NUMERICAL STUDY OF ION THRUSTER PLUME - SPACECRAFT INTERACTIONS

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Abstract

An axisymmetric model of the plume and backflow contamination from an ion thruster based on the plasma hybrid particle-in-cell (PIC) technique is presented. Components included are primary beam ions, thermal propellant ions created mainly by charge-exchange (CEX) collisions between primary beam ions and neutral propellant, non-propellant efflux (NPE) sputtered from thruster components, and neutralizing electrons. Simulation results of plume properties such as ion density and ion flow angle are compared with experimental data, and scaling relationships for the backflowing contamination as a function of thruster operating conditions are presented.

Nomenclature

- $A_g$: sputtered grid area, m²
- $A_n$: grid neutral flow through area, m²
- $C$: neutral average value speed, m/s
- CEX: charge exchange (ions)
- $I_b$: thruster beam ion current, A
- $N_{ces}$: CEX ion production rate, #/m³/s
- $Q_e$: electron heating term, W/m³
- $R_C$: radius of curvature of grids, m
- $T_e$: electron temperature, °K
- $T_w$: wall temperature of neutrals, °K
- $\epsilon$: electron charge, C
- $J_{bi}$: beam ion current density, A/m²
- $k$: Boltzmann's constant (MKS)

- $m_e,i$: electron, ion mass, kg
- $m_T$: thruster total mass flow rate, kg/s
- $n_{bi}$: beam ion density, m⁻³
- $n_{i-e,n}$: total ion, electron, neutral density, m⁻³
- $\rho_e$: electron pressure, N/m²
- $r_T$: thruster radius, m
- $v_{bi,e}$: beam ion, electron drift velocity, m/s
- $M$: molecular weight, kg/mole
- $N_A$: Avogadro's number
- $\Phi_b$: beam acceleration voltage, V
- $\Gamma_s$: sputtered grid material flux, #/m²s
- $\chi$: CEX ion production scaling factor
- $\alpha$: beam divergence angle, radians
- $\eta_p$: propellant utilization efficiency
- $\phi$: electric potential, V
- $\kappa_e$: electron thermal conductivity, W/m°K
- $\sigma_{ces}$: CEX cross-section, m²

I. Introduction

The potential problems of spacecraft contamination by the effluents of electric propulsion (EP) thrusters have been known for some time [1, 2]. However, ground-based experiments produce estimates of thruster contamination that is questionable due to vacuum chamber facility effects such as chamber wall sputtering and the presence of residual chamber gases. The prediction of backflow contamination is of increasing importance now that EP is earnestly being considered for a variety of applications, including station keeping on commercial geostationary communications satellites [3]. Among the various types of EP thrusters, ion thrusters have reached a relatively high state of maturity, and thus have received much attention in regards to spacecraft contamination and integration issues.

The model presented in this paper addresses two important issues dealing with ion thruster backflow.
One issue associated with ion thrusters is that complete ionization is not achieved with reasonable levels of power, and hence, neutral propellant is emitted at thermal speeds. We are interested in these slow neutrals because they undergo CEX collisions with the fast beam ions producing fast neutrals and slow ions which can be influenced by local electric fields in the plume. Slow ions can also be produced by electron impact ionization if the electron temperature is sufficiently high, but CEX is generally the dominant collisional process. The electric field structure in the plume, as seen in experiments is radial, and hence the slow propellant ions are pushed out of the beam and move back towards the spacecraft. These ions, typically xenon, do not pose a serious contamination hazard unless spacecraft surfaces are extremely cold. However, they can present a current drain to biased surfaces. More importantly, is the second issue that the grids of ion thrusters are bombarded by some of these propellant CEX ions, causing erosion. Hence, molybdenum, a common grid material, is sputtered into the plume. A fraction of the sputtered grid atoms becomes charged, and flows back towards the spacecraft creating a potentially serious contamination hazard due to the low vapor pressure of these metals. For spacecraft designers and integrators, it is important to have models for plume backflow and to understand how these contaminating species behave as a function of thruster operating conditions.

The outline of this paper is as follows. Section II presents the physical model of the ion thruster plume and the effluents. This model is incorporated into a numerical simulation which is discussed in Section III. In Section IV, the model is compared with experimental data, and other results regarding the physics of the plume expansion are presented and discussed. Lastly, conclusions are offered in Section V.

