Ion Thruster Life Models

Ira Katz,* Ioannis G. Mikellides,† Richard Wirz,‡ John R. Anderson,§ Dan M. Goebel**
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

Many of the missions considered under the Space Vision demand electric propulsion lifetimes that far exceed what has been demonstrated. Some missions for example, such as the recently studied Prometheus 1, require thruster operation life, including margin, in excess of a decade. That length of thruster operations essentially precludes relying exclusively on testing for life validation. A coordinated program of experimental measurement and computer simulation has produced analytical models of several of the most important ion thruster physics and life limiting mechanisms. In this paper we review the most recent 2-D and 3-D plasma simulation models for ion thruster hollow cathodes, discharge chambers, and ion optics.

I. Introduction

Many of the missions considered under the Space Vision demand electric propulsion lifetimes that far exceed what has been demonstrated. Some missions for example, such as the recently studied Prometheus 1, require thruster operation life, including margin, in excess of a decade. That length of thruster operations essentially precludes relying exclusively on testing for life validation. There have been several successful long duration life tests of gridded ion thrusters, most notably the Extended Life Test (ELT) of the NSTAR flight spare thruster, during which the thruster operated for 30,352 hours. The significance of this test was twofold. First, it demonstrated that an ion thruster could operate successfully for years. Second, it provided clear evidence of the mechanisms that, over time, would lead to thruster failure. The identification of these mechanisms combined with first principles based models of the physical processes in an operating thruster that cause these life limiting mechanisms form the basis of the life validation methodology.

The major life limiting mechanisms identified during the ELT post test analysis were accelerator grid erosion, discharge cathode orifice plate erosion, and depletion of the discharge hollow cathode barium impregnated insert. All three mechanisms are controlled by plasma fluxes generated by the normal operation of ion thrusters. There were other issues discovered that could eventually lead to thruster failure, but these three mechanisms operate much more quickly. Accelerator grid aperture erosion prevented thruster operation at maximum power before the test ended, post test examination showed that the discharge cathode orifice plate was almost eroded through, and there was substantial barium depletion in the downstream end of the discharge hollow cathode insert.

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* Group Supervisor, Advanced Propulsion Technology Group, 4800 Oak Grove Drive, Pasadena, CA, 91109, Mail Stop 125-109, Senior Member AIAA.
† Member Technical Staff, Advanced Propulsion Technology Group, 4800 Oak Grove Drive, Pasadena, CA, 91109, Mail Stop 125-109, Member AIAA.
‡ Member Technical Staff, Advanced Propulsion Technology Group, 4800 Oak Grove Drive, Pasadena, CA, 91109, Mail Stop 125-109, Member AIAA.
§ Member Technical Staff, Advanced Propulsion Technology Group, 4800 Oak Grove Drive, Pasadena, CA, 91109, Mail Stop 125-109, Member AIAA.
** Section Staff, Thermal and Propulsion Engineering Section, 4800 Oak Grove Drive, Pasadena, CA, 91109, Mail Stop 125-109, Senior Member AIAA.
The unifying thread among these major life limiting mechanisms is that they all result from plasma fluxes impinging on the hardware. These fluxes of ions and electrons are generated by normal thruster operation. The fundamental purpose of the models below is to calculate these fluxes. Direct measurements of the fluxes in operating thrusters are very difficult due to component dimensions and interference by probes. The computer models also have the advantage of being able to model how the plasma fluxes vary as the thruster ages. Validation of the computer models can be made through comparison with measured plasma parameters measured nearby in the thruster where it may be easier and less intrusive to make the measurements.

II. Overall Modeling Approach

Models need to be validated with laboratory and flight data. The ion thruster models were developed in close coordination with detailed measurements of ion thruster plasmas. It was only through the close interactions between experimentalists and modelers that much of the underlying physics was determined (see Figure 1).

Theoretical models alone not sufficient
Experiments alone not sufficient

Focused efforts combine experiments with theoretical modeling to determine fundamental thruster physics

Figure 1. The models were developed in close coordination with detailed measurements of ion thruster plasmas.

