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Review of Hall Thruster Plume Modeling

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Hall thrusters are an attractive form of electric propulsion that are being developed to replace chemical systems for many orbit propulsion tasks on communications satellites. A concern in the use of these devices is the possible damage their plumes may cause to the host spacecraft. The present status of computer modeling of Hall thruster plumes is reviewed in the context of being able to address spacecraft integration concerns. A simple, empirical approach is described that can be used as a quick engineering tool. However, accurate modeling of Hall thruster plumes requires use of kinetic-based simulation techniques. In particular, particle methods are discussed with respect to the physical modeling required to accurately simulate the plasma and collision processes that are significant in Hall thruster plumes. An assessment is made of the computer models through direct comparison between simulation results and detailed experimental measurements.

Nomenclature

$\boldsymbol{B}$ = magnetic field, T
$\boldsymbol{E}$ = electric field, V/m
e = unit charge, 1.6×10^{-19} C
g = relative velocity, m/s
k = Boltzmann constant, 1.38×10^{-23} J/K
m_e = electron mass, 9.1×10^{-31} kg
n_e = electron number density, m^{-3}
n_{ref} = reference electron number density, m^{-3}
p = pressure, Nm^{-2}
T_e = electron temperature, K
t = time, s
$\boldsymbol{v}_e$ = electron velocity, m/s
$\boldsymbol{v}_i$ = ion velocity, m/s
ν_{ei} = ion–electron collision frequency, s^{-1}
σ_{CEX} = charge exchange cross section, m^2
σ_{EL} = elastic collision cross section, m^2
ϕ = plasma potential, V

Introduction

HALL thrusters are under development in several countries, including the United States, Russia, Japan, and France. These electric propulsion devices typically offer a specific impulse of about 1600 s and a thrust of about 80 mN. These characteristics make them ideally suited for spacecraft orbit maintenance tasks such as north–south stationkeeping. Under typical operating conditions, at a power level of about 1.5 kW, a voltage of 300 V is applied between an external cathode and an annular anode. The electrons emitted from the cathode ionize the xenon propellant, efficiently aided by magnetic confinement within an annular acceleration channel (creating an azimuthal Hall current). The ions are accelerated in the imposed electric field to velocities on the order of 17 km/s. New classes of Hall thrusters are being developed at low power (100 W) for use on microspacecraft and at high power (25 kW) for spacecraft orbit raising.

As with any spacecraft propulsion device (chemical or electric), there are two important roles for computer modeling. The first is to aid in the optimization of the performance of the thruster. In the case of Hall thrusters for station keeping, a typical overall efficiency is about 55%. Models of the interior flows of Hall thrusters have been developed using hybrid fluid/particle approaches.[1,2] In addition to aiding in the understanding of how Hall thrusters operate, these models are useful in providing boundary conditions for plume modeling. This is important for the second role of computer modeling, which is to assess any interactions between the plume of the thruster and the host spacecraft. In the case of Hall thrusters, there are three particular spacecraft integration issues:

1) The first issue is that the divergence angle of these devices is relatively large (about 60 deg), leading to the possibility of direct impingement of high-energy propellant ions onto spacecraft surfaces that may result in sputtering and degradation of material properties. Material sputtered from spacecraft surfaces in this way may ultimately become deposited on other spacecraft surfaces such as solar cells, causing further problems.

2) Another issue is the backflow impingement of ions caused by formation of a charge-exchange plasma.

3) The third issue is that the high-energy ions created inside the thruster cause significant erosion of the walls of the acceleration channel (usually made of metal or a ceramic such as boron nitride), and the erosion products may expand out from the thruster and become deposited on spacecraft surfaces.

