Modelling of plasma thruster plumes for spacecraft plume-impingement analysis

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**Abstract**

Plasma thruster plume models for two types of electric thrusters are implemented in the SPIS software along with several other developments to allow the analysis of the plasma impingement on spacecrafts

**Keywords:** Spacecraft-plasma interactions, electric propulsion, SPIS software, electric thrusters modelling

1 Introduction

Electric propulsion (EP) systems in spacecrafts represent a strong alternative to the traditional chemical propulsion (CP). Due to their high exhaust speed, much higher thruster efficiencies can be reached when comparing to CP. This leads to a better propellant use and makes EP the most attractive technology to be used in the future for long space missions. EP systems produce the thrust to move a spacecraft by accelerating and ejecting highly energetic particles. These ejected particles are mostly charged and form a plasma plume that involves the spacecraft and interacts directly and indirectly with it. The interactions may originate several issues and represent a high risk for a space mission. The charging effect on a spacecraft is one of the biggest issues that may arise. It induces an electric field that affects the environment surrounding the spacecraft and that can cause various disorders to the spacecraft’s systems. The electric field can create acceleration of particles in the direction of the spacecraft’s surface increasing the degree of erosion and contamination and, eventually, lead to powerful electrostatic discharges that may damage electronics and electric components onboard.

The European Space Agency (ESA) is very inter-
ested in developing tools to analyze the plasma plume interactions with spacecrafts since many of the planned future missions will carry EP systems onboard. With this objective ESA is funding a project called AISEPS (for Assessment of the Interaction between Spacecraft and Electrical Propulsion Systems) where a consortium of companies and institutes are working with the objective of developing a simulation tool to analyze the effects of EP thruster on satellites. EADS Astrium Satellites is one of the companies involved in this project where its main objective is to implement a plume thruster model into an existent software that is already capable of calculate the interaction between the plasma and the spacecraft. The work here presented was performed during a six month internship at Astrium and consisted of plume models implementation into the SPIS software (Spacecraft Plasma Interaction System) and the development of several tools needed to better simulate and analyze the plume models.

This paper is organized as follows: a brief description of the operation of the two used types of EP thruster is given in Chapter 2. Chapter 3 reviews the concept of plasma simulation. Chapter 4 describes the models and some evolutions made to the SPIS software. Chapter 5 presents the results obtained using the implemented models. Finally, a summary of the work is presented in Chapter 6.

2 Electric Propulsion Systems

Two types of electric thruster plume models were implemented in this work: an electric thruster (the ion thruster) and an electromagnetic thruster (the Hall effect thruster).

**Ion Thruster**

A simple model of the ion thruster is depicted in Fig. 1.

![Figure 1: Ion thruster model](image)

The basic elements of this thruster are a cylindrical chamber containing a centerline cathode emitting electrons, a surrounding anode shell and three ring magnets efficiently disposed in the chamber to generate as azimuthal and radial magnetic field. This configuration of the magnetic field constrains the electrons to gyrate within the chamber for a sufficient time to ionize the injected propellant gas and to direct it to the extractor and accelerator grids. The disposition of the magnet rings yields a highly divergent and doubly cusped pattern inside the chamber, which is implemented in a way to optimize the ionization discharge and the ion extraction. Along with the magnetic field inside the thruster’s chamber, an electric field is created by a system of grids that allows the acceleration of the created ions. The typical ion thruster contains two electrodes, also called
ions optics, in the downstream part of the chamber; the upstream electrode (screen grid) is charged highly positive, and the downstream electrode (accelerator grid) is charged highly negative. The greater this voltage difference between the two grids is, the higher will be the ion acceleration and the energy of the ejected ions. The constant emission of positive ions would charge negatively the spacecraft. In order to avoid this charging effect and the associated problems, a separate cathode emits electrons assuring that the same positive and negative charge is ejected. Given its function the cathode is also called a neutralizer.

**Hall effect thruster (HET)**

The HET mode of operation is more complex than the ion thruster one. Depicted in Fig.2, the HET consists of a ring-shaped channel with an interior anode, a magnetic circuit that generates a primarily radial magnetic field across the channel and an external hollow cathode. In HET most of the propellant gas is ejected from the anode located in the upstream part of the thruster’s channel.