The models of operating thruster plasmas have been developed by relying on a few simplifying assumptions. Without these assumptions, the complexity and run times of the models would have made them impractical. The primary assumption is that we can divide the thruster plasmas into four regions that interact with each other through relatively simple interfaces. The four regions are shown in Figure 2. Region 1 is the discharge hollow cathode insert region. Plasma fluxes in this region heat the insert, impact surface morphology, and are the ultimate cause of one of the major life limiting mechanisms, insert barium depletion. Region 2, the main discharge chamber, is the most complex to model. Ions, electrons, and neutral gas enter this region from the discharge cathode, additional neutral gas enters through a ring injector, electrons and ions are collected on surfaces, and ions and neutral gas exit through the grids. Ions that impinge the discharge cathode surfaces cause keeper and orifice plate erosion, also major life limiting mechanisms. Region 3 is the ion optics, where ions are accelerated out of the discharge chamber. This region of high electric fields contains a non-neutral plasma and limits plasma interactions between the discharge chamber plasma and the exterior plume plasma. Ions generated and accelerated in this third
region cause accelerator grid erosion, the most important life limiting mechanism. Region 4 is the ion beam expansion region, downstream of the accelerator grid. The plasma in this region is quasi-neutral, but its high velocity ions can cause substantial erosion to spacecraft and thruster surfaces. For example, during the ELT ions in this region caused substantial erosion to the neutralizer keeper. The neutralizer cathode insert plasma has the essentially the same physics as the discharge cathode, but operates at substantially reduced currents. As a consequence, the insert temperatures are typically much lower and the life much longer than the discharge cathode.

We have developed computer codes that model each of these regions and an additional code that models the combined discharge cathode insert region, the orifice region, and the near cathode plume region. Two ion optics regions codes have been developed, a 2D and a 3D code. The 2D code models individual beamlet ions, assuming axial symmetry. This is a good approximation for most current densities, and the code is very quick running. It is sufficiently accurate to model accelerator grid barrel erosion and ion optics performance. The 3D code models one twelfth of a single aperture, and is most useful for modeling erosion of the downstream surface of the accelerator grid. All the other codes are 2D and assume axial symmetry.

In all regions, at a minimum, there are codes that model the plasma ion densities and dynamics, neutral gas densities, and electron densities. In the insert region there is also a thermal model that uses the plasma fluxes as input to determine the insert temperature distribution. Described below are the models employed in the Regions 1, 2 and 3, their status, the model validation approach, and how the models will be applied to assess ion thruster life.

Figure 2. Ion thruster regions modeled.
III. Theoretical Models

A. Region 1: Hollow Cathode

1. General Description
A hollow cathode is a device that provides amperes of electrons to ionize electrons (discharge cathode) or neutralize the thrust producing ion beam (neutralizer cathode). Both cathodes share the same design, consisting of a hollow tube capped at the end with a plate with a small orifice. The tube wall immediately upstream of the orifice plate is lined with barium impregnated sintered tungsten that serves as a low work function thermionic electron emitter. Xenon gas flows through the cathode and is partially ionized by electrons from the emitter. The ions both neutralize the spacecharge of the emitted electrons and serve to heat the impregnated tungsten emitter. Electrons, gas, and ions leave the orifice and enter the neighboring discharge chamber or ion beam expansion region.

Figure 3. Top: Hollow cathode emitter region schematic showing the region modeled by IROrCa2D. Bottom: Hollow cathode schematic showing the region modeled by OrCa2D.

Three computational models of the hollow cathode have been developed at JPL: 1) the 2D, time-independent Insert Region of an Orificed Cathode (IROrCa2D) code, 2) the 2D, time-dependent Orificed Cathode (OrCa2D) code and 3) a 2D thermal model. The main motivation for developing IROrCa2D was to identify those mechanisms that affect the life of the emitter. The objective was to develop a theoretical model that predicts the steady-state, two-dimensional distributions of all pertinent plasma properties, including electron and ion fluxes and the sheath potential along the emitter. The
geometrical simplicity of the emitter region (see Figure 3, top) allowed us to focus on accurately
developing and validating the complex physics associated with the neutral and ionized gases in the
presence of electron emission from the insert surface. The absence of time-dependent terms in the plasma
conservation equations, and the neglect of neutral gas dynamics also simplifies the numerical approach,
and reduces the computational times required to attain the steady-state solution.

