsion concepts utilizing a helicon plasma source. Several research groups are currently working on the development of helicon plasma thruster (HPT). The study focuses on the implementation of the permanent magnet, optimizing magnets for required magnetic flux, operating power range, antenna optimization.

Mini helicon experiment (mHTX) at MIT, Helicon Plasma Hydrazine Combined Micro (HPHCOM) by ESA and Helicon Double Layer Thruster (HDLT) at Australian National University are potential HPT prototypes. The thruster performance of these various technology demonstration prototypes are presented in Table 2 and described below.

HPHCOM prototype operates at nominal power 700 W, magnetic field strength 200 G, novel resonant Antenna called S-helicon operates at frequency 13.25 MHz, managing power of the antenna is optimized to a very low range below 100 W. Permanent magnets were proposed with the different arrangement, the magnetic field range 400-1100 G.

HDTL uses electromagnets with a magnetic strength 100-200 G with operating range 200-800 W. The RF antenna has an operating frequency of 13.25 MHz. Experimental result detects a steady state current, expected thrust up to 6 mN and specific impulse 800 S using argon propellant.

Mini helicon thruster experiment (mHTX) projected a collimated plasma plume with a single magnet configuration, which is potential for electric propulsion application. Different measurement technique proved, mini helicon produces real thrust operating on atomic Ar and Molecular $N_2$. In comparing to HDTL its highly ionized propellants with fuel utilization efficiencies of 90%. Single magnet configuration is used, gas flows along the dielectric quartz tube with an antenna embracing it. The nominal operating power in the range 700-1000 W.

The antenna operating frequency is 13.25 MHz. Experimental results of mHTX presented 12% efficiency with 2000 S specific impulse and providing thrust up to 20 mN. Varying plasma beam velocity using different means of controls made the helicon most suitable for variable specific impulse [6].
Table 2. HPT main prototypes: summary of propulsive performances [5].

| Prototype | Power          | Thrust | $I_p$(s) | η(%) | η_a(%) |
|-----------|---------------|--------|----------|------|--------|
| HDLT      | < 1.5kW       | 6mN    | 800      | 25-35| 1-3    |
| mHTX      | 700-1500W     | 20mN   | 2000     | 90   | 10-20  |
| HPHCOM    | 50W           | 1.5mN  | 1200     | 90   | 13     |
| PMEP      | 700W          | 3mN    | 500      | < 50 | 1      |
| HPHT      | 20-50kW       | 1-2N   | > 2000   | ~100 | 55     |

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is a hybrid thruster. Currently, under-development by Ad Astra Rocket Co. It is not exactly considered as a helicon plasma thruster, but it uses helicon plasma sources to produce plasma. Ion cyclotron resonance energizes the plasma and accelerates through the magnetic nozzle, in contrast, produces thrust. The nominal power of operation 200 kW, with a thrust efficiency, reaches near 50%, able to produce 3 N thrust. The RF operating powers estimated ∼ 30 kW. Sizeable magnetic field >1T is necessary, which can only be achieved by the superconducting magnet [5]. Thermal behavior is also an important issue. High-temperature effects the optimal operations of the magnets, solar radiation effect of the different orbit is explained [7].

3. Helicon thruster regime of operation

Helicon plasma thruster prototypes are characterized by the RF power range and the magnetic field strength in which thruster operates. The design incorporates a wide range of controlled variables; Ionization Chamber length $L$, mass flow $m$, RF power $P_{RF}$, magnetic field strength $B$, RF frequency $\omega_{RF}$. The prime design parameters define the performance of thrusters are ionization chamber dimension, input mass flow, input RF power and frequency. The antenna shape and location, the magnetic field strength. These design parameters interact in an insignificant way and influence outright processes in the thruster, from ionization to internal plasma losses and external expansion.

3.1. Ionization chamber

Efficient ionization from the neutral gas into plasma occurs in the ionization chamber. The neutral gas propellant flows along the Dielectric quartz tube; the RF antenna generates electromagnetic waves propagate and energizes the electrons, ionized the gas. During the ionization process, major loss mechanism at a low electron temperature below 5-7 eV is excitation, de-excitation or permanence as a meta-stable state.

To achieve effective ionization requires high electron temperature (>10 eV) and mean free path smaller than the chamber length $\lambda_{ion} < L$. The dimension of the chamber has to comply so that the electromagnetic wave mode can propagate in it.

Electron Larmor radius required less then quartz tube radius $l_e < R$ for better electron magnetization for low plasma losses to the wall. Dielectric quartz tube has high heat resistance, and low thermal expansion as the electrons and ions reaching the wall and constantly deposit energy and tube is exposed to constant heat flux. The strong magnetic field is required for the plasma confinement. The optimal position for magnet, antenna, and the tube is required for efficient thruster operation [8].