In this paper, we review the physics of Hall thruster plumes that are of most relevance to the computational modeling of the first two types of spacecraft interaction effects just listed. One of the few studies on the third type of problem is described by Pencil et al.[3] We first begin by considering a semiempirical approach to modeling the plume based on experimental measurement. We then consider in detail the accuracy of existing computational procedures with respect to simulating the physics of these plumes most relevant to understanding the spacecraft interaction phenomena. The computational approaches employ particle methods to simulate the plasma and collision physics. Various aspects of these simulation methods are reviewed, and their shortcomings are highlighted. The current status of modeling Hall thruster plumes is discussed, and this is followed by consideration of areas requiring further work.

Semiempirical Approach

It can be argued that the primary physical property of the Hall thruster plume with respect to prediction of spacecraft integration issues is the ion current density. This argument has validity because it is the impact of energetic ions on spacecraft surfaces that leads to erosion of spacecraft materials that may subsequently change their physical properties (thermal, optical, and electrical). Fortunately, the ion current density is readily measurable in the laboratory using a Faraday cup, and this has been performed in the plumes of several Hall thrusters including the Stationary Plasma Thruster-100 (SPT-100),[4,5] the D-55,[4] and the BPT-2000.[6] When the assumptions are made that the velocity at some small distance away from the thruster is constant (because the electric fields are weak in this region) and that the ion density decays with the inverse square of distance from the source, it is possible to use a single angular profile of experimental data to extrapolate the entire ion current density flowfield.[3,7,8] A number of different semianalytical approaches are reviewed and compared in Ref. 9. These are all based on the source

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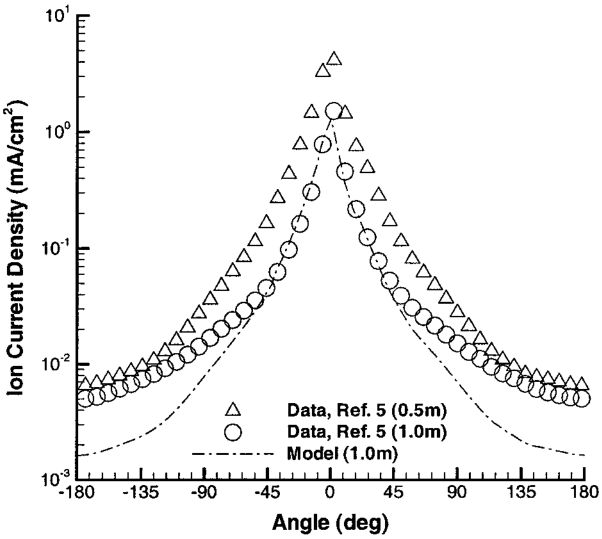

Fig. 1 Angular profiles of ion current density in plume of SPT-100.

flow approximation and include different expressions to describe the angular variation of the plasma plume.

An example of results obtained from the approach of Ref. 8 are shown in Fig. 1 for the SPT-100 Hall thruster, where angular profiles of the ion current density are plotted at distances of 0.5 and 1.0 m from the thruster exit. The measurements are those of King et al.,[5] and the measured data at 0.5 m are used together with the preceding assumptions to compute the ion current density at 1.0 m. The comparison of the measured and model data at 1.0 m indicate that this simple approach is very effective in the core of the plume, at angles below about 45 deg. However, at larger angles, the model shows a significantly lower ion current density than that measured experimentally. The higher-angle regions are strongly affected by the charge-exchange (CEX) plasma, and the background pressure in the experimental facility. Both of these issues are discussed in detail later in the paper. It is clear in this case that the simple semiempirical model gives significant disagreement with available experimental data in the regions of the plume where spacecraft interaction effects are most likely to occur. In Refs. 3 and 7–9, the analytical models are more successful when sufficient experimental measurements are available for a particular thruster. However, in the absence of such data, the models are of limited use.

An additional failing of the simple approach to modeling the Hall thruster plume concerns the ion energy. In Ref. 7, experimental measurements of the average ion energy in the plume are also fit to an analytical form. However, this data is, in general, more difficult to measure and in any case provides no information on the distribution function of ion energy contained in the current. Experimental evidence shows that there is significant variation of the xenon ion energy distribution as a function of angle in the plume. Failure to describe this behavior represents an important shortcoming of the model because the sputter yield of typical spacecraft materials (the number of material atoms sputtered for each impact of an ion) is strongly dependent on the incident energy[10] and angle of the ion. The semiempirical model is very useful as a preliminary evaluation tool of different Hall thrusters integrated on different spacecraft configurations, but a much more detailed analysis of the plume is required to accurately predict spacecraft integration concerns. This requirement has led to significant activity in the development of more sophisticated prediction models.

