Simulation of plasma plume experiments with Hall Thrusters: on-ground chamber effects on measurements and extrapolation to in-flight situation

IEPC-2019-833

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: This study present the implementation and the validation of an electron cooling model that can be used in plume simulations. This model implemented in SPIS-EP permits to represent the temperature of electron for different point on thruster operation. This model has been compared to dedicated experiments and shows a good agreement with experiments using Faraday cups and Langmuir probes.

Nomenclature

EP	=	Electric Propulsion
FC	=	Faraday Cup
PIC	=	Particle In Cell
R&T	=	Research and technology program
SPIS	=	Spacecraft Plasma Interaction System

I. Introduction

INFLIGHT, it is commonly assumed that the interactions between the plasma from the thrusters and the spacecraft are not directly due to the plasma plume itself. The plume is essentially composed by the directed ions coming from the thruster toward space with a quite small divergence. As the thrusters are not directed to spacecraft components in most of the cases, the plasma does not interact directly with the spacecraft. Nevertheless, a backflow of the plasma is coming from the collisions in the plume (charge exchange, elastic collisions and ionization in the near field). This secondary plasma is less directed and it can be transported by the electrostatic forces created by the electron pressure. This plasma is able to interact with all the surfaces of the spacecraft and can create secondary effects such as surface charging and erosion. These effects could be responsible of lifetime limitation of sub-systems such as solar arrays or are able to create arcing phenomena that can lead to the failure of a sub-system [1].

To be able to prevent these effects, the SPIS (Spacecraft Plasma Interaction System) [2] software has been improved to better model the plume interactions with the spacecraft platform. The surface charging and the erosion phenomena on the spacecraft are dependent on the properties of this plasma. The erosion is directly related to the energy and the incidence angle of the ions in the backflow coming from charge exchange (CEX ions). The CEX ion energy is directly depending of the plasma potential in the plume that is proportional to the electron temperature. In the new version, an improved electron model has been implemented (based on physical assumptions) in order to model the electron cooling effect in the plume [3]. To complete the physical model plume spacecraft interaction, a

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cathode model has been developed. It permits to simulate the floating potential of the thruster and the plume consistently with the current balance to the spacecraft and to the environment (or to the vacuum chamber walls).

In addition to the phenomena occurring inside the plume inflight (in vacuum), some effects are specially presents and dominant inside a vacuum chamber. It is well known that the residual neutrals that are not pumped have an influence on the measurements made in the backflow. We will show that it is important to model this residual pressure to be able to analyze the results of the measurements. We will present how the backflow plasma is affected by the pumping efficiency and location of the cooled walls and the pumps inside the chamber. We will present the maps of residual neutral pressure inside the chamber and how it affects the measurements of current at large angle and the plasma properties along the axis [4]. We demonstrate that, in some cases, the local neutral density and the electron temperature, even small, are locally sufficient to create ionization far inside the chamber. In some case, this ionization dominates the effect of charge exchange and elastic collision of ions in the backflow. In a second part, we selected different cases representing a SPT100 operating at different working points in the ESA chamber CORONA. These results will be compared to the results obtained during a dedicated experimental campaign that permits to measure the plasma parameters such as the ion current, the plasma density and temperature at different location in the plume. In the last part, we will present an extrapolation of these measurements to the situation inflight and the consequences of the backflow modeling on the erosion on the spacecraft solar arrays.

II. Plasma plume modelling

A. Chamber geometry

The simulation geometry is decomposed in different zones. The vacuum tank by itself which is composed by two tanks that are connected (the principal tank and the secondary tank in which the thruster can be retracted). The pumping zone is at the opposite side of the thruster. We consider that the pumping zone is composed by the pumping connection itself plus the cold zones around it. The thruster zone is composed by the surfaces of the ion injection plus the body of the thruster. The cathode is not geometrically modelled. The geometry obtained is shown in the following figure.