Although a descendent of IROrCa2D, OrCa2D is a major advancement over IROrCa2D both in the
physics and numerical algorithms. The main motivation behind the development of OrCa2D is the
assessment of keeper erosion and lifetime. Thus, in addition to the insert region, the computational region
in OrCa2D includes the orifice channel and conical regions as well as the keeper and plume regions as
shown in Figure 3 (bottom). The plume region extends up to an anode boundary several centimeters
downstream of the orifice. Since the assumption of a uniform total pressure is not valid in the orifice and
plume regions, OrCa2D includes neutral gas dynamics. Past simulations of the NEXIS insert region using
IROrCa2D suggested that anomalous transport due to oscillations between the heavy species and the local
fields may be responsible for the heating and high potential gradients measured near the orifice and near-
field plume regions. Since IROrCa2D is time-independent with a computational region that ends at the
orifice entrance, it was not possible to assess such mechanisms with that code. Thus, OrCa2D is being
developed to include all time-dependent terms that may be pertinent to ion acoustic and/or ionization
oscillations. By extending the computational region to include the anode boundary and by including
neutral gas dynamics, OrCa2D requires only knowledge of the cathode operating conditions (such as
mass flow rate and discharge current) and emitter temperature, but does not depend on experimental
measurements of any of the plasma properties.

The 2D thermal code uses the ion and electron fluxes from the plasma codes above as input to predict the
temperature distribution in the cathode. A sample problem geometry modeled by the thermal code is
shown in Figure 4. The positive numbers identify different materials, and negative numbers are used to
identify radiative boundary conditions.

Figure 4. An input geometry for the hollow cathode thermal model. The orifice plate is located at the right
of the model.

2. Model Physics
IROrCa2D: The governing conservation laws of IROrCa2D have been derived in detail by Mikellides et
al. The electron and ion momentum equations, in the absence of the inertia terms, are added to yield an
expression for the diffusive ion particle flux, $n u_i$, with $n$ being the plasma density and $u_i$ is the ion
velocity. The ion flux is substituted into the ion continuity law which is solved for the plasma density in
the presence of an ionization rate term $\dot{n}$. The conservation of energy for the electrons yields the electron
temperature $T_e$ (in eV), and includes thermal conduction of the electrons, work done by the electric field
$E \cdot j_e$ (with $j_e$ being the electron current density) and loss of electron energy by ionization (inelastic)
collisions. By assuming that ions and neutrals are in thermal equilibrium, a single equation is used for the

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conservation of energy of the heavy species, to yield the heavy species temperature $T$. Since the neutral dynamics are neglected in IROrCa2D ($u_n=0$), the heating term due to charge-exchange collisions includes only the ion velocity $u_i$. Subtraction of the electron continuity equation $\nabla \cdot (nu_e) = \dot{n}$ from the ion continuity equation yields the statement for the conservation of total current $\nabla \cdot (j_i + j_e) = 0$ which is combined with the electron momentum and $E=-\nabla \phi$ to yield an expression for the plasma potential gradient, which is solved for the plasma potential $\phi$. Assuming uniform total pressure throughout the channel, the neutral particle density is updated using the ideal gas law, $n_n=p_n/kT$, taking into account the partial pressure from electrons and ions. The system, along with appropriate boundary conditions yields the 2D profiles of $n$, $nu_i$, $j_e$, $E$, $T_e$, $T$, $n_e$ and $\phi$. In IROrCa2D both ions and electrons are allowed to penetrate the sheath and be absorbed by the insert region walls. Ions at wall boundaries are assumed to have attained the Bohm velocity and so the ion flux at wall boundaries is prescribed by $nu_i \cdot \hat{n} \approx 0.607 n \sqrt{kT_e/m}$ with $k$ denoting the Boltzmann constant and $m$, the ion mass. The absorbed electron current density follows the one-sided thermal flux assuming Boltzmann electrons. The emitted electron current density from the insert is modeled after the Richardson-Dushman equation for thermionic emission, and includes the effect of the Schottky potential $\phi_{SH}$. The emitter temperature $T_w$ (K) as a function of the emitter length is prescribed as a polynomial fit to measurements. A model improvement proven critical by the NSTAR simulations with IROrCa2D is emission enhancement under high plasma density conditions. This mechanism may be best characterized as “sheath funneling.” In cathodes where the plasma density is high enough that the Debye length becomes smaller than the mean pore radius the sheath can be funneled into the pores thereby enhancing the effective emission area. This increase in area is modeled by assuming that the pores are cylinders with radius $r_p$ and that the sheath penetrates the cylinder a distance $h$ from the pore entrance. The penetration height $h$ is approximated by assuming that the (collisionless) ions enter the pores along straight-line trajectories with an axial velocity component that equals the Bohm speed $\sqrt{kT_e/m}$ and a radial component that equals their thermal speed, $\sqrt{kT_e/m}$.

