



A global model study of argon plasma chemistry used as propellant of a gridded ion thruster

Um estudo do modelo global da química do plasma de argônio usado como propelente de um propulsor iônico com grades

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ABSTRACT

The search for new propulsion devices for corrections and adjustments in the orbits of space systems composed of constellations of satellites in specific arrangements has progressively increased with the growth of requests for data transmission with greater speed and capacity. Electric propulsion is the best solution to reduce the propellant mass, in addition to allowing long mission times. Among the various types of thrusters, electrostatic thrusters have a better-defined physics, making possible the development of computational models for the study and optimization of their operational parameters. A global model was developed for a cylindrical ion thruster with the inductively coupled plasma (ICP) generator originated by the circulation of a radio-frequency current in an inductive coil that surrounds the thruster, having at the output a polarized grid extraction system accelerating the ionized argon gas (propellant). The global model is formed by charged and neutral particle balance equations and energy equations of electrons and gas. Neutral and excited species are accelerated by drift out of the thruster and ionized species accelerated for the reason of the electric field generated by the pair of polarized grids in direct current. The most in-depth study of argon plasma chemistry found that, among the various parameters that interfere with species density, the number of excited species has a direct influence on ionization, although it does not interfere much with ion density, what can be translated into a higher rate ion replacement, which is extremely important to gain thrust and specific impulse.

KEYWORDS: Plasma chemistry, Global model, Argon, Electric propulsion, Gridded ion thrusters.

RESUMO

A necessidade de novos dispositivos de propulsão para correções e ajustes nas órbitas de sistemas espaciais compostos de constelações de satélites em disposições específicas tem aumentado cada vez mais com o crescimento da demanda por transmissão de dados com maior velocidade e capacidade. A propulsão elétrica é a melhor solução para a redução de massa do propulsor, além de permitir longos tempos de missão. Entre os diversos tipos de propulsores, os propulsores eletrostáticos apresentam uma física mais bem definida, permitindo a elaboração de modelos computacionais para o estudo e a otimização de seus parâmetros operacionais. Um modelo global foi desenvolvido para um propulsor iônico cilíndrico com o gerador do plasma acoplado indutivamente (ICP) gerado pela circulação de uma corrente de radiofrequência em uma bobina indutiva que circunda o propulsor, tendo na saída um sistema de extração de grades polarizadas acelerando o gás argônio ionizado (propelente). O modelo global é formado por equações de balanço de partículas com carga e neutras e por equações de energia dos elétrons e do gás. As espécies neutras e excitadas são aceleradas por deriva para fora do propulsor, e as espécies ionizadas, aceleradas por causa do campo elétrico gerado pelo par de grades polarizadas em corrente contínua. O estudo mais aprofundado da química do plasma de argônio verificou que, entre os vários parâmetros que interferem na densidade das espécies, o número de espécies excitadas tem influência direta na ionização, embora não interfira muito na densidade dos íons, o que pode ser traduzido em maior taxa de reposição iônica, que é extremamente importante para ganhar empuxo e impulso específico.

PALAVRAS-CHAVE: Química de plasma, Modelo global, Argônio, Propulsão elétrica, Propulsor iônico com grades.



INTRODUCTION

The growing demand for data transmission with greater speed and capacity has proved to be a major challenge facing humanity today. Many of these obstacles can be solved by space systems composed of an infrastructure of small constellations of nanosatellites in low orbits. Frequent orbit adjustments are necessary for the disposition of these satellites, which result in increased propellant consumption and, consequently, the need for a small propulsion system. Electric propulsion systems feature ion exhaustion at high speed, reducing the mass of the propellant and allowing long mission times. Electric thrusters can be classified according to the method used to accelerate and produce the respective thrust. Electrostatic thrusters use the stationary electric field to accelerate ions, and gridded ion thrusters (GIT) have been used widely since the 1960s^{1,2}.

The physics associated with electrostatic thrusters is better defined than the one of other types of engines, enabling a more in-depth initial study to optimize the efficiency of these thrusters. Global model, or zero-dimensional modeling, was developed based on fluid theory, used in the transport equations obtained from the Boltzmann equation, in order to request a low computational resource, but can be applied for chemically complex discharges of the types of propellants used^{2,3}.