![Figure 2: Hall effect thruster model](image)

Usually the electrons would go directly from the cathode to the anode inside the chamber due to the potential difference kept between the two elements. However, the radial magnetic field created by the coils in the thruster prevents the electrons from directly moving to the anode. Instead the electrons start spiraling along the magnetic field gaining a drift velocity of the order of $v = (\mathbf{E} \times \mathbf{B})/|\mathbf{B}|^2$. Given the radial profile of the magnetic field ($\mathbf{B}$) and the axial profile of the electric field ($\mathbf{E}$) originated by the potential anode-cathode difference, one can notice that the drift velocity will keep electrons in a circular motion around the center of the thruster. This azimuthal drift of the electrons around the channel is reminiscent of the hall current and gives the name to the thruster. The effect is also the reason why some authors call it a closed drift thruster. The Xe particles of the gas released from the anode will eventually collide with the trapped electrons in the cross electric and magnetic fields, producing charged ions. The axial mobility of the electrons is highly reduced by the radial magnetic field, which permits a discharge voltage to be distributed along the channel axis in the formed quasi-neutral plasma. This results in an electric field in the axial direction that accelerates and ejects the ions in the downstream direction, forming the thruster’s plume. The electrons on the other hand diffuse in the direction of the anode and thruster’s walls by collisions and electrostatic fluctuations. In the downstream part of the thruster, and like in the ion thruster description, the cathode also has the function of neutralizing the plasma, preventing the spacecraft from getting negatively charged.
3 Plasma simulation and the SPIS software

The software adopted for this work, SPIS, uses an hybrid Particle-in-Cell method where ions are treated with a microscopic, kinetic approach and electrons are treated with a macroscopic, fluid approach. The kinetic approach of the simulation adopts the concept of superparticles, where several physical particles are grouped into one simulated superparticle. The properties of the real particles are averaged and added as properties of the superparticle. To each superparticle a weight is attributed relating each superparticle to the number of physical particles it represents. A simulation using the PIC method implies the usage of a volume mesh where at each time step several properties are attributed to the nodes of the grid that will influence the evolution of the plasma in the following time step. For the kinetic approach the PIC method attributes the characteristics (mass, charge, velocity) of the superparticles to the nodes of the cell where the superparticle is included. A fraction of each characteristic is given to each node as a function of the distance to the node, so that the closer the superparticle is, the higher the fraction of the deposited characteristic will be. Apart from the characteristics of the simulated superparticles there is also the calculation of electron density with the fluid approach that is added to the properties of each node. This is usually done by solving the Boltzmann relation

\[ n_e = n_{\text{ref}} \exp \left( \frac{-e \phi}{k_B T_e} \right) \]  

where \( e \), \( k_B \) and \( T_e \) represent, as usual, the electron charge, the Boltzmann constant and the electron temperature. The parameter \( \phi \) is the old potential on the same node where the electron density is being calculated and \( n_{\text{ref}} \) is a reference density corresponding to the density obtained when the potential equals zero.

After finding these plasma properties, the electric fields are calculated by solving the Poisson’s equation, where both ion and electron densities are considered:

\[ \nabla^2 \phi + \frac{\rho_i}{\epsilon_0} - \frac{\rho_{\text{ref}}}{\epsilon_0} \exp \left( \frac{e \phi}{k_B T_e} \right) = 0 \]  

These electric fields will then be used to move particles to new positions which will change the properties of each node and in this sense evolve the plasma profile.

Apart from this method, the SPIS software also simulates the interactions of ions with background neutrals. The interactions simulated only take into account the process of charge exchange (CEX) collisions, which consist of the interaction between a fast ion (typically ejected from a thruster) and a slow neutral (typically a neutral with a thermal velocity, part of the background population). In these interactions an electron is transferred from the neutral to the ion. As a result the initial population will be changed to a slow (thermal) ion and a fast neutral. When simulating these interactions the rate of collisions that take place at each time step is given by the following expression:

\[ dp = n_z \Delta v \sigma(\Delta v) dt \]  

where \( \sigma \) is the CEX cross section and \( \Delta v \) the relative velocity between the two particles. The CEX cross
section values used correspond to the most recent measurements performed by Miller et al.[1] and are modeled by $\sigma(\Delta v) = a - b \ln \Delta v$, where the two constant parameters $a$ and $b$ are derived by fitting experimental curves. In the SPIS software the collisions are simulated using the Monte-Carlo collision (MCC) method which assumes the initial population unchanged and so, instead of transforming the characteristics of the colliding particles, the software only adds new particles to the already existent ones. This originates some issues when simulating the plasma involving a thruster and needs to be taken into account when analyzing the results. It is also important to refer that even though ions are treated as particles, the neutrals in this software are treated with an analytical and constant distribution.