II. Physical Model

The ion thruster plume and backflow contamination model used in this study, accounts for the five major thruster effluents: 1) fast (>10 km/s) propellant beam ions that provide the thrust, 2) ionized propellant neutrals with thermal energies that flow from both the discharge chamber and the neutralizer, 3) slow (initially thermal) propellant ions created predominantly from charge-exchange (CEX) collisions between the beam ions and neutrals, 4) non-propellant efflux (NPE) that consists mainly of eroded grid material, typically molybdenum, of which a fraction is charged due to either CEX or electron bombardment ionization, and 5) electrons. We will consider each of these species below summarizing from (4.5). The focus of our model is the production of propellant and NPE ions within the beam, and their transport outward.

2.1. Beam Ions

The thruster grid is assumed to be a spherical segment of radius \( r_T \) (convex side downstream), with the velocities of the beam ions normal to the surface. Hence, the ions appear to be leaving a point source located at the radius of curvature of the grids, a distance \( R_c \) behind the thruster exit plane. The velocity of the singly-charged beam ions of mass \( m_i \) is expressed as, \( v_{bi} = \left( \frac{2e\Phi}{mv_i^2} \right)^{1/2} \). The radial current density profile of the collimated beam ions (given in spherical polar coordinates \( (R, \theta) \)) for simplicity) is taken to be approximated by a parabolic axisymmetric profile given by,

\[
\dot{j}_{bi}(R, \theta) = e v_{bi} n_{bio} \left( \frac{R_c}{R} \right)^2 \left( 1 - \frac{\theta^2}{\alpha^2} \right)
\]

which is a good approximation for modern thrusters. This parabolic profile in the core of the beam is smoothed at the edges with an exponential decay. Given the beam ion current density, the beam ion density is then determined by,

\[
n_{bi}(r,z) = \frac{\dot{j}_{bi}(r,z)}{e v_{bi}}
\]

The effect of doubly ionized ions is neglected since their density, depending on thruster operating conditions, is at most, an order of magnitude less than the singly charged ions.

2.2. Neutral Model

The propellant that remains unionized in the thruster effuses out from the discharge chamber, and exits through the grids in free-molecular flow with a temperature close to that of the thruster discharge chamber walls, typically around 500 K for thrusters using xenon. The average neutral density right at the thruster grids, is determined from the beam ion current and the propellant utilization efficiency by the relation,

\[
n_{no} = \frac{4 I_b}{e C A_n} \left( \frac{1 - \eta_p}{\eta_p} \right)
\]

where \( C \) is the mean thermal speed given by, \( \left( \frac{8kT_n}{\pi m_i} \right)^{1/2} \). The propellant utilization efficiency is based on the total neutral flow rate (discharge + neutralizer),

\[
\eta_p = \frac{I_b/m_T}{e}
\]

The neutral density field is modelled as the flow from a single point source that is located one thruster radius behind the exit plane of the grids. The neutral gas density is given by,
modelled as a local Boltzmann distribution with a computational domain. Neutral molybdenum can become ionized via sputtered flux by the most probable ejection speed. The production rate within the plume. At steady-state, the molybdenum is found to be close to a Maxwellian speed becomes constant. i.e. the loss of particles at the efflux rate of time r. then the average flux is. density is much smaller than the propellant plasma density. Given an amount of mass M lost over a period of time τ, then the average flux is,

\[ \Gamma_s = \frac{M}{\tau A_s} \frac{N_A}{M} \] (8)

The spatial distribution of the sputtered neutrals is assumed to be a cosine distribution as described by Eqn. (5). The measured ejection energy distribution of molybdenum is found to be close to a Maxwellian speed distribution, and the density is found by dividing the sputtered flux by the most probable ejection speed. The neutral molybdenum can become ionized via CEX and electron impact ionization collisions - the latter which are important at electron temperatures above 1.5 eV.