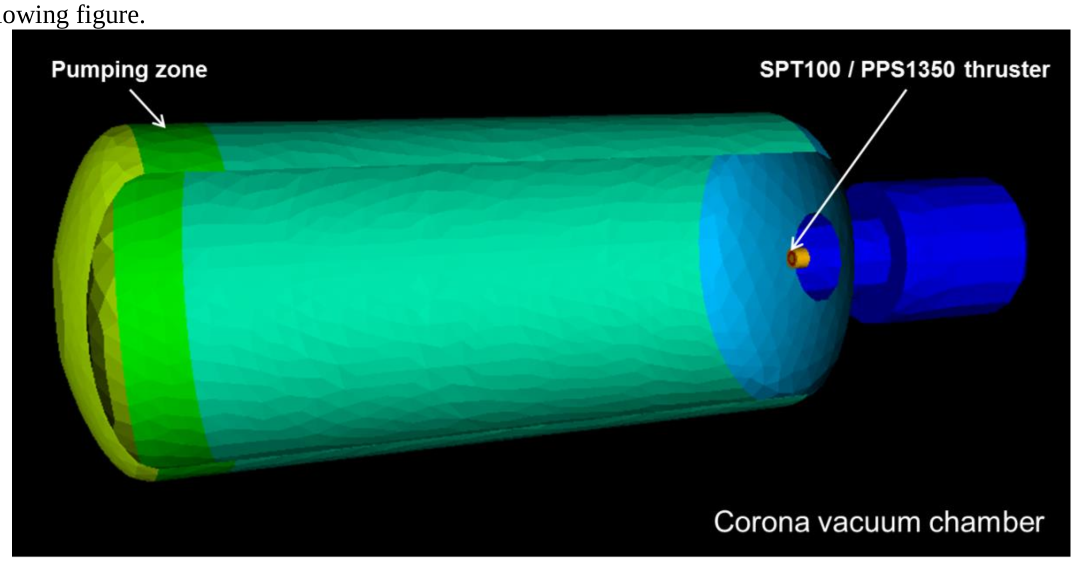


Figure 1 : Corona vacuum chamber representation with pumping and cooling zones

B. Populations definition

The thruster source definition is the basis of a plume simulation definition. It means the definition of the heavy particle (not the electrons that are considered in the cathode model) boundary condition. As we model the source of xenon neutrals and ions as a kinetic approach, we only have to define the injection flux and distribution functions of each particle type.

In the present paper, all the thruster source conditions are defined by four populations:

- One Maxwellian population of neutral xenon Xe
- Two Maxwellian populations of singly ionized xenon Xe+
- One Maxwellian population of doubly ionized xenon Xe++

These four populations are defined with different parameters depending on the operation case simulated in this paper. The configuration cases are defined as follow:

Case	ID	1	2	3	4	5	6
	Name	150V _2mg	225V _2mg	300V _2mg	400V _2mg	150V_4 mg	300V_4 mg
	Operating voltage [V]	150	225	300	400	150	300
	Xe mass flow rate [mg/s]	2	2	2	2	4	4

Table 1 : Cases definitions

From these inputs concerning the thruster configuration, we suppose that the current to inject are depending from two parameters:

- The ionization fraction: quantity of the mass flow that is ionized at least one time (singly plus doubly ionization)
- The doubly ionized xenon fraction: the quantity of Xe++ ion with respect of the total ionized population
- The calculations of the current and mass flow coming with these assumptions are reported in the following tab. We suppose that the ionization fraction is the same for all the configurations because we have no data to do better. The ionization ratio is supposed to increase with the operating voltage. The higher the voltage, the higher the ionization efficiency is.

Nevertheless, these input data are not sufficient to define the particle boundary conditions; we have also to define the velocity distribution functions of each population. In order to extract these parameters, we have used the Faraday Cup measurement done in the frame of the current project to obtain these values. We use the high Mac part of the distribution (M > 2, that we observe for angles lower than 25°) and a deconvolution tool, the results are report in the next table that contain all the population parameters that we use in SPIS.

Case	ID	1	2	3	4	5	6
Xe currents and flux	*Ionization fraction*	*0.7*	*0.85*	*0.9*	*0.95*	*0.7*	*0.95*
	Xe++ fraction [-]	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*	*0.1*
	Xe neutrals flux [kg/s]	6.0E-07	3.0E-07	2.0E-07	1.0E-07	1.2E-06	2.0E-07
	Xe+ current [A]	0.916	1.113	1.178	1.244	1.833	2.487
	Xe++ current [A]	0.204	0.247	0.262	0.276	0.407	0.553
	Total current [A]	1.120	1.360	1.440	1.520	2.240	3.040

Table 2 : Population characteristics

C. Cathode model

The model proposed in the previous section was based on the assumption of the quasi-neutrality. Even if this assumption is verified in a pure plume model, this assumption is no longer valid in case of interaction of the plume with the spacecraft. In particular, it requires describing the sheath that appears by the interaction of the plasma and the SC surfaces, and the space-charged zones created by the solar array (back faces with respect to the thruster side). A solution to generalize the quasi-neutral model to a non-quasineutral one is to allow a deviation from the quasi-neutrality in the models.