### 4 Thruster models

**Hall thruster model**

Tajmar et al.[2] have proposed a mathematical model to describe the plasma plume ejected from a Hall thruster. Taking into account experimental data [3] and theoretical analysis [4] of a HET it was suggested that the creation of ions in the thruster’s channel was greater near the inner wall and that the current density could be assumed constant in the whole surface of ejection. Considering these characteristics and assuming a constant speed of ejection for each type of particle, a model was created in which the ejection angle of the particles varies linearly with the distance to the thruster’s axis. The angle variation with the radial position where the particle is created is given by:

$$\alpha(r) = \alpha_i + \frac{(r - R_i)\alpha_o - \alpha_i}{R_o - R_i} \tag{4}$$

where the parameters $\alpha_i$ and $\alpha_o$ correspond to the inner and outer angles of ejection, and $R_i$ and $R_o$ to the inner and outer radii of the thruster’s exit, as depicted in Fig. 3.

![Figure 3: Implemented model of the HET. Adapted from [2]](image)

Taking the considerations mentioned above, the mass flow rate, $\dot{m}$, and velocity, $v$, of the singly and doubly charged ions ejected were calculated:

$$v_i^+ = \frac{T \left(1 + \sqrt{2} \eta_p\right)}{m_i \eta_u \eta_o \left(1 + 2 \eta_p\right) \left(\sin \alpha_{aver}/\alpha_{aver}\right)^2} \tag{5}$$

$$\dot{m}_i^+ = \frac{T}{v_i^+ \left(1 + 2 \eta_p\right) \left(\sin \alpha_{aver}/\alpha_{aver}\right)^2} \tag{6}$$

$$v_i^{2+} = \sqrt{2} v_i^+ \quad ; \quad m_i^{2+} = \eta_p \sqrt{2} \dot{m}_i^+ \tag{7}$$

With these characteristics, each superparticle is ejected to the simulation volume and the usual PIC-MCC method is used to move it and in this way to evolve the plasma profile.
Ion thruster model

Another model implemented in the SPIS software was the Ion thruster plume model. This model is a modification of the HET plume model described above. The first big difference that can be noticed between the two types of thrusters (see Chapter 2) is that the Ion thruster is not ring shaped but instead has a completely circular surface of injection. By assuming the same model of the HET only the outer divergence angle $\alpha_o$ is defined and $\alpha_i$ is taken as $0^\circ$ in expression (4).

The velocity vector (both speed and direction) and mass flow rate for each type of particles are calculated by the same expressions presented for the HET and the speed of the ejected particles is still assumed constant. In contrast to the HET model, experimental results with Ion Thrusters by de Boer[5] suggest that the current density profile is Gaussian. Therefore, instead of the uniform ion density distribution used in the HET plume model, a Gaussian ion density profile should be used at the exit plane. The ejection of superparticles is still performed with an uniform distribution on the surface of ejection, however since the number of physical particles ejected is always represented by the weight of a superparticle, it is the weight that changes with the radial distance in order to follow the Gaussian profile. By doing so, even considering uniform distribution of superparticles, the correspondent number of physical particles is changing and the correct amount is being ejected in each place. This is done by randomly choosing a position on the surface of ejection and then attributing a weight to the superparticle by considering the radial Gaussian distribution:

$$G(r) = K \exp \left[ -\frac{r^2}{2 R_o^2 \sigma^2} \right]$$ (8)

where the the variables $r$ and $R_o$ are the same as before and $\sigma^2$ is the variance of the distribution. The constant $K$ is calculated taking into account all the particles ejected from the exit surface.

Other developments to the SPIS software

Apart from the implementation of the plume thruster models, several developments to the software were performed in order to allow the utilization of the models and the analysis of the results. Current density and energy profiles of the plasma on each cell node were exported to post-processing software in order to validate the plume models. The Poisson solver described in Chapter 3 was modified and a new solver was implemented where it was assumed a quasi-neutral plasma both with a constant and variable electron temperature following the suggestions in [6] and [7]. To test the quality of simulations several options were also added to the SPIS software, such as the verification of the number of superparticles per cell at each time step and also a tool that compares the Debye length with the cell size in each point of the volume, indicating if the quasi-neutrality assumption may be used or if the Poisson solver is necessary.

5 Results with the new models

The Hall effect thruster and the ion thruster were simulated using the implemented plume thruster models. To validate the HET the parameters of a SPT100 thruster were chosen. Some of the parameters used were the
inner (28mm) and outer (50mm) radius, the total produced thrust (84mN) and mass flow rate (5.6mg/s), the percentage of doubly charged ions (10%) and the ionization efficiency (95%) of the thruster.