2.5. Electrons

The electrons emitted from the neutralizer are modelled as a local Boltzmann distribution with a spatially varying temperature, \( T_e(x) \).

\[ n_e(x) = n_{e_0} \exp \left( \frac{e \phi(x)}{k T_e(x)} \right) \] (9)

The electron temperature is determined by solving the electron energy equation,

\[ \frac{3}{2} n_e v_e \nabla kT_e + p_e \nabla \cdot v_e = -\nabla \cdot q_e + Q_e \] (10)

where \( q_e = -k_e \nabla T_e \) is the conductive heat flux, and \( p_e = n_e kT_e \). The electron heating term, \( Q_e \), is due to collisional transfer and ohmic heating. Inside the beam, the electron drift velocity is taken to be the beam ion velocity, and zero outside. The electrons, as well as the ions, are unmagnetized in the model.

III. Numerical Methods

Figure 1 shows a schematic of the general computational domain which includes a model spacecraft with optional solar array panels. Typical axisymmetric domain sizes are 1-3 meters. All surfaces of the spacecraft are biased - either at fixed potentials, or they are allowed to float as a single isolated conductor. An optional plume shield can be included to investigate its effect on reducing the backflow. The beam ion and neutral propellant models developed give the beam properties in the region of the plume, and the volumetric CEX propellant ion production model is used to determine the number of propellant CEX ions that are created per unit time per unit volume within the plume. To model the expansion of the CEX ions, a hybrid electrostatic plasma particle-in-cell (PIC) technique is employed [7]. The PIC method follows the propellant CEX ions under the influence of self-consistent electric fields as they are transported out of the beam and form a plasma cloud that surrounds the spacecraft. The NPE ions are also created volumetrically - either by CEX or ionization at higher electron temperatures. However, since the NPE ion density is much smaller than the propellant plasma densities, the effect on the potential is negligible. Hence, the NPE plasma propagation is determined solely by ion tracking in the potential determined from the propellant CEX expansion.

The simulation is run until steady-state is achieved when the number of particles within the domain becomes constant, i.e. the loss of particles at the boundaries and spacecraft surfaces balances the production rate within the plume. At steady-state, the current backflowing to biased spacecraft surfaces due to propellant CEX and NPE ions can be computed, and assessments of surface deposition can be made. In this work, the surfaces are assumed to be absorbing. The nonlinear Poisson equation for the potential, and the nonlinear electron temperature equation which is strongly elliptic, are both solved throughout the computational domain. The far right, top, and far left
upper boundaries shown in Figure 1 are left open to space, although potentials can be fixed to simulate a ground testing chamber. At the thruster front, the electron temperature is fixed based on experimental measurements. The lower boundary of the domain in front of the spacecraft is the plume centerline; particles that reach this boundary are reflected. A uniform background plasma density is assumed. Since the thruster produced plasma environment is orders of magnitude larger than the ambient, we ignore the dynamics of the background plasma over the length scales of interest.

IV. Results

4.1. CEX Ion Density

The propellant CEX flowfield of a 30 cm beam diameter 900-series Hughes mercury ion thruster was investigated in two different experiments by Carruth and Brady (C-B) [8] and Carruth, Gabriel, and Kitamura (C-G-K) [9].

In the C-G-K experiments, the beam current was 1 A, with a propellant utilization efficiency of 0.95. The screen potential of the thruster was fixed at 1100 V, yielding a beam ion velocity of 32.525 m/s. From other measurements [10] the electron temperature in the beam ranged from 0.2 to 1 eV, thus the electron temperature at the thruster exit was fixed at 1 eV. Based on the experimental measurements, a uniform plasma background of $10^{13}$ m$^{-3}$ was imposed in the simulations. The plasma density at a radial distance of 48 cm was measured from 30 cm in front of the thruster to about 40 cm behind the thruster. Figure 2 shows the data points, along with model calculations at $r=47$ cm for both variable and constant temperature models. It can be seen that there is very good agreement between model and experiment, with the constant temperature model giving slightly higher values. Differences between the temperature models have been discussed elsewhere [5].