The generalized model can be written as follow. In a first approximation, it can be supposed that the electron density to deviate locally from the quasi neutral approximation

$$n_e = n_{e,qn} + \delta n_e$$

Then, solving the linearized Poisson equation one obtains:

$$e(n_e - n_{e,qn})/\varepsilon_0 = \Delta V \sim (V - V_{qn} - V_{ref})/\lambda_D^2$$
$$n_e/n_{e,qn} = 1 + (n_e/n_{e,qn})e\,(V - V_{qn} - V_{ref})/kT_{e,qn}$$
$$n_e = n_{e,qn} \exp(e(V - V_{qn} - V_{ref})/kT_{e,qn})$$

Where k is the Boltzmann constant.

In this model, $n_{e,qn}$, V_{qn} and $T_{e,qn}$ are the solution of the quasi-neutral problem and are function of the ion density exclusively, and not on the electron density. V_{ref} is the reference potential of the electron population. It can be the potential of the exit surface of the cathode.

The exact expression of the quasi-neutral model depends on the selected model. Some of these models (that are implemented in SPIS) are described in the next sections. All of these models derive from the same approximations. These models are based on the quasi neutral approximation in which the quasi-neutral electron density equals the ion density:

$$n_{e,qn} = n_{i.}$$

Since there is no net charge, the electric potential balances the thermal pressure forces:

$$q\, dV_{qn} = k/n_{e,qn}\, dn_{e,qn} T_{e,qn}$$

Note that the electron temperature $T_{e,qn}$ can depend on the quasi-neutral electron density. Typically, such dependence is given by a polytropic index. We note hereafter f the function giving the temperature from the quasi-neutral electron density.

$$T_{e,qn} = f(n_{e,qn})$$

The mathematical form of the above equation is exactly the same as that of the usual Poisson-Boltzmann distribution, except that the reference density temperature and potential of the distribution are local and not global and that they may vary in time. Except for the additional constraints it imposes to the Poisson solver in term of preconditioning to converge, this equation can be solved using the exact same solver than the usual Poisson equation. Contrary to the pure quasi-neutral case, it is possible to simulate non-neutral sheaths close to polarized surfaces with this model. Another interest of this model is that the electron density tends naturally towards zero without requiring infinite potentials. Thus, it becomes possible to couple the cathode electrons with the environment.

The SPT100 cathode model is used for these paper. The influence of the electron modelis not discussed in this report This model derives from the polytropic model but using the possibility to define a tabulated function of gamma as a function of the plasma density. The fit is obtained by using the definition of the polytropic coefficient in 5 zones:

1) $\frac{n_e}{n_{e,ref}} > 1,\ \gamma_1 = 1.4$
2) $1 > \frac{n_e}{n_{e,ref}} > 0.1,\ \gamma_2 = 1.15$
3) $0.1 > \frac{n_e}{n_{e,ref}} > 10^{-3},\ \gamma_3 = 1.4$
4) $10^{-3} > \frac{n_e}{n_{e,ref}} > 10^{-4},\ \gamma_4 = 1.25$
5) $10^{-4} > \frac{n_e}{n_{e,ref}} > 1,\ \gamma_5 = 1$

It gives a quite good approximation as it can be seen below:

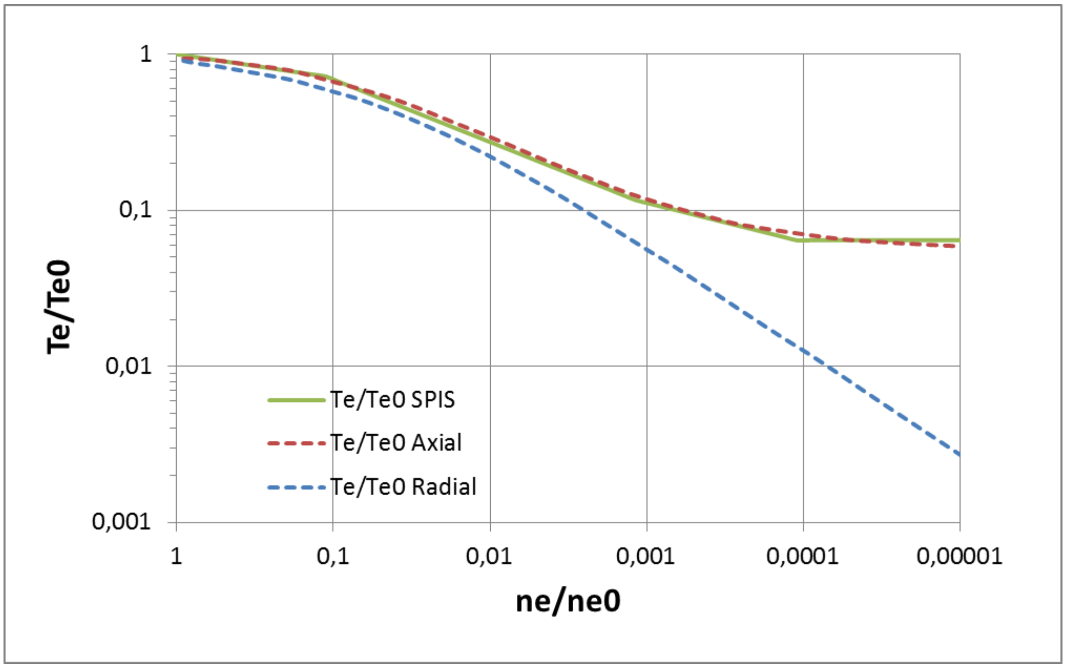


Figure 2 : Fitting of the electron temperature law as a function of the plasma density

For all the cases, the cathode is supposed to be electrically floating with a capacitance in order of 1mF.

D. Neutrals transport model

Two population of neutral are present in the simulations. The neutrals coming directly (not ionized) from the thruster as defined previously. The neutrals that are coming from the neutralization (recombination) of the ions impinging a tank wall. We call this population the "Pumping neutral" as they are neutral that should be avoided with a "perfect" pumping system. These both populations are considered by a kinetic approach.

E. Collisions and surface interactions

Different collisions are taken into account in the volumes and at the surfaces. In the volume, the simulations take into account. The charge exchanges collisions between Xe+ and Xe, and Xe++ and Xe; The elastic collisions between Xe+ and Xe; The ionization of both populations of Xe by the cathode electron population

The surface interactions are the neutralization of ions, the thermalization of all the population at the tank walls temperature (300 K everywhere except in the pumping zone 40 K) ant the loss of particle by pumping (definition of a pumping efficiency).

F. Electric circuit

All the tank walls are electrically connected at the ground. The thruster is electrically floating with respect to the ground with a capacitance of 1mF.

G. Faraday cup model

A Faraday Cup model has been developed in SPIS in order to compare the simulation results to the experimental measurements. By definition, a Faraday cup is an instrument that measures a directed current (in this case of ions) on a localization. A Faraday cup is thus defined by its location, its cross section and its orientation direction. In the frame of this study, the Faraday Cups has been placed on a rotating arm to have an angular measurement of the ion current density.

In order to get all the rotation angle in one simulation, the model in SPIS defines a hemispheric shell (by a center and a radius) where the macroparticle are detected during the simulation. It mimics the measurement done by a FC on a rotating arm but some assumptions are done. First, the current is not influenced by the probe potential. Second, there is no cross effect between the different probes

III. Plume simulation results

In this section, the plasma plume simulation results for the case 6 at 300V and 4mg/s are presented. We separate the effect of the plasma tank from the plasma present in an in-flight situation.