**OrCa2D**: The system of conservation laws in OrCa2D is listed in Mikellides, et al. As alluded to above, the system includes time-dependent terms in the ion continuity and electron energy laws. Also, both the neutral continuity and momentum equations are included, none of which appear in IROrCa2D system. Time-dependence has not yet been implemented in the ion momentum equation and therefore the expression is almost the same as in IROrCa2D. As in IROrCa2D, the heavy-species energy equation assumes that the ions and neutrals are in thermal equilibrium but the addition of neutral dynamics demands additional terms involving $u_n$ which are included in the OrCa2D system. Several additional boundary condition types are required in OrCa2D compared to IrOrCa2D. The extended computational region in OrCa2D includes the orifice channel walls, keeper walls, free-flow boundaries at the end of the plume region and the anode boundary. The addition of neutral gas dynamics also requires conditions at boundaries that exist in both IROrCa2D and OrCa2D. No changes exist between the two codes for the emitting boundary and conducting wall adjoining the emitter. The reader is referred to Ref. 3 for a detailed description of these boundary conditions, and to Ref. 6 for a description of the added boundary conditions. The numerical advancements made in OrCa2D compared to IROrCa2D are also outlined in Ref. 6.

**2D Thermal Model**: The hollow cathode thermal code models heat conduction and radiation in a simple geometrical representation of the cathode. The purpose of the code is to provide a rapid (calculations take less than a minute) assessment of how insert plasma thermal fluxes influence the cathode insert and orifice plate temperatures. The code includes thermal conduction, radiative heat losses, and, within the insert region, radiative heat transfer. The code is written in Visual Basic for Applications (VBA) and is run within an Excel spreadsheet.
3. Results
Comparisons between IROrCa2D code results and measurements for the NEXIS cathode produced very good agreement with measurements of the plasma density, plasma potential and electron temperature along the axis of symmetry. The simulations also suggested the possibility of anomalous transport in the orifice region. Without an extended computational region that includes the orifice and plume regions however, the hypotheses of anomalous mechanisms could not be substantiated. This has been one of the main reasons for developing the time-dependent OrCa2D. Validation of IROrCa2D continued with comparisons between theoretical results and measurements taken in the NSTAR cathode. Figure 5 shows a comparison between the computed and measured plasma densities along the axis of symmetry of the NSTAR cathode operating condition of 12A discharge current and 4.25 sccm. The measured total pressure during operation of the cathode was 7.9 T. The comparison suggests poor agreement without emission enhancement by sheath-funneling (i.e. b=0, where b is the total pore area over the emitter surface area), but the agreement is excellent if enhancement is included using b=0.5. The average pore radius used in the calculations presented below is 2e-6 m. The calculations show that contrary to the NEXIS cathode, the majority of the emission in the NSTAR cathode comes from within a few mm of the emitter tip and that the rest of the emitter is negligibly utilized. For example, as shown in Figure 6, approximately 1 mm upstream of the orifice entrance, the net electron current density in the NSTAR cathode is almost six times the current density in the NEXIS cathode.

While OrCa2D is a descendent of IROrCa2D, the augmentated physics and numerics described above effectively make OrCa2D a new code. Validation of OrCa2D requires that it re-produces the agreement with experimental measurements achieved by IROrCa2D in the emitter region at the same total pressure. At t=3ms OrCa2D computes the average total pressure in the emitter region, up to z=4cm, to be 1.03T; the deviation from this average does not exceed 1.5%. At this pressure it is found that indeed the plasma density, potential and electron temperature are in close agreement with the results of IROrCa2D. Figure 7 below shows the 2D plasma density profile, overlaid by electron current density streamlines, as computed by OrCa2D. No emission enhancement (b=0) has been employed in the simulations. The peak heavy-species temperature is found to be approximately 400 K higher which is a result of the higher relative velocities between ions and neutrals by the addition of the neutral velocities. It is recalled that IROrCa2D assumes that u_e=0 everywhere in the emitter region. OrCa2D computes velocities in the order of a few hundred meters per second near the orifice entrance (z<4cm). The agreement also suggests that the assumptions made in IROrCa2D on the uniformity of total pressure are good inside the cathode.

Preliminary results of a calculation of the temperature distribution along the NSTAR discharge cathode insert using the 2D thermal model is shown in Figure 8.