Particle Approach

To understand the type of numerical approach required to accurately model Hall thruster plumes, it is informative to consider some of the basic physical characteristics of the flow exiting from the thruster. In Table 1, typical values of some of the pertinent properties are listed at the thruster exit for the SPT-100. For these plasma densities, the debye length is very small, on the order of 10^{-5} m, which indicates that the plume is charge neutral for a relatively large distance away from the thruster. At the same time, the collision mean free paths are very large, on the order of 1 m. These fundamental physical properties of the plume suggest that a kinetic approach is necessary that simulates both plasma and collision effects. A numerical model that solves the velocity distribution functions for ions and neutrals and assumes adiabatic, collisionless, unmagnetized electrons is described by Bishaev et al.[11] The model includes CEX phenomena in a very macroscopic sense (using a constant cross section). Agreement with experimental data was achieved for ion current density by assuming relatively large values of the ion temperature at the thruster exit plane (20–25 eV). Although this model represents a significant improvement over the semi-empirical model, it cannot be expected to accurately provide the detailed information on the ion energy distribution function that is needed for spacecraft integration analysis.

Table 1 Properties at the exit of the SPT-100 Hall thruster

Property	Value
Inner diameter, mm	60
Outer diameter, mm	100
Plasma density, m^{-3}	10^{17}–10^{18}
Neutral density, m^{-3}	10^{18}
Ion velocity, m/s	17,000
Neutral velocity, m/s	300
Electron temperature, eV	4–10
Ion temperature, eV	1–4
Neutral temperature, K	1,000

In this paper, the status of particle simulation methods for computing Hall thruster plumes is discussed. The particle-in-cell method (PIC)[12] is employed to model the plasma dynamics, and the direct simulation Monte Carlo method (DSMC)[13] is used to simulate the collision dynamics. In the following, we discuss in detail the various aspects of the physical modeling that are required to accurately model Hall thruster plumes.

Plasma Dynamics

The first efforts to use a combination of the PIC and DSMC methods to model the plumes of Hall thrusters were made by Oh et al.,[14] and this approach has formed the basis for subsequent work.[15,16] In general, the PIC method accelerates charged particles through applied and self-generated electric fields in a self-consistent manner. In Ref. 14, based on the plasma jet physical properties, the ions are modeled as particles and the electrons as a fluid. The plasma potential is obtained by assuming quasi neutrality, which allows the ion density to represent the electron density. By the further assumption that the electrons are isothermal, collisionless, and unmagnetized, the Boltzmann relation can be invoked:

$$n_e = n_{\text{ref}} \exp(\phi / kT_e) \tag{1}$$

where n_e is the electron number density, n_{ref} is a reference density where the potential ϕ is zero, k is Boltzmann's constant, and T_e is the constant electron temperature. Inversion of Eq. (1) gives the potential, which can then by differentiated spatially to obtain the electric fields.

There are several limitations of this approach. First, experimental evidence[17,18] indicates that there is variation of the electron temperature in Hall thruster plumes. The variation occurs mainly in the near field of the plume. At the thruster exit the electron temperature can be as high as 10 eV (Ref. 18), and in the far field typical values are 1–2 eV (Ref. 17). This creates a difficulty in the choice of T_e to be used in Eq. (1). A further difficulty with application of the Boltzmann relation to Hall thruster plumes is the possible effects of the magnetic field. The combination of permanent and electromagnets employed in Hall thrusters are designed to provide optimum device performance. However, some of the magnetic field may leak out into the plume of the thruster. The amount of this leakage will depend strongly on the Hall thruster type and configuration.