![Graph](image)

**Figure 4:** Current density profile as a function of the angle to the thruster axis, at a distance of 1m

Also the inner and outer angles showed above where introduced as -12° and 40°, respectively. The results presented here correspond to a simulation with a duration time of 4ms and a background pressure of 2.9×10^{-4}Pa. Fig. 4 plots a comparison of the current density profile of the simulation results obtained with the SPIS software and the experimental data obtained by Manzella and Sankovic [8] at a distance of 1m from the thruster. The background conditions used in both cases were the same. The two curves show a fairly good fit for angles greater than 10° but they are clearly below on axis measurements. On axis the values reach a relative error to the measurement data of 60.8%, decreasing then to errors around 1% in the region from 10° to 30°. In order to understand the discrepancy of the simulation results and the experimental data for small angles the analysis of the particle density and the energy profiles was performed. Fig. 5 presents the simulation results for these quantities plotted against experimental data. On the left side of the figure the beam energy per charge of ion is plotted against the angle to the thruster’s axis for both the simulation results and the experimental data obtained by Kim et al. [9]. It can be noticed that the simulation results fit well to the experimental data and the relative error obtained between the two is around 15%. On the right side of Fig. 5 the dependence of total ion number density (Xe^+ and Xe^{2+}) on the angle to the thruster’s axis is plotted. Since the energy profile was quite similar to experimental values it would be expected a depression of ion number density on axis in order to explain the lower values in the same region for current density. This is indeed what can be observed on the presented plots where the relative error to the experimental data on axis is 69.3%. These results prove that the biggest source of error comes from the profile of density. One of the reasons to have such a discrepancy can come from the inner angle value used in the proposed model. The inner angle has an influence on the potential profile on the axis region which changes the distribution of particles above the thruster’s exit and may be repelling some of the particles that would go to this axial region. Even though the electric field created by the potential difference is not sufficient to change the trajectory of the ejected ions (which are very energetic), this can affect the slow ions (created by collisions) since they are readily deviated when created near the exit region of the thruster.
Effect of pressure on the current density profile

Several tests were performed to the variation of the current density profile with the background pressure. Fig. 6 shows the comparison of current density profiles from simulations run with two different background pressure values.

Analyzing the figure it can be seen that, as expected, the current density values increase with the increase of pressure and that the greatest increase occurs for big angles. When comparing to the experimental data from Manzella and Sankovic [8], the ion density increase is bigger than the expected. The justification for this fact is that in the SPIS software the initial population is unchanged and slow particles are created (instead of changing the properties of the initial particles). This leads to an increase of the total number of particles, which does not correspond to the reality and which also increases the values of current density around the thruster.

The ion thruster model

The T5 thruster parameters were used in order to validate the plasma thruster plume model for the ion thruster. Similar parameters to the ones used for the SPT100 model were taken into account: a 50mm outer radius, a total thrust of 18mN, a mass flow rate of
0.677mg/s, 5% of Xe$^{2+}$ ions and an ionization efficiency of 77.6%. Since no inner angle exists for this thruster only the outer angle was used with the value of 12°. The Gaussian parameter FWHM used for Eq. (8) was 0.35. The duration of simulations presented here was 6ms and a background pressure of $3 \times 10^{-4}$ Pa was used. Fig. 7 plots the results of the ion density profile measured along a line parallel to the thruster at several axial distances. For each distance the variation of the ion density with the horizontal distance to thruster axis is plotted. The plot on the left presents the simulations results obtained with the SPIS software and on the right is presented the experimental data obtained by de Boer [10]. The article presented the measurements performed with an UK-10 ion thruster, which was the precedent thruster of the T5 thruster and has similar properties.

Analyzing the figure it can be seen that, even though the profile of the curves seems correct, the values obtained for the ion density profile are one order of magnitude higher than the experimental data. Furthermore it can be noticed that for the experimental data, the current density values at distances of 10cm and 15cm to the thruster’s surface of ejection are higher than at 7.5cm, which does not correspond to the simulation results, where the values of current density always decrease with the distance. According to de Boer’s article this is explained by the inward curvature of the thruster’s accelerator grid. The T5 model was implemented in the SPIS software with a cylindrical geometry and the particles were ejected from the surface of the cylinder without any curvature. This difference in the geometry explains why the current density profiles of the three closest curves to the thruster are different from the experimental results.

Figure 7: Simulation results (left) and experimental data (right) of the ion density profile as a function of horizontal distance to the thruster’s axis and axial distance to the T5 thruster.
6 Conclusion

Models of plasma thruster plumes were implemented in the SPIS software along with several developments in order to allow the study of the plasma interaction with a spacecraft. The description of the implemented models was given as well as a comment on the new tools added to the software. All the implementations described will be included in the next version of the SPIS software. Simulations were performed using these models and the results were compared with experimental data for the case of the SPT100 and the T5 thrusters. For the first case the simulations results showed a fairly good agreement with experimental data for angles greater than $10^\circ$ but the model still needs some adjustments in order to get the good values for small angles. Regarding the T5 thruster the ion density profiles obtained with the simulation matched the experimental ones. However the magnitude of values was one order greater than the expected, and the curvature of the thruster’s grid was found to have a big influence on the profiles.

References