A. Thruster particle source

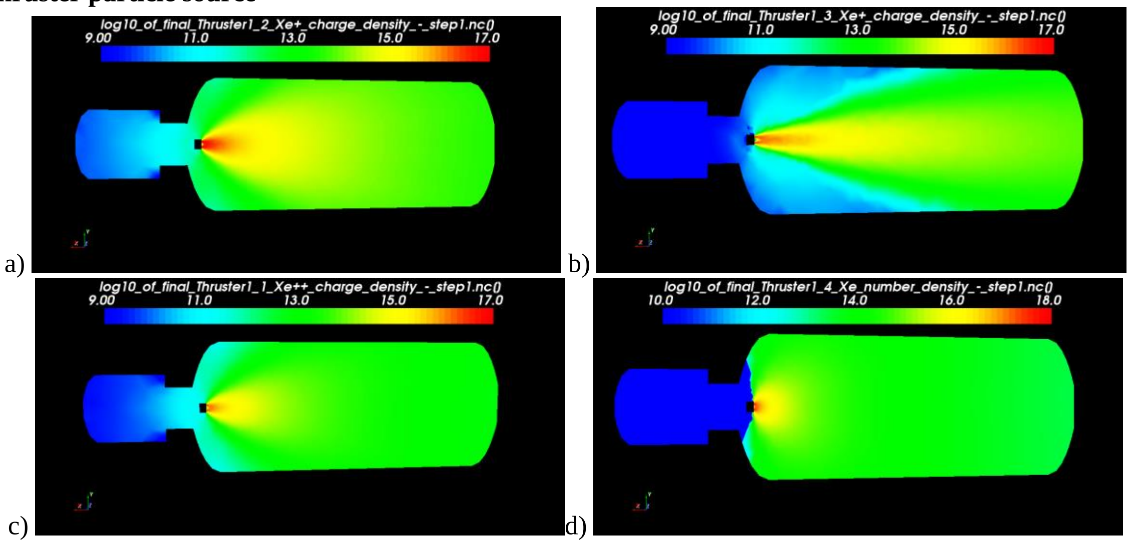
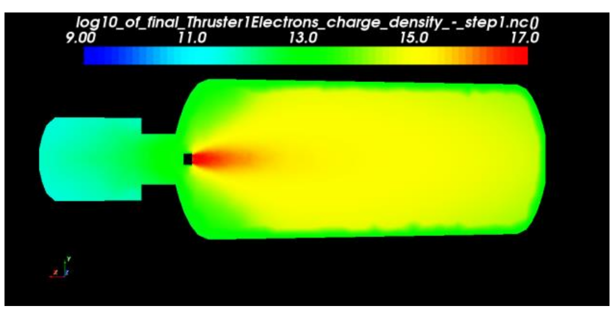


Figure 3 : Density of the primary plasma coming from the thruster at the stationary state for the case n°6 at 300 V and 4 mg/s: a) Xe+ (low Mach number M = 4 b) Xe+ (high Mach number M = 14) c) Xe++ (low Mach number M = 4) and d) Xe (low Mach number M = 0.5)

The primary plasma is presented on the Fig. 3. We can see that different populations with different Mach numbers compose the simulation. The use of an high Mach number and a low Mac number is due to the fact the ions population does not come from the same location inside the thruster. The high Mach population is coming from the ionization zone and is accelerated without any collisions. The low Mach population are ions created after an charge exchange collision inside the thruster.

B. Cathode electrons and potentials

In the Fig. 4; the temperature, the density and the polytropic coefficient of the electron population are represented. At measure of the electron density decreases, the electron temperature also decreases. The polytropic coefficient varies from 1.4 in the near field of the thruster to 1.3 in the far field. A minimum of 1.2 is observed at a distance of 50 cm from the thruster.

a)


b)
c)

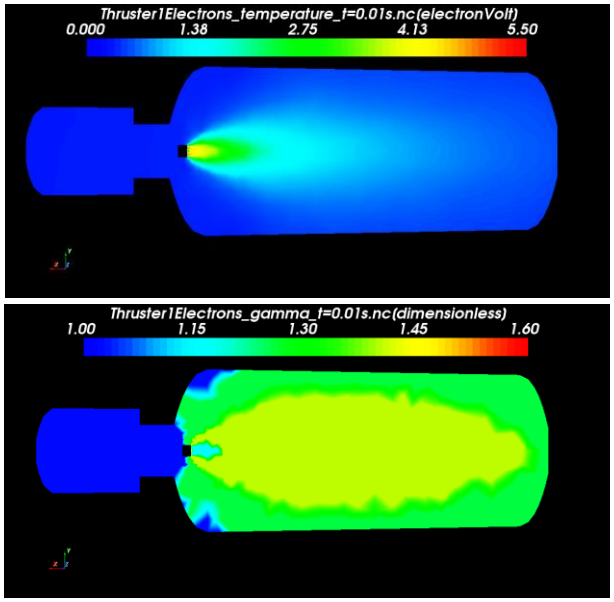


Figure 4 : Electrons (polytropic law) coming from the thruster at the stationary state for the case n°6 at 300 V and 4 mg/s: a) Density, b) temperature and c) polytropic coefficient

The consequence of this temperature decrease is that the potential decrease is lower along the axis. On Fig. 5, the potential map is presented. We can see that a sharp decrease of potential is observed in the near field where the electron temperatures are high. Than, in the far field, the potential is flatten. The potential difference between the cathode reference potential and the tank ground is 22 V.