The effects on the Hall thruster plume of variation in electron temperature and magnetic field can be modeled using the full electron momentum equation:

$$m_e n_e \frac{d\boldsymbol{v}_e}{dt} = -n_e e(\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \nabla p - n_e m_e \nu_{ei}(\boldsymbol{v}_e - \boldsymbol{v}_i) \tag{2}$$

where m_e is the electron mass, e is the electron charge, $\boldsymbol{v}_e$ and $\boldsymbol{v}_i$ are the electron and ion velocities, $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field, p is the pressure, and ν_{ei} is the electron–ion collision rate. Given currentless flow, the left-hand side is zero. The plume is essentially collisionless, which allows the third term on the right-hand side to be neglected. The pressure is conveniently represented by the ideal gas law:

$$p = n_e k T_e \tag{3}$$

Of course, Eq. (2) reduces to the Boltzmann relation under the relevant assumptions.

The electron momentum equation neglecting the magnetic field but including an imposed variation of electron temperature was employed within a PIC–DSMC model by VanGilder et al.[15] to compute the SPT-100 plume. The variation of electron temperature was obtained by fitting a simple analytical model to available experimental measurements[18] as shown in Fig. 2. In Figs. 3a and 3b, comparisons are made between model predictions and measurements[18] of the ion current density in the plume near field. It is found that the variable T_e model significantly improves the agreement with the measured data, although some differences persist. Angular profiles of electron number density at a distance of 31 cm from the thruster are shown in Fig. 4. Use of the variable electron temperature leads to a small widening of the plume profile that is in better agreement with the measured data of Ref. 17. Radial profiles of plasma potential are shown in Fig. 5 at an axial distance of 48 cm from the thruster. The variable electron temperature model predicts a less rapid decrease in potential that is in excellent agreement with the measured data of Marrese and Gallimore (C. M. Marrese and A. D. Gallimore, personal communication, 1999). These comparisons illustrate that variation of the electron temperature should be included in the computation of the electric field by using Eq. (2).

The effect of magnetic field on the plumes from three different Hall thrusters was studied using a semi-analytical fluid model by Keidar and Boyd.[19] The main result of this study is illustrated in Fig. 6, which shows the variation of plasma potential along the plume axis for three different values of B_0, the magnetic field strength at the thruster exit. These values cover the range of magnetic fields of three actual Hall thrusters: the SPT-100 ($B_0 = 0.02$ T), the D-55 ($B_0 = 0.018$ T), and a device studied by Kusamoto et al.[20] ($B_0 = 0.1$ T). The results indicate that there are three different regimes for the effects of the thruster magnetic field on the plasma potential in the plume: 1) at low values of B_0, there is no effect and the potential decreases away from the thruster, resulting in continued acceleration of the ions (this is the behavior predicted by the Boltzmann relation); 2) at intermediate values of B_0 the potential is almost constant; 3) at high values of B_0, the plasma potential actually increases away from the thruster, which leads to deceleration of the ions. Comparison of the model predictions with experimental measurements of potential is shown in Fig. 7 for the Hall thruster with large magnetic field considered in Ref. 20.

It is clear that accurate computation of Hall thruster plumes requires consideration of the effects of electron temperature and magnetic field. To compute the variation of electron temperature in the

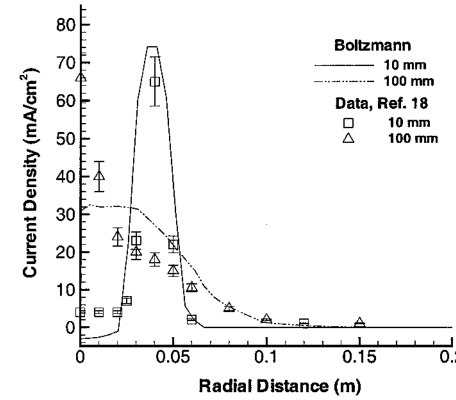

Fig. 3a Radial profiles of ion current density in near field of SPT-100: comparison of measured data with Boltzmann PIC–DSMC model.