4.2. CEX Plasma Flow Angle

Based on the CEX ion velocities, CEX plasma flow direction vectors can be mapped out. Figure 3 shows the computed CEX ion current density vector flowfield, with the vectors normalized so that only direction is indicated, and not magnitude. CEX ions that are created in the beam near the centerline do not see a strong radial electric field, and hence they are carried downstream by the axial potential gradient in the beam. However, as they move farther out radially in the beam, the radial potential gradient starts to turn the CEX ions towards the beam edge, and as shown in Figure 4, the CEX ions reach the beam edge, and leave completely radially. Outside of the beam, at and behind the thruster exit plane, the electric fields turn the CEX ions towards the backflow direction. Also, it can be seen that CEX ions that are close to the top edge of the thruster body are turned back the most, and some are even pulled down toward the thruster body top. In addition, CEX ions are shown to be directly attracted back to the negatively biased accelerator grid, which constitutes the grid impingement current.

Figure 4 shows a vector plot of the self-consistent electric field, normalized so that only direction is indicated. A comparison of Figures 3 and 4 clearly shows how the CEX ions are influenced by the electric field. Note that the electric field is almost radial at the beam edge even though the beam is divergent, and is axial in the backflow direction 90° above the thruster exit. In addition, the electric fields in the sheaths surrounding the thruster body that serve to accelerate CEX ions to the surfaces can be seen. Above the thruster body for $r<30$ cm, the electric field is noisy due to differentiating the potential which is noisy since the CEX ion density is low in that region.

In the C-B experiments, the CEX plasma flow angles were measured at distances of 48 and 66 cm from the plume centerline. Measurements up to 51 cm in both the up and downstream directions were taken. Experimental error on measurements was assessed to be ±2-5°. We have performed simulations with both variable and isothermal models, and the computed flow angles are shown with experimental data in Figure 5 for a radial distance of 65 cm. The simulation results shown are displaced one cm radially with respect to the experimental data due to the computational grid structure.

In the region behind the thruster exit in Figure 5, which is of most concern for contamination, there is excellent agreement with experiment.

4.3. CEX Plasma Backflow Scalings

The propellant CEX plasma backflow was examined as a function of thruster operating conditions for the NASA 30 cm Xe NSTAR thruster [11] to see how the backflow scaled with thruster parameters. The numerical simulation model is applied to six operating points for both variable and constant temperature cases. The constant temperature model does not involve the solution of the electron energy equation, Eqn. (10), and hence is more computationally efficient for parametric studies. Comparisons with data show that the isothermal model yields higher, more conservative, values for the backflow than the variable temperature model. Ambient conditions appropriate to the LEO environment were used, with a background plasma density of $10^{10}$ m$^{-3}$, an ambient electron temperature of 0.1 eV, and no neutral background pressure. The computational domain was 1 m by 1 m, and the thruster body was taken to be 50 cm long and 20 cm wide (half-width). The beam divergence angle is taken to be 20°, and the neutral propellant grid transparency ratio is
0.24. The spacecraft/thrustor body was assumed to have a floating potential of -1 V, and the beam electron temperature at the thruster exit was set to 5 eV, although only CEX collisions were included. This higher electron temperature will give a more conservative estimate of the backflow.

The backflow current was computed on two planes extending from the top of the thruster body. One is located at the thruster exit plane (plane 1), and another at z=0 (plane 2). The planes are separated by 50 cm, and the radial height of the planes is 80 cm. In Figure 6, the ratio of the computed backflow current on the two planes to the beam current as a function of the thruster operating power is shown.

There is a wide range of thruster operating conditions, (i.e. fb, \eta_p, and \Phi_p), that are covered as the power is throttled from 0.5 kW to 2.3 kW. Kaufman and Carrath [12] proposed a scaling relationship for the CEX propellant ion backflow that is based on the CEX ion production rate which is proportional to the beam ion and neutral densities given by:

\[ N_{\text{ceX}} \cdot I_{\text{bf}} \cdot \frac{1 - \eta_p}{\eta_p} \cdot \sigma_{\text{ceX}}(V_{\text{bf}}) = \chi \]  

(11)

This relationship was validated by applying this scaling factor to the numerical results. In order to do so, given \chi and the backflow current for the first point, the backflow current for any other point \(i\), \(I_{\text{bf}}^i\), is computed by multiplying the backflow current of the first point by \(\chi^i/\chi^1\).

\[ I_{\text{bf}}^i = I_{\text{bf}}^1 \left( \frac{\chi^i}{\chi^1} \right) \]  

(12)