3.2. RF Antenna

The helicon antenna generates electromagnetic wave decompose power to the plasma. Helicon waves are known as whistler waves, a low-frequency wave, where $\omega$ is below plasma frequency $\omega_p$, in between lower hybrid frequency $\omega_{LH}$ and the electron cyclotron frequency $\omega_e$. Helicon discharge has high ionization efficiency. With lower RF power 1-2 kW relatively fully ionized plasma $\eta \geq 10^{14}$ cm⁻³ can achieve[9]. The applied current to the antenna and waves can be reflected by the plasma, partially be radiated to free space and re-absorbed by the antenna as reactive power. The high plasma resistance and power factor are the key factors for the optimal design of antenna [8].
3.3. **Superconducting Magnet**
Magnetic field generator is significant components of Helicon plasma thruster. The helicon plasma thruster design mainly incorporates radio frequency plasma discharge in the presence of a magnetic field. Optimal design of the electromagnets to create requisite magnetic field is one of the key factors that define the performance and efficiency of the thruster. Magnetic field allows the electromagnetic wave to propagate through the plasma, reducing the plasma losses to walls and creates a magnetic nozzle for the supersonic plasma expansion.

4. **Regime of Operation**
The schematic process of HPT thruster shown in figure 1.

![Figure 1. Sketch of mini-helicon thruster operation.](image)

4.1. **Design Constraints**
Nominal values of plasma thruster for simulation is presented in Table 3.

|   |   |
|---|---|
| Ionization chamber dimensions [mm] | Length: 100; Inner radius: 23 |
| Power input at RF generator [W] | 1000 |
| Magnetic field in chamber [G] | 350 |
| Antenna RF frequency [MHz] | 13.56 |
| Antenna geometry [mm] | Nagoya type III antenna, 50 mm long |

5. **Simulation COMSOL Multiphysics**
The helicon plasma thruster design mainly incorporates radio frequency plasma discharge in the presence of a magnetic field. Radio Frequency plasma discharge was carried out using, COMSOL Multiphysics a cross-platform FEA multiphysics software. Plasma Module simulates low-temperature plasma sources, systems and discharges. Radio Frequency module is used to simulate antenna electromagnetic wave propagation, and the AC/DC module is used to simulate the magnetic field configuration. The simulation process is described below.

5.1. **2D Geometry**
The 2D cross section of the thruster used in the simulation process is shown in figure 2.

![Figure 2. 2D Sketch of mini-helicon thruster simulation](image)
5.2. **Simulation Steps**

5.2.1. **Plasma Module:** COMSOL solves for drift diffusion equation for the electron density and energy density. The Mathematical model of COMSOL plasma Simulation is explained in mathematical modeling section.

5.2.2. **Magnetic field:** The superconducting magnet configuration composed of Solenoids coil which surrounds the ionization chamber chosen for the required magnetic field strength. The solenoids coils are placed accordingly, so it limits interactions with the RF antenna.

5.2.3. **Electromagnetic Wave Guide:** A Nagoya type III antenna used for the simulation. The antenna is placed outside of the dielectric quartz tube. The length of the antenna is 100 mm and designed for the Argon Plasma. The RF antenna emits the 13.56 MHz frequency, and nominal power is about 1000 W.

5.3. **Mathematical modeling**

Mathematical model used in COMSOL Multiphysics, Frequency - transient study is described below [10].

Wave-heated plasma discharge mostly higher number density. The electron density and mean electron density is computed by solving drift-diffusion equation.

Electron number density:

\[
\frac{\partial (n_e)}{\partial t} + \nabla \cdot \Gamma_e = \dot{R}_e
\]

\[
\Gamma_e = - (\mu_e \cdot \textbf{E}) n_e - D_e \cdot \nabla n_e
\]

\[n_e\] Denotes the electron density, \((1/m^3)\), \(\dot{R}_e\) is the electron rate expression \((1/(m^3 \cdot s))\), \(\mu_e\) is the electron mobility \((m^2/(V \cdot s))\), \(\text{E}\) is the electric field \((V/m)\), and \(D_e\) is the electron diffusivity.

\[
\frac{\partial (n_e)}{\partial t} + \nabla \cdot -n_e (\mu_e \cdot \text{E}) - D_e \cdot \nabla n_e = \dot{R}_e
\]  \hspace{1cm} (3)

Electron energy density:

\[
\frac{\partial (n\epsilon_e)}{\partial t} + \nabla \cdot \Gamma\epsilon_e + E \cdot \text{E}_\epsilon = \dot{R}_\epsilon
\]

\[
\Gamma\epsilon_e = - (\mu_e \cdot \text{E}) \text{ne} - D_e \cdot \nabla n\epsilon_e
\]

\(R_e\) is the energy loss/gain because of inelastic collisions \((V/m^3 \cdot s)\), \(\mu_e\) is the electron energy mobility \((m^2/V \cdot s)\), \(E\) is the electric field \((V/m)\), and \(D_e\) is the electron energy diffusivity \((m^2/s)\).