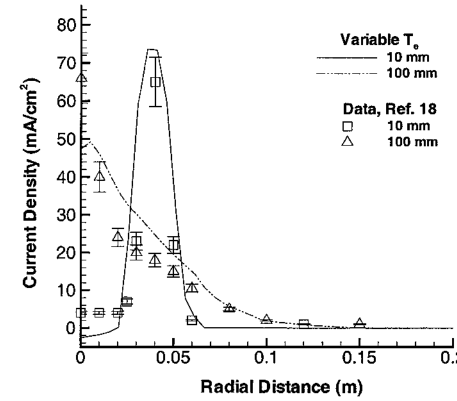

Fig. 3b Radial profiles of ion current density in near field of SPT-100: comparison of measured data with nonisothermal PIC–DSMC model.

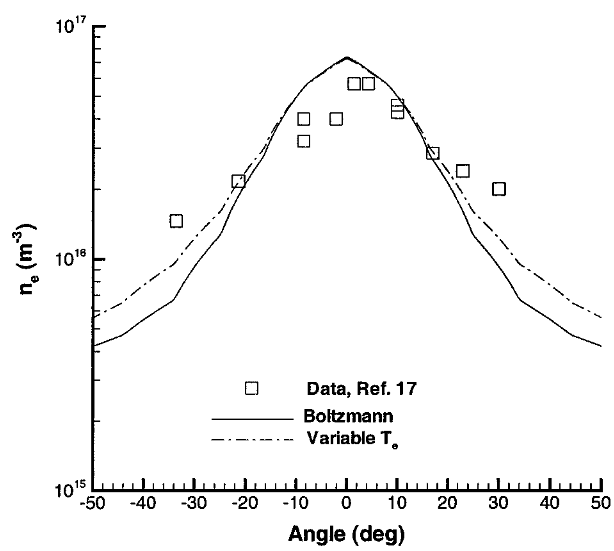

Fig. 4 Angular profiles of electron number density in far field of SPT-100.

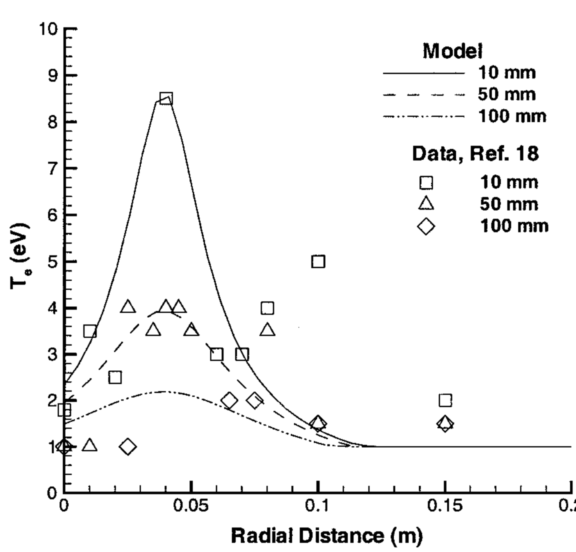

Fig. 2 Radial profiles of electron temperature in near field of SPT-100.

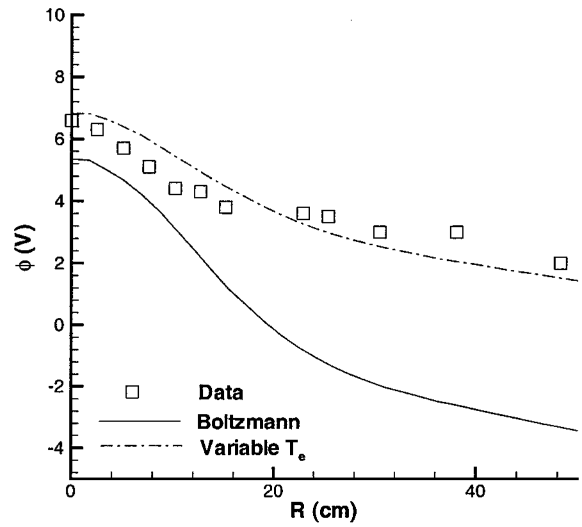

Fig. 5 Radial profiles of plasma potential in far field of SPT-100: □, data of Marrese and Gallimore.