4. Status
IROrCa2D: Improvements of the IROrCa2D physics are continuing as our understanding of the driving processes in these cathodes improves. Specifically, comparisons between model results and data for the plasma potential suggest that there is no emission nor ionization 4-5 mm upstream of the orifice entrance. Currently, the IROrCa2D emitter boundary conditions do not account for the turn-off of emission at very low plasma potentials. Both of these effects will be included in IROrCa2D in the near future.
Figure 5. Comparisons between IROrCa2D results for different emission enhancement parameters and measurements for the plasma density taken inside the NSTAR hollow cathode.

Figure 6. Comparison of the (net) electron current density normal to the emitter wall boundary between the NSTAR (at b=0.5) and NEXIS hollow cathodes (b=0.5) at nominal operation.
Figure 7. Plasma particle density overlaid by electron current density streamlines for the NEXIS cathode as computed by OrCa2D.

Figure 8. Emitter temperature distribution for the NSTAR discharge cathode calculated using the hollow cathode thermal model.
OrCa2D: Currently, all time-dependent terms have been included in OrCa2D except for ion inertia in the ion momentum equation which is planned for the very near future. With the inclusion of ion acceleration physics it will then be possible to quantify the ion energies in the keeper region and the mechanisms that drive them. Also, OrCa2D presently under-predicts the total pressure in the NEXIS cathode in steady-state. The under-prediction is currently being addressed as we continue with the development and validation of the code.

Hollow Cathode Thermal Model: The Hollow Cathode Thermal Model has not yet been validated by comparison with data. The driving uncertainties are the material properties, particularly the emissivities of the exterior surfaces. The development of this code will be coupled with the development of IROrCa2D, through the plasma particle flux boundary conditions.

B. Region 2: Discharge Chamber

1. General Description
Ion thruster discharge chambers create the positive ions that are extracted to form the beam. For DC ion thrusters, the power needed to ionize the neutral propellant atoms comes from high-energy electrons emitted from the discharge cathode. These primary electrons (or “primaries”) are accelerated to relatively high energies by the (~25V) voltage between the cathode and anode surfaces, which is applied by the discharge power supply. Magnetic fields prevent the loss of plasma to the anode surface, increasing ionization efficiency. In a ring-cusp discharge, as shown in Figure 1, alternating rings of high-strength magnets (typically SmCo) provide magnetic confinement of the primaries at the magnetic cusps and throughout the discharge volume. For a typical ring-cusp thruster, the magnets are arranged so that the magnetic field lines primarily terminate on cathode potential surfaces or at cusps on the anode surfaces. In this way, primaries are confined by magnetic reflection at the cusps or by electrostatic forces at the cathode potential surfaces. The magnetic cusps are placed at anode surfaces to allow lower energy electrons (“secondaries”) to be lost along the field lines to carry the discharge current and maintain discharge stability. The low-energy secondaries are produced by primary electron collisions with plasma species and ionization by other secondaries.

A multi-component hybrid 2D computational “Discharge Model” has been developed to simulate ion thruster discharge processes and provide a framework for a full thruster model. The model is designed to integrate thruster component (cathode and grid) wear models to allow the determination of thruster life and long-term performance. Figure 9 gives an overview of the major components of the Discharge Model and its relationship with the cathode and ion optics models. The model accounts for the five major chamber design parameters (chamber geometry, magnetic field, discharge cathode, propellant feed, ion extraction grid characteristics) and self-consistently tracks four plasma species (neutral propellant atoms, secondary electrons, primary electrons, and ions). The model reaches a steady-state solution by first assuming very low density thermal plasma (at least an order of magnitude less than the anticipated final condition) and incrementally increasing the primary electron current until full primary current is reached.

2. Model Physics
The Discharge Model is composed of the species-specific sub-models shown in Figure 9. The sub-models use computational techniques that yield sufficient accuracy while minimizing run-time. For example, the 2D neutral atom sub-model is based on techniques used to calculate thermal transport view factors. This technique provides over an order of magnitude savings in run-time compared to a simple 2D steady-state Monte Carlo simulation was used in preliminary versions of the code. In the Electron Collision Sub-Model, high-energy primary electrons are tracked with a Boris-type predictor-corrector algorithm. At this time, the primary electrons are assumed to possess an accelerated half-Maxwellian energy distribution that is approximated from discharge cathode experimental data. Future versions of the
model will utilize cathode plume characteristics determined by the discharge hollow cathode plume model. The secondary electrons are treated as a quasi-neutral component of the plasma with a depleted-tail Maxwellian distribution. The CEX2D Ion Optics Model, described below, is used to determine grid transparency to ions and neutrals. Ion diffusion is assumed ambipolar and a non-classical correction is used for the perpendicular diffusion of secondary electrons. A correction for double ions is used to approximate double ion content inside the chamber and in the beam. The non-uniform secondary electron temperature is determined by the Electron Thermal Sub-Model that accounts for the transfer of primary electron energy to the secondary population. Detailed descriptions of the assumptions and techniques used for Discharge Model are given in Reference 8.