\[
\frac{\partial (n\epsilon_e)}{\partial t} + \nabla \cdot -n\epsilon_e (\mu_e \cdot \text{E}) - D_e \cdot \nabla n\epsilon_e + E \cdot \text{E}_\epsilon = \dot{R}_\epsilon
\]  \hspace{1cm} (4)

Electrostatic field is computed,

\[
-\nabla \cdot \epsilon_o \epsilon_r \nabla \text{V} = \rho
\]

High frequency electric field is computed in the frequency domain,

\[
\nabla \times (\mu_r^{-1} \nabla \times \text{E}) - k_0^2 (\epsilon_r - \frac{j\sigma}{\omega\epsilon_0}) \text{E} = 0
\]  \hspace{1cm} (8)

Where plasma current density and the electric field are more complicated,

\[
\sigma^{-1} \cdot J = \text{E}
\]  \hspace{1cm} (9)

Plasma coupling between electromagnetic wave and magnetic field. \(\sigma\) is plasma conductivity tensor, function of electron density collision frequency and magnetic flux.
\[ \alpha = \frac{q}{m_e(\beta + j \omega)}, \quad \beta = n_e q \alpha \] (10)

Where, \( q \) = Electron charge, \( m_e \) = Electron mass, \( n_e \) = Collision frequency and \( \omega \) is angular frequency of electromagnetic field.

5.4. Cross Section Data Argon (Ar)
Plasma consists of three species ions, electrons and mostly neutral atoms and molecules. The density of electrons and ions are a small fraction of the neutral atoms and molecules, exceptions in earth-based plasma nuclear fusion where it’s fully ionized. Plasma used in the application of industrial and commercial are not necessarily entirely ionized. Because of the high density of neutral atoms and molecules collisions between them and the electrons and ions become significant. The central parameter of the collisions process is the cross-section. Electrons collide with the gas particles or ions, several reactions are possible. The electron can ionize the gas, impart momentum to it, could excite the energy levels of the electrons around the molecules and ions, and could recombine with the ions and many more. In all of this stochastic process, electrons lose energy. The cross-section data for neutral gas Ar is presented in the Table 4. Cross section is denoted as the area available for electrons for the collision to happen. Cross section data permits the rate coefficient for a particular reaction to compute using Electron Energy Distribution Function (EEDF).

Table 4. Argon Collision and reactions modeled [10].

| Reaction | Formula          | Type         | \( \Delta(eV) \) |
|----------|------------------|--------------|-----------------|
| 1        | \( e+Ar=e+Ar \)  | elastic      | 0               |
| 2        | \( e+Ar=e+Ar+ \) | excitation   | 11.5            |
| 3        | \( e+Ar=e+Ar+ \) | super-elastic| -11.5           |
| 4        | \( e+Ar=e+Ar+ \) | ionization   | 15.8            |
| 5        | \( e+Ar=e+Ar+ \) | ionization   | 4.24            |
| 6        | \( Ar+Ar=Ar+Ar+ \) | Penning ionization | -          |
| 7        | \( Ar+Ar=Ar+Ar \) | metastable quenching | -        |
| -        | \( Ar=Ar \)      | deexcitation | -               |
| 9        | \( e+Ar=Ar \)    | recombination | -               |

6. Result and discussion
COMSOL solves for drift diffusion equation for the electron density and energy density. Electron density distribution is shown in the figure 3 along the mid cross section towards the length of the ionization chamber.
Figure 3. Electron energy density distribution along the length of ionization chamber.

The maximum electron density is in the plasma column and the value is about $1.8 \times 10^{12} \text{ cm}^{-3}$. Nagoya III type helicon antenna is used and placed in the middle embracing quartz tube, ionization chamber. The critical factor of RF driven Plasma engine lies in the antenna, it energies the neutral flow of initial neutral gas into a magnetized plasma with respectively high ionization density. The plasma discharge initiates near to the antenna and expands towards the center position of the ionization chamber.

Figure 4. Electron Temperature distribution along the length of ionization chamber.

The electron temperature distribution is illustrated in the figure 4. Maximum electron temperature reaches 2.25 eV. In the presence of a magnetic field, electrons get magnetized and having cyclotron gyration collides with neutral atoms. In the process, electrons lose their energy because of atoms
collisions and lose the ability to reach higher plasma temperature. Electron potential distribution presented in the figure 5.

![Electronic potential distribution](image)

**Figure 5.** Electron potential distribution along the length of ionization chamber.

**Nomenclature**

- $\lambda_{ion}$: Ion Mean free path
- $\omega_{RF}$: Radio frequency
- $B$: Magnetic flux density vector
- $E$: Electric field vector
- $EM$: Electromagnetic wave
- $P_{RF}$: Radio frequency power
- HPT: Helicon plasma thruster
- $L$: Ionization chamber length

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