This study aimed to evaluate the zero-dimensional modeling of argon plasma chemistry for a cylindrical ion propellant based on inductively coupled plasma (ICP) whose output had a polarized grid system. The neutral propellant (argon gas) was injected at a fixed gas flow into the thruster chamber, and an ICP was generated by circulating a radio-frequency current in an inductive coil that surrounded the cylinder. Neutral and excited species were ejected out of the chamber by drift, while ionized species were accelerated due to the electric field generated by the pair of polarized grids in direct current.

The global model developed was based on the particle and energy balance equations, in which the latter considered both charged species and neutral species. Thus, the model allowed the determination of the temperature of the neutral gas. Finally, the model took into account the effect of single and multi-stage ionization, as well as the effect of the electron energy distribution function (EEDF)^{3,4}.

The option for the use of argon was due to the fact that it is economically more interesting, since its commercial and maintenance cost is very low when compared to other inert gases with greater atomic mass. But this study also aimed to evaluate the chemical properties of argon plasma, because of the generation of excited species in several metastable states. These metastables significantly affected the EEDF and, consequently, all reaction rates that involve electrons, reducing, thus, the energy cost to sustain the ionic density in the thruster³.

THEORY

For this study, a plasma composed of three interactions of mutual fluids was considered: neutral atoms, positive ion with a single charge, and electrons. Particle balance differential equation takes into account species production and loss through many processes: reactions between electrons and gas species, reactions between two-gas species, recombination of neutral species on chamber walls, ion neutralization positive in the chamber walls, extinction of metastable states in the chamber walls, and the pumping of all neutral and positive ions species out of the chamber⁴.

For each species, there is a particle balance equation given by Eq. 1:

$$\frac{dn_{(x)}}{dt} = \sum_i R_{(x) \text{ production},i} - \sum_i R_{(x) \text{ loss},i} \quad (1)$$

In which $\sum_i R_{(x) \text{ production},i}$ and $\sum_i R_{(x) \text{ loss},i}$ represent the sum of all reaction rates that contribute to the production and loss of X species, respectively. Electron density is obtained through charge neutrality (Eq. 2)⁵:

$$n_e = n^+ \quad (2)$$

Since collisions among charged and neutral particles lead to significant gas heating, the neutral energy balance equation to calculate the gas temperature (T_g) is given by the collision terms given by Eq. 3⁶:

$$\frac{d}{dt}(W_g) = G_{el} + G_{in} - L_p - L_i - L_{in} \quad (3)$$

The neutral energy density (in J/m³) is given by $W_g = \frac{3}{2}n_g k_B T_g$, the gains are associated to gas heating due to electron-neutral elastic collisions, $G_{el} = 3 \frac{m_e}{M} k_B (T_e - T_g) n_e n_g K_{el}$, and to ion-neutral collision heating, $G_{in} = 3 \frac{m_i}{M} k_B (T_e - T_g) n_e n_g K_{in}$, with the losses given by the heat flow to the walls, $L_p = \kappa \left(\frac{T_g - T_{g0}}{\Lambda_0} \right) \frac{A}{V}$, by the heat conduction by thermal diffusion to the walls, which are at a fixed temperature, T_{g0} , by the thermal loss due to ionization collisions, $L_i = \frac{3}{2} k_B T_g n_e n_g K_{in}$, and finally by the thermal loss due to the collisions ion-neutral, $L_{in} = \frac{3}{4} k_B (T_g - T_i) n_e n_g K_{in}$. The electron neutral moment transfer rate and neutral ion is given by $K_x \equiv \sigma_x \bar{v}_x$ with $\bar{v}_x \equiv (8k_B T_x / \pi m_x)^{0.5}$ ^{6,7}.