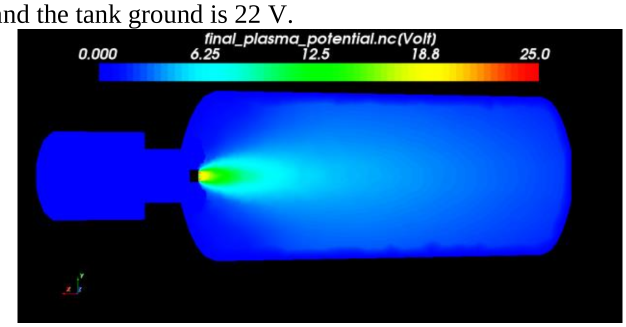
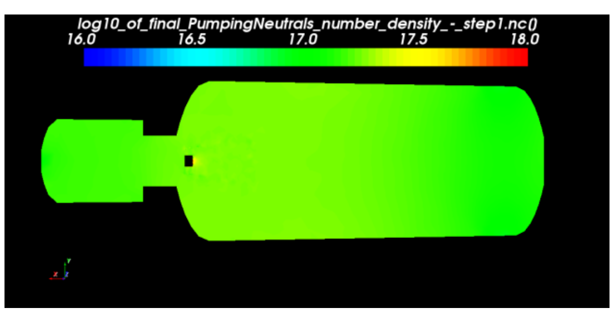


Figure 5 : Electric potential at the stationary state for the case n°6 at 300 V and 4 mg/s

C. On ground tests effects

At the difference of an in-flight situation, on ground, a residual neutral density exists. This population is composed by ions thermalized at walls and not pumped by the pumping system. In Fig. 6, we can see that the density of this neutral population is almost homogeneous (a bit lower near the pumping system). This population makes a residual neutral pressure around 10^{-5} mbar.

a)



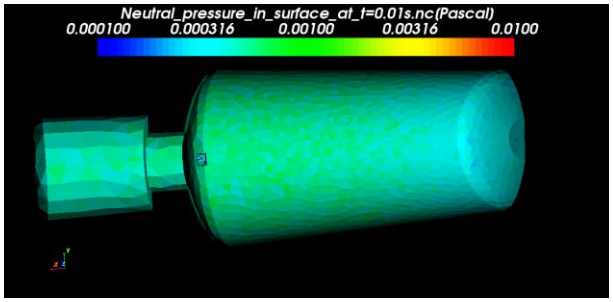
b) 

Figure 6 : a) Density of the residual neutrals not pumped and coming from the thermalization and the neutralization an b) Neutral pressure (excluded plasma charged species) at walls at the stationary state for the case n°6 at 300 V and 4 mg/s

This residual population makes the plasma in the plume is collisional. We can see in Fig. 7 that the charge exchange population create in the plume is quite important. But this population is not the dominant secondary population in the plume. At such a pressure and with such electron temperatures, the ionization in the plume has to be considered. In this figure, we can see that the density of the population create by ionization is one order of magnitude higher than the charge exchange population.