![Discharge Model Flowchart](image)

**Figure 9. Discharge chamber model flowchart.**

### 3. Results
The Discharge Model has been verified against beam profile and performance data for the 30cm NSTAR thruster and the 3cm Miniature Xenon Ion (MiXI) thruster. A brief overview of a comparison of the model with NSTAR data is given below; along with a prediction of the performance that may result from a simple design modification of the NSTAR magnetic field. Further details of these results are given in Reference 8. As detailed in Reference 9, the model also accurately predicts the beam profile and the performance trends for the MiXI thruster.

Discharge Model results for the NSTAR thruster at throttle condition TH15 are shown in Figure 10 where the beam current density profile calculated by the model (jB [original]) agrees well with experimental data (jB [original, Data]) obtained in the 8200 hour test. The “modified” results in Figure 10 are discussed below. The ion density and double-to-total ion ratio distribution throughout the discharge chamber are shown in Figure 11. These results agree with experimental data that suggest the on-axis peak in the NSTAR beam profile is due to high centerline double ion content. Analysis of the Discharge Model results shows that the original NSTAR magnetic field configuration tends to trap primary electrons.
on-axis; which increases the generation of double ions in this region. This trapping of primary electrons also manifests in a noticeable dip in the neutral density on-axis, as shown in Figure 10.

![Figure 10. Beam and Neutral Density Profiles at Grids for TH15.](image)

The Discharge Model was used to perform a design analysis for the NSTAR thruster by doubling the magnetization length of the magnets on the middle magnetic ring. This modified thruster design was simulated at the TH15 operating condition and demonstrated noticeable improvements in propellant efficiency, \( \eta_{\text{prop}} \), discharge loss, \( \varepsilon_B \), and beam flatness, \( F_B \), as are summarized in Table 1. Figure 10 clearly shows the improvement in both the beam and neutral density profiles for the modified configuration. As discussed in Reference 8, these improvements are due to a combination of reduction in on-axis primary electron confinement and increasing the plasma confinement between the magnetic cusps. The qualitative

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characteristics of these results have been recently verified by experimental tests,11 showing that the Discharge Model can serve as a useful tool for aiding in the optimization of thruster life and performance.

Table 1. Discharge Performance Parameters (NSTAR TH15 - Original vs. Modified Design).

<table>
<thead>
<tr>
<th>Discharge Parameters</th>
<th>( \eta_{\text{wall}} )</th>
<th>( \varepsilon_B )</th>
<th>( F_B )</th>
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<tr>
<td>Units</td>
<td>%</td>
<td>eV/ion</td>
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<tr>
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<td>0.47</td>
</tr>
<tr>
<td>Modified</td>
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<td>179</td>
<td>0.68</td>
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</table>

4. Status

In summary, the 2D Discharge Model currently predicts the properties (density, temperature, flux) of resident propellant atoms, ions, double ions, primary electrons, and secondary electrons. The model has been validated against beam profile and performance data from the 30cm NSTAR and 3cm MiXI thruster. Present discharge modeling efforts focus on integrating a magnetically-aligned mesh to allow the determination of important characteristics such as plasma potential and detailed species energy distributions.12 The Discharge Model provides the framework for a full ion thruster model and is designed to integrate with the hollow cathode and extraction grid models to allow long-term performance and life assessment. Future efforts are planned to fully and self-consistently integrate the models.

C. Region 3: Ion Optics Grids

1. General Description

In the ion optics grid region ions from the quasi-neutral discharge chamber plasma are accelerated by strong electric fields to energies in excess of 1000 electron volts. The electric field strengths typically exceed 2000 volts per millimeter. The positive electrode, called the screen grid, “screens” the discharge plasma from the accelerating electric field. Ions enter the region through circular holes in the screen grid and leave through concentric holes in the accelerator grid. The diameter of screen grid holes is typically larger than those in the accelerator, and the electric fields focus the discharge chamber ions in to narrow beamlets. As a result, the large screen grid holes determine the ion current in the beam. Neutral gas atoms from the discharge chamber also exit through the screen grid and accelerator grid holes, but, since they are not focused by the electric fields, the smaller accelerator grid hole size limits their escape. Resonant charge exchange collisions between beamlet ions and escaping neutral gas generates slow moving ions near and just downstream of the accelerator grid. The local electric fields accelerate many of these ions such that they impact the accelerator grid with sufficient kinetic energy to cause sputter damage.