The electron power balance closes the set of differential equations. It can be written as Eq. 4⁸:

$$\frac{d}{dt}(W_e) = \frac{(P_{abs} - P_{loss})}{V} \quad (4)$$

in which: $W_e = \frac{3}{2} n_e T_e$ = the electron energy density (in J/m³); P_{abs} = the power absorbed by the plasma; P_{loss} = the loss power; V = the volume of the discharge chamber.

The most general form to the power loss equation is given by Eq. 5⁹:

$$P_{loss} = P_{iw} + P_{ew} + P_{ev} \quad (5)$$

The power lost by the positive ions on the walls is given by $P_{iw} = eA \epsilon_{iw} n_{+s} u_B$, in which n_{+s} is the ion density in plasma sheath region, and u_B is the average Bohm velocity. Assuming a Maxwellian distribution for the electron energy, $\epsilon_{iw} = \frac{T_e}{2} + V_s$ is the average kinetic energy lost by the ions to the walls, in which $T_e/2$ is the energy gained by the ion on entering the plasma sheath, and $V_s = \frac{T_e}{2} \ln \left(\frac{M_i}{2\pi m_e} \right)$ is the potential drop in the sheath formed on the walls of the reactor¹⁰. $P_{ew} = eA \epsilon_{ew} n_{es} u_B$ is the power lost by electrons on the chamber walls, in which A is the chamber's internal area, $\epsilon_{ew} = 2T_e$ is the mean kinetic energy per electron lost, and n_{es} is the electron density at the sheath edge. $P_{ev} = e n_e V \sum_x k_{ix} n_{(x)} \epsilon_{c(x)}$ is the power lost due to electron-particle reactions.

The four main variables of the model – the density of the plasma n , the density of the neutral gas (atom) n_g , the electron's temperature T_e and the temperature of the neutral gas T_g – were calculated by numerically integrating the four first order nonlinear differential Eqs. 1, 2, 3 and 4, until the steady state is reached.

RESULTS AND DISCUSSION

A special region near the walls of the propellant chamber due to the electrical properties of the particles that advance to the grids creates the so-called Child-Langmuir sheath, changing the balance of the particles, their density in the plasma, and the potential¹. The most common form of Child-Langmuir's law is given by Eq. 6:

$$J_i = \frac{4}{9} \epsilon_0 \left(\frac{2e}{M} \right)^{0.5} \frac{V_{grid}^{1.5}}{s^2} \quad (6)$$

in which: J_i = the current density; ϵ_0 = the permissiveness of the free space; s = the distance between the grids, also known as Child-Langmuir length³.

The Child-Langmuir sheath that accelerates the ions to high energy and reflects the electrons varies in proportion to the mass of the ions, needing to be adjusted the distance between the grids according to each propellant used. For the setting of $V_{grid} = 1,000$ V and $s = 1.0$ mm, the maximum ion current density extracted by the grids is given when $J_i = e \Gamma_i$ is equal to the Child-Langmuir limit⁴. Child-Langmuir limit for the current density of extracted ions was $J_{CL} = 273.4$ A/m², which is obtained at $P_{RF} = 665.5$ W, as Fig. 1 shows, corresponding to $I_{coil} = 5.23$ A. However, the thruster parameters can be adapted, in order to achieve a better result for specific chosen propellant and the demand that the mission will present. Therefore, the same parameters used by Chabert et al.⁴ will be adopted in order to analyze the plasma chemistry of argon and from these results verify the other parameters in future studies.

The gas chemistry model used in this article includes six species: argon in the fundamental state (Ar), positive argon ion (Ar^+), metastable argon atoms (Ar_m), resonant argon atoms (Ar_r), atoms in the state $4p$ (Ar_p), and electrons (e). Ar_m includes the two metastable states $^3\text{P}_0$ and $^3\text{P}_2$, and Ar_r includes two resonant states $^1\text{P}_1$ and $^3\text{P}_1$. The excited state $4p$ has 10 energy levels in the range of 12.9–13.5 eV. The two metastable levels are combined in the calculations: the radioactive and $4p$ levels.