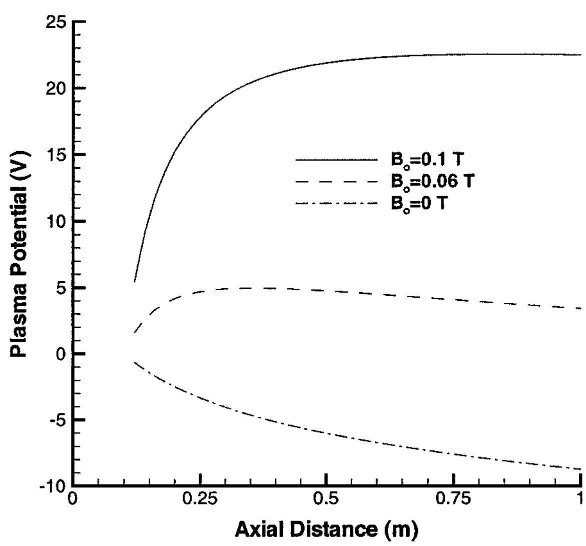

Fig. 6 Plasma potential along axis as function of thruster exit magnetic field strength.

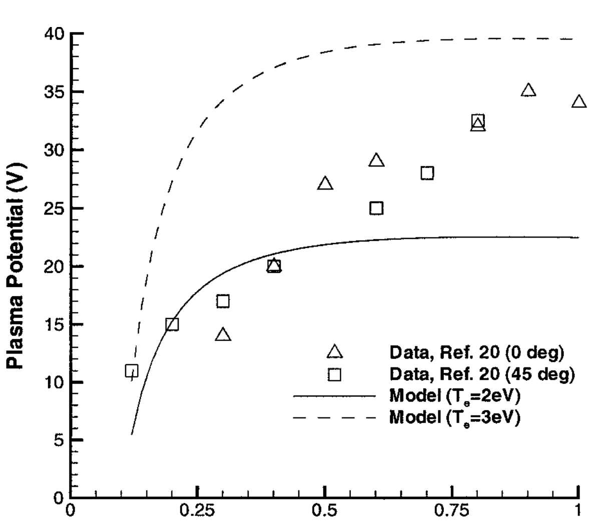

Fig. 7 Plasma potential along axis for Hall thruster of Ref. 20 with B_0 = 0.1 T.

plume, rather than imposing a measured profile, an electron energy equation can be solved, as has been performed by Samanta Roy et al.[21] for an ion thruster plume. For magnetic effects, it is reasonable to impose the magnetic field (obtained from measurements or from a separate computation) because the self-induced magnetic fields are negligible under the conditions found in Hall thruster plumes. This approach has not yet been studied in the framework of a PIC–DSMC simulation.

Collision Dynamics

The DSMC method uses particles to simulate collision effects in rarefied gas flows by collecting groups of particles into cells, which have sizes of the order of a mean free path. Pairs of these particles are then selected at random and a collision probability is evaluated for each pair that is proportional to the product of the pair's relative velocity and collision cross section. The probability is compared with a random number to determine whether that collision occurs. If so, some form of collision dynamics is performed to alter the properties of the colliding particles.

There are three basic classes of collisions that may occur in Hall thruster plumes: 1) elastic, 2) charge exchange, and 3) Coulomb. At first glance, based on the low number densities at the thruster exit, it appears that collisions are unimportant in Hall thruster plumes. However, it will be found in the discussion of results that CEX collisions have a profound effect on the Hall thruster plume structure even though the mean free path for all collisions is large. Each of the collision classes is distinguished by its cross section and collision dynamics. These issues are discussed in the following.