This procedure has been applied, and the results are overlayed on Figure 6, where the 'x' symbols indicate the scaled predictions of the backflow current that have been normalized by the beam current. As an example, with the variable temperature model, the backflow current over plane 1 for the first point is 4.13x10^{-4} A, and \(\chi^1=0.3995\). For the third point, \(\chi^3=0.5459\) and the predicted backflow current is found to be (0.5459/0.3995)(4.13x10^{-4}) = 5.6x10^{-4} A. The numerical result, with the variable temperature model, is 5.3x10^{-4} A, which is very close. Figure 6 demonstrates that this scaling relationship is in good agreement with numerical predictions. From Figure 6, it appears that the ratio of the backflow current to the beam current is almost constant as a function of power. However, it must be pointed out that the propellant utilization efficiency is also changing from (0.71 to 0.89).

It should be expected that these backflow currents scale with the rate of CEX ion production, which is a statement of continuity. However, the structure of the backflow field must be examined as the thruster is throttled through various operating conditions. Figure 7 depicts the CEX plasma density distribution computed with the variable temperature model for all six operating points along an angular arc through the plume 35 cm from a point 10 cm downstream of the thruster exit.

The density has been normalized with the value of the density at the plume centerline (\(\theta=0^\circ\)). Within numerical noise levels of the PIC method, all six cases spanning a power range of a factor of almost five appear to follow the same shape.

4.4. Sputtered NPE Deposition

The backflow of sputtered charged molybdenum from the accel grids was computed based on grid mass loss measurements [11]. In Figure 8, the ratio of the molybdenum to xenon CEX ion current density is shown for thruster conditions of \(I_p=3\ A, \eta_p=0.82\), and \(\Phi_p=1091\ V\). Within the beam, the ratio is about 10^{-4}, however, in the backflow region, it is below 10^{-5}. The important point is that the molybdenum ion distribution is considerably different spatially than the xenon CEX ion distribution. In previous analytical models of molybdenum deposition, the spatial distribution of both species was assumed to be the same, only differing by a constant [12]. This assumption led to higher estimates of the molybdenum deposition and increased concern for spacecraft contamination. However, simulations show that in the backflow region, the molybdenum density is noticeably less. The reason is the higher energy of the molybdenum ions that makes them less likely to turn back towards the spacecraft. The most probable energy of the sputtered molybdenum is about 5 eV, with the average being 15-20 eV. In contrast, the thermal xenon neutrals only have an energy around 0.02 eV (500°K).

An analysis of the trajectories of xenon and molybdenum ions show that the less energetic xenon ions are turned back more than the molybdenum ions. Hence, even in a case of equal Mo* and Xe* production rates, the density of the molybdenum in the backflow area will be less. In addition, the values in Figure 8 show that neglecting the molybdenum ion density in Poisson's equation is a good approximation, since the density is negligible compared to the propellant ion density.

VIII. Conclusions

We have developed a physical and numerical model of the backflow contamination of an ion thruster plume. Detailed models for all the thruster effluents and plume components including the beam ions, neutral propellant, CEX propellant ions, sputtered grid ions, and neutralizing electrons were developed and integrated into a comprehensive numerical model for axisymmetric geometry. Simulation results were compared with experimental data, and comparisons of ion density, electron potential and temperature, and CEX ion flow angle showed good agreement. The model was applied to predict the backflow contamination of the NASA 30
cm xenon ion thruster over an operating envelope of the thruster. The CEX propellant backflow was computed, as well as the deposition of sputtered molybdenum from the thruster grids. A scaling relationship for the propellant CEX ion backflow previously proposed by Kaufman and Carruth was verified and shown to be useful in predicting backflow contamination as a function of thruster operating conditions. The ratio of the xenon propellant to sputtered molybdenum ions was found not to be a constant throughout the backflow region, a commonly used assumption in previous studies. Hence, molybdenum deposition is not as high as previously expected.

What is most important is a modern experimental effort to characterize ion thruster plume backflow of xenon thrusters by using modern diagnostic techniques to provide a complete database of the plume densities, current densities, electron temperatures, and potentials in the backflow regions that can be used to validate plume contamination models. These models will enable spacecraft designers and integrators to more confidently assess, and control if necessary, EP thruster contamination and will thus help EP emerge as a commonly accepted form of spacecraft propulsion.

References

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