There are two codes that describe the processes in this region. The first, CEX2D, models in two dimension, the focusing and acceleration of discharge chamber ions through a single set of concentric screen and accelerator grid apertures. The code assumes axial symmetry, an approximation valid for all but the lowest density beamlets. Besides predicting ion optics extraction capability, the code also is useful in predicting accelerator aperture sputter erosion. Accelerator grid aperture sputter erosion was the first life limiting mechanism encountered in the ELT. The second code, CEX3D, models in three dimensions one twelfth of the hexagonally symmetric region encompassing a concentric accelerator and screen grid aperture. This code is primarily designed to model the “pits and groove” erosion of the accelerator grid downstream face and the deviations from cylindrical symmetry for low density beamlets.

2. Model Physics

The codes solve for the potential in the computational domain and then solve for the ion trajectories to obtain the space-charge density. The potential is obtained using a finite element approximation to solve Poisson’s equation,
\[ \nabla^2 \phi = -\frac{\rho}{\varepsilon_0} \]

where \( \phi \) is the potential, \( \rho \) is the charge density, and \( \varepsilon_0 \) is the permittivity of free space.

With a few exceptions, the codes use a combination of algorithms similar to those in previously reported ion optics codes [Ref 1-7]. Ions enter the computational region from the upstream boundary at the Bohm velocity, and their charge density is found by following their trajectories in a stationary electric field (as compared with time dependent PIC simulations). The upstream electron density is found assuming a Maxwellian distribution, as compared with the sharp sheath approximation used in the OPT and IGX codes. The downstream electron population is also assumed to be a Maxwellian with a different reference potential. As a result downstream potentials are determined self consistently; there is no need to assume a neutralization plane.

Beam ions are approximated by uniformly spaced particles injected at the upstream boundary of the computational domain. The current per particle is found by dividing the total beam current by the number of particles. To determine the ion trajectory, the electric field at the location of the particle is computed and the particle speed and position is updated using a time step that allows the particle to move about 0.1 times a typical element dimension. The current of particles striking each grid is summed to determine the total grid current. The beam current is determined by summing the currents of the particles reaching the downstream boundary. Ions reaching the axial boundaries are reflected back into the computational domain; by symmetry, ions flowing out of the sides are replaced by ions flowing into the computational domain from the adjacent region.

In addition to beam ions, charge exchange ion production rates and charge exchange trajectories are computed. Erosion of the accelerator grid is caused by these charge exchange ions and the location, kinetic energy, incidence angle and current of each particle is recorded and used to compute erosion rates. Charge exchange ions that strike the downstream surface of the accelerator grid can come from several centimeters downstream of the grid; therefore, the computations domain is usually set to extend 5 cm downstream of the grids. The current to the accelerator grid was computed for the NSTAR ion thruster operating at full power.

The code solves for the potential and particle trajectories iteratively. First the Laplace solution for the potentials is obtained; then the particle trajectories are computed based on this potential. A fraction of the total ion density is added to the nodes and the potential is recalculated. With this new potential the trajectories are recomputed and a weighted combination of the old and new ion charge is assigned to each node. This process can be repeated until the code converges.

Although both the three-dimensional \texttt{CEX3D} code and two-dimensional \texttt{CEX2D} codes can predict accelerator grid aperture wall erosion rates and electron backstreaming voltages, the two-dimensional code is typically used for these calculations because the apertures are cylindrical and the \texttt{CEX2D} code can produce these results more quickly. \texttt{CEX2D} and \texttt{CEX3D} use the same algorithms for the discharge chamber plasma for beam ion trajectories. The codes have been benchmarked with each other, and for round beamlets, their results are within a few percent.

3. Results

Example results from both \texttt{CEX2D} and \texttt{CEX3D} compared with data are shown below. In Figure 12 beamlet diameters calculated using \texttt{CEX3D} are compared with measurements of Soulas and Rawlin.\textsuperscript{13} The accuracy of the calculated beamlet diameters is within 5\% over the central region of the accelerator.
grid, where the pits and grooves erosion occurs. Significant variations occur only for the lowest current beamlets at the periphery of the grid.