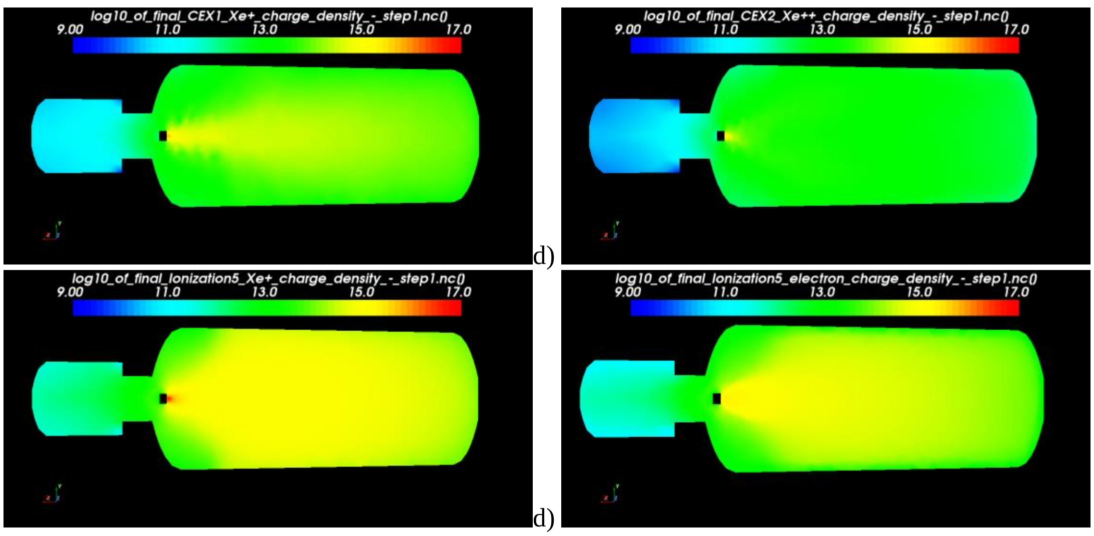


Figure 7 : Secondary plasma particles created inside the plume at the stationary state for the case n°6 at 300 V and 4 mg/s: a) Density of the charge exchanged ions Xe+ b) Density of the charge exchanged ions Xe++ c) Density of the ions created by ionization and d) Density of the electrons created by ionization

IV. Comparison to experiments

The secondary populations have a quite high influence on the measurement made by Faraday cups or by Langmuir probes.

A. Faraday cup

On Fig. 8, the simulation results are compares to Faraday cup measurements. We can observe the good agreement between simulations and experiments. It also shows that the pumping efficiency (and then the background pressure) has a big effect on the measurements at angle greater than 300. The ionization dominates at large angles and the CEX population is not important in that case. The best results agreement is obtained for a pumping efficiency of 0.05.

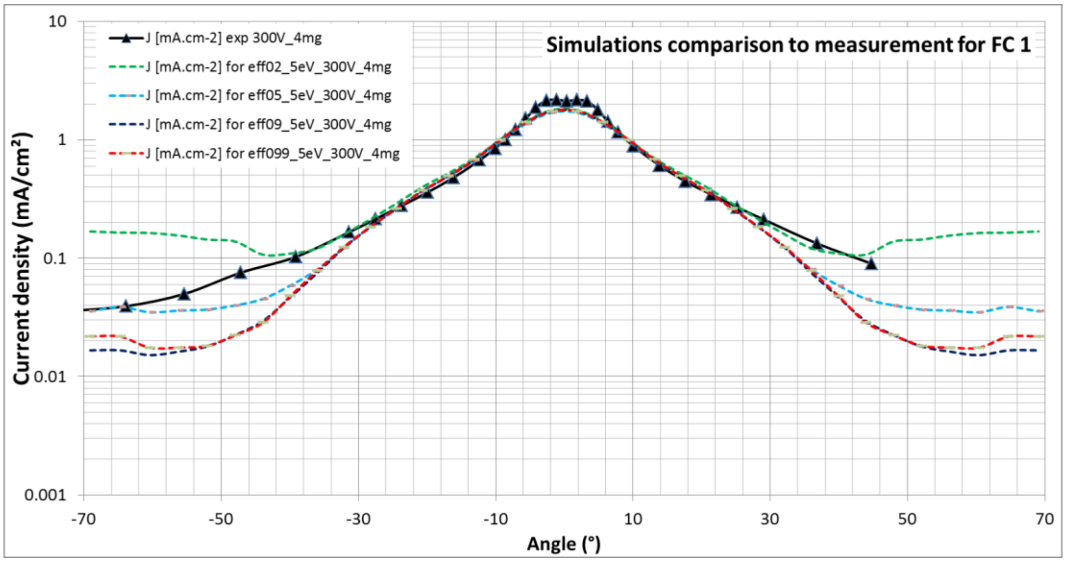
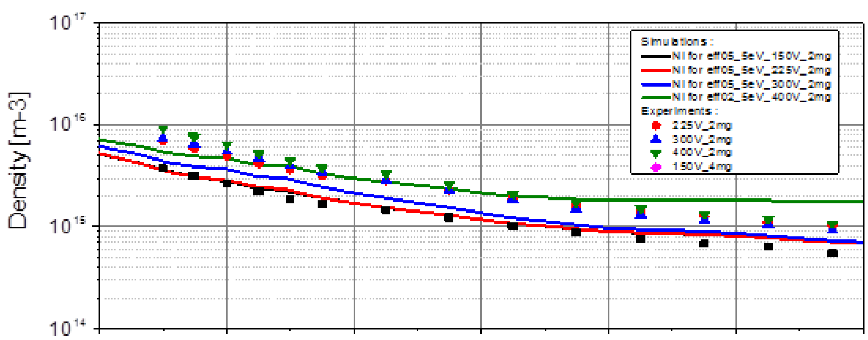