Figure 2 shows the densities of the argon plasma species (Ar , Ar^+ , Ar_m , Ar_r , Ar_p and electrons) as a function of the radiofrequency (RF) power. Argon produces an electropositive plasma, i.e., it has no negative ions, and low pressure has only one ionized species. The ionization energy grows as the atomic mass of the noble gases decreases, giving argon a high-ionization energy. However, the high concentration of metastable species facilitates multiple steps ionization, thus reducing the energy cost to sustain the discharge, increasing the electron density and consequently reducing the electron temperature, as shown in Fig. 3. Regardless the limit of the ionic density current, it is possible to perceive that for slightly higher powers the temperature of the electrons tends to increase in order to stabilize the formation of ions despite the tendency to deplete the densities of neutral species.

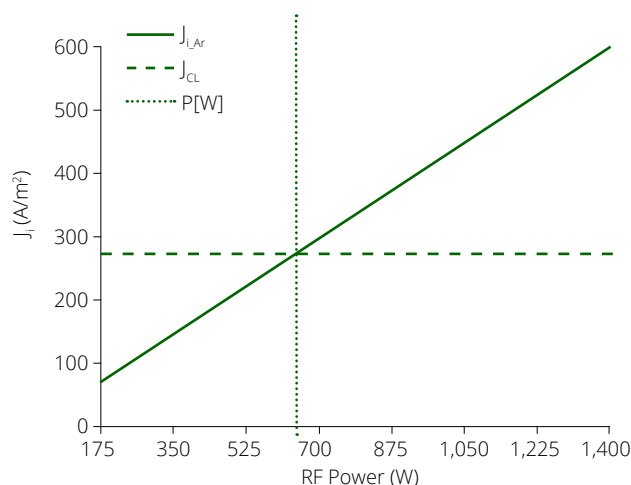


Figure 1: Current density in the thruster chamber as function of the radiofrequency power.

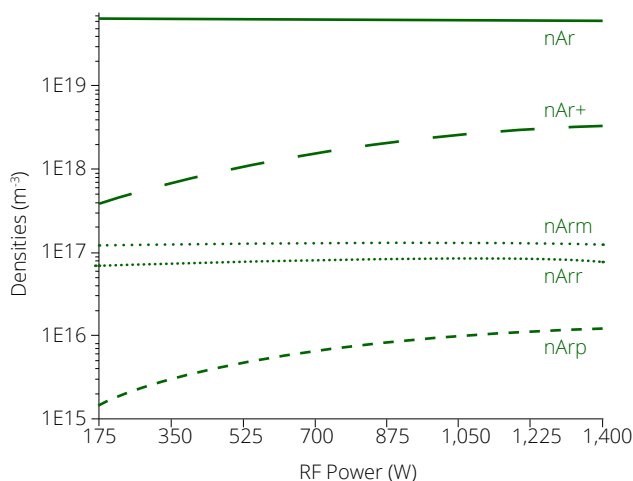


Figure 2: Densities of neutral and charged species inside the thruster as function of radiofrequency power.

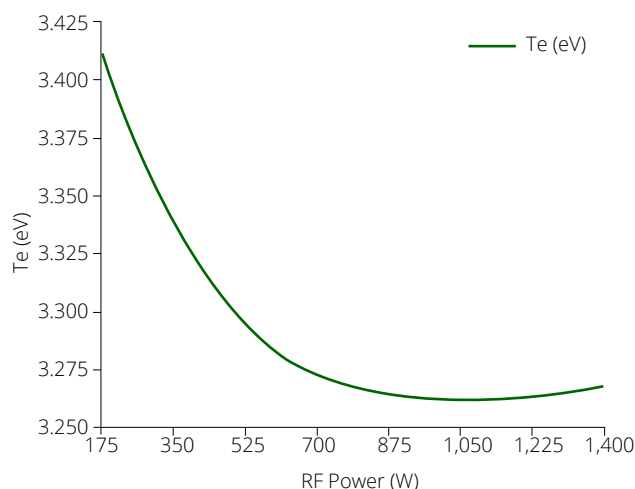


Figure 3: Electron temperature versus radiofrequency power.