Figure 12. Calculated and measured exit beamlet diameters.

The ions that cause “pits and grooves” erosion are generated downstream of the accelerator grid. To accurately calculated the number of ions the computation must extend downstream well past where the beamlets overlap. While the distance between beamlets is just over 2 mm, charge exchange ions generated as far as 5 cm downstream may still return to hit the grid. Calculations that didn’t include the region several centimeters downstream typically predicted much lower accelerator grid currents compared with measurement. CEX3D employs variable axial grid spacing to limit the number of zones in the problem. Accuracy is maintained since the radial potential gradients are much greater than those normal to the beam direction. For the NSTAR long duration test parameters, CEX3D calculated an accelerator current of 6.8 mA compared with the 6.5-7mA observed during the last 6000hrs of the Long Duration Test.  

The pits and grooves pattern cannot be modeled with an axis-symmetric code and must be modeled with the three-dimensional CEX3D code. As noted earlier, erosion of the accelerator grid by charge exchange ion sputtering was the major life limiting observed during the ELT of the NSTAR flight spare thruster. Photographs of center holes in the grid at the beginning and the end of the test are shown in Figure 13. Note that the triangles in the end of test picture are patches where the erosion has completely penetrated the grid. Laser profilometry measurements shown in Figure 14 indicate that the grid was nearing structural collapse when the test was stopped.
Figure 13. NSTAR thruster accelerator grid at 125 hours (left) and 30,352 hours (right).

Figure 14. Laser profilometry shows that sputtering in the webbing between the holes had almost destroyed the structural integrity of the NSTAR grids.

Figure 15 is a contour plot of erosion rate for the NSTAR ion thruster predicted by CEX3D; two-dimensional and three-dimensional views of the same data are shown. Shown is the region surrounding 3 holes; pits form at the center of the triangle between three holes and grooves run along the webbing between the pits. Figure 16 shows that CEX3D over estimated the pits and grooves erosion rate.

4. Status
Both CEX2D and CEX3D have been validated with laboratory data and conservatively predict thruster grid wear.
Figure 15. CEX3D Wear Pattern Prediction for NSTAR Thruster.

Figure 16. Comparison of Pits and Groove Shape After LDT and Predicted Erosion Rate.
IV. Conclusion

The models overviewed in this paper have advanced significantly our understanding of life processes in ion thrusters and continue to aid the design of thruster components that will last longer and perform better. Simulations of the NSTAR cathode with the Insert Region of an Orificed Cathode code (IROrCa2D) and comparisons with measurements taken inside the emitter region, suggest that emission enhancement by “sheath funneling” into the insert pores is a dominant mechanism in cathodes that operate at high plasma densities (\(>5 \times 10^{20} \text{ m}^{-3}\)). It is found that most of the net electron flow in the NSTAR cathode originates from within a few millimeters of the insert edge nearest to the orifice plate. Due to the order-of-magnitude smaller peak plasma densities attained in the larger-size NEXIS cathode, the Debye sizes are larger and sheath funneling does not affect the emission characteristics significantly. The second theoretical model, the 2D axisymmetric, time-dependent code OrCa2D, simulates the plasma and neutral gas dynamics in the emitter, orifice, keeper and plume regions and is more advanced in the physics and numerical approach. OrCa2D lifts all dependencies of the model on plasma measurements. Simulations using classical transport show that the electron drift velocity outside the orifice, in the near-plume region, is several times (kTe/me)\(^{1/2}\) and may therefore be a region of enhanced resistivity due to two-stream instabilities. The region may also be dominated by electrons that deviate substantially from the Maxwellian distribution function and would therefore require a kinetic or modified fluid modeling approach for the electrons. The Ion Engine Discharge Model has also directly impacted the design of an improved NSTAR thruster. By doubling the magnetization length of the magnets on the middle magnetic ring a modified thruster design was simulated at the TH15 operating condition and demonstrated noticeable improvements in propellant efficiency, \(\eta_{\text{ud}}\), discharge loss, \(\epsilon_B\), and beam flatness, \(F_B\). The improvements have recently been verified by performance measurements in the improved NSTAR design. Finally, the ion optics grid codes, CEX2D and CEX3D, have been used to design the grids of the NEXIS thruster. The grids were designed, incorporated and operated flawlessly in the NEXIS engine.

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