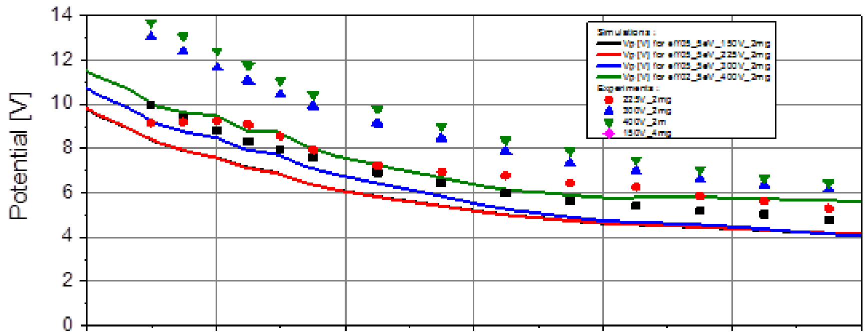
Figure 8 : Comparison of simulation results for different pumping efficiency (ie background pressure) to experimental measurement of current density by the Faraday cup 1 at the stationary state for the case n°6 at 300 V and 4 mg/s

B. Langmuir probes

On Fig. 9, the Langmuir probes measurements results are compared to the simulation results. Whatever the functioning point, a good agreement is observed for the density and the temperature. The comparison of the potential is a bit more difficult and the agreement is less good. It is due to the fact that the Langmuir probes do not measure the local potential but also the floating potential. The difference between the floating potential and the local potential depend on the ion mass and essentially on the electron temperature. Thus it is normal that the discrepancy between measurements and simulation decreases along the axis at measure the electron temperature decreases.



a)



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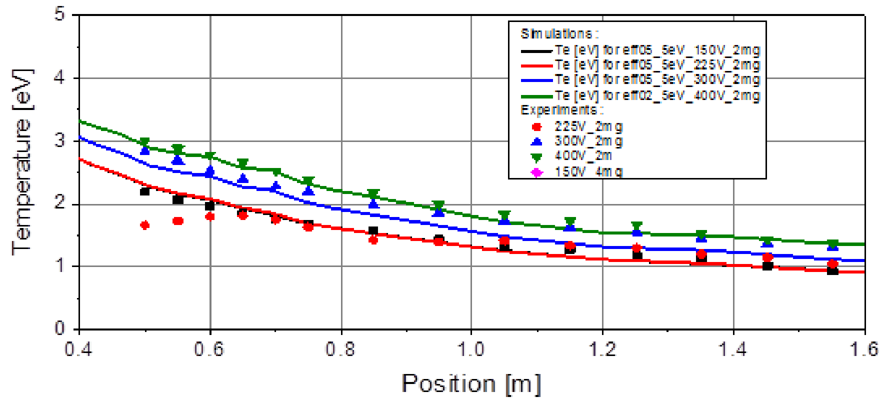

c)

Figure 9 : Comparison of simulation results of electron a) density, b) potential and c) temperature along axis to experimental measurement by Langmuir probe

V. Conclusion

This study has permitted to validate an electron cooling model that can be used in plume simulations. This model permits to represent the temperature of electron for different point on thruster operation. This model has been compared to dedicated experiments and shows a good agreement with experiments.

VI. Acknowledgements

This work has been supported by ESA project 4000116180/15/NL/PS, "Model and experimental validation of spacecraft-thruster interactions (erosion) for electric propulsion thruster plumes" and Onera R&T program.

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