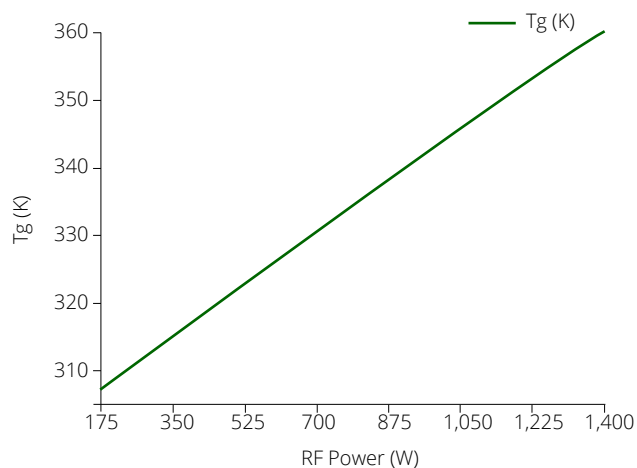


Figure 4: Neutral gas temperature as function of the radiofrequency power.

In Fig. 4, the neutral gas heating increases with the discharge power, maintaining this growth because the drop in the density of the neutral gas is too small to change the heating rate. The gas pressure is a function of the gas flow entering the chamber, so that the density of neutral gas does not vary as a function of pressure, but rather as a function of the reaction rate that varies with the RF power. A deeper analysis of the influence of the collisional loss terms given in Eq. 3 shows that the thermal loss terms due to ionization collisions (L_i) and the thermal loss due to ion-neutral (L_{in}) collisions have great influence on the gas temperature, since the presence of both terms shows how the gas loses much of its temperature through these collisions, even reaching 40 K above the temperature, in Fig. 4. The gas temperature is extremely mattering for a thermal study of the propellant, since the propellant and many of its components have low efficiency, or even loss of certain properties required for the application in a real mission, like the propeller coils, that are made of copper, which has a melting point of 1,085°C.

Further study of the chemistry of argon plasma has already allowed factors such as gas temperature to be influenced by the terms of heat exchange and electron temperature to interfere with species densities, so that the number of species closest to reality has a direct influence in the ionization rate. Although it does not interfere much in the density of ions, it ends up leaving a higher rate of ion replacement, which is extremely important for a propellant that uses the acceleration of ions to gain thrust and specific impulse.

CONCLUSION

From this significant study of the plasma parameters, it was possible to determine a series of factors that will assist in a more realistic analysis the numerical development of the GIT model ICP. When developing a more detailed study of the collisional terms in the neutral gas energy balance, in view of a deepening in the quantity of metastable species, it was comprehended that the greater number of reactions and species close to physical reality better approximates the characteristic properties to the ones of the experimental models, and thus make argon a viable propellant, even though it is a noble gas with atomic mass three times smaller than xenon, and with high-ionization potential.

Another perception is that the variation in the geometry of the propellant has a direct influence on the yield of the plasma chemistry output parameters, and can be better evaluated in a second moment, after the predefined plasma parameters, depending on the type of propellant used. This geometry control can be a solution to the demands of new specific space missions and conditions.

AUTHOR'S CONTRIBUTION

Conceptualization: B. V. Magaldi, R. S. Pessoa, A. S. da Silva Sobrinho; **Data Curation:** B. V. Magaldi; **Formal Analysis:** B. V. Magaldi; **Funding Acquisition:** A. S. da Silva Sobrinho; **Investigation:** B. V. Magaldi, R. S. Pessoa; **Methodology:** B. V. Magaldi, R. S. Pessoa, A. S. da Silva Sobrinho; **Project Administration:** B. V. Magaldi, R. S. Pessoa, A. S. da Silva Sobrinho; **Software:** B. V. Magaldi; **Supervision:** R. S. Pessoa, A. S. da Silva Sobrinho; **Validation:** B. V. Magaldi, R. S. Pessoa; **Visualization:** B. V. Magaldi; **Writing – Original Draft Preparation:** B. V. Magaldi; **Writing – Review & Editing:** R. S. Pessoa, A. S. da Silva Sobrinho.

DATA AVAILABILITY STATEMENT

All dataset was generated or analyzed in the current study.

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