Elastic Collisions

Elastic collisions involve only exchange of momentum between the participating particles. For the systems of interest here, this may involve atom–atom or atom–ion collisions. For atom–atom collisions, the variable hard sphere[13] collision model is employed. For xenon, the collision cross section is

$$\sigma_{\mathrm{EL}}(Xe, Xe) = [(2.12 \times 10^{-18})/g^{2\omega}]\,\mathrm{m}^2 \tag{4}$$

where g is the relative velocity and $\omega = 0.12$ is related to the viscosity temperature exponent. For atom–ion elastic interactions, the following cross section of Dalgarno et al.[22] is employed:

$$\sigma_{\mathrm{EL}}(Xe, Xe^+) = [(6.42 \times 10^{-16})/g]\,\mathrm{m}^2 \tag{5}$$

The model of Ref. 22 predicts that the elastic cross section for interaction between an atom and a doubly charged ion is twice that for an atom and a singly charged ion. Note that the model of Ref. 22 employs a polarization potential and, therefore, is only valid for low energy (a few electron Volts) collisions. Further work is required to determine more accurate cross sections for high-energy atom–ion elastic interactions for xenon. In all elastic interactions, the collision dynamics is modeled using isotropic scattering, together with conservation of linear momentum and energy to determine the postcollision velocities of the colliding particles.[13]

CEX Collisions

CEX concerns the transfer of one or more electrons between an atom and an ion. This is a long-range interaction that involves a relatively large cross section in comparison to an elastic interaction. This is an important mechanism in Hall thruster plumes because at the thruster exit plane the atoms and ions have velocities that differ by almost two orders of magnitude (see Table 1). Whereas the ions have been accelerated electrostatically, the atoms remain at thermal speeds. Thus, CEX leads to a slow ion and a fast atom. The slow ion is much more responsive to the electric fields set up in the plume and are easily pulled behind the thruster into the back flow region. Thus, the so-called CEX plasma is formed near the thruster exit. It is because we need to model the CEX behavior accurately that we go to the trouble of using the DSMC technique.

For singly charged ions, the following theoretical cross section of Rapp and Francis[23] has been widely used:

$$\sigma_{\mathrm{CEX}}(Xe, Xe^+) = [-0.8821\log(g) + 15.1262]^2 \times 10^{-20}\,\mathrm{m}^2 \tag{6}$$

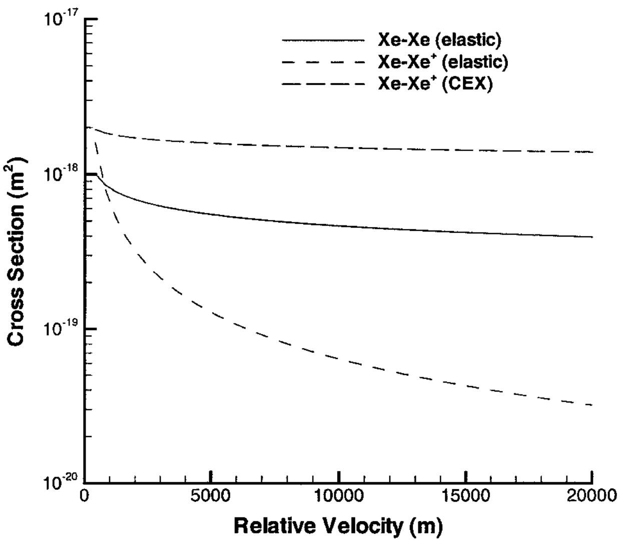

Fig. 8 Various collision cross sections as function of relative velocity.

Recently, new measurements have become available based on crossed beam experiments.[24] These data yield CEX cross sections that are about 30% higher than those of Eq. (6). Also reported in Ref. 24 are CEX cross sections for the interaction where a doubly charged ion transfers two electrons from an atom. These cross sections are a factor of two lower than the values for the singly charged ions. Several of these cross sections are shown in Fig. 8 as a function of relative velocity for the range of interest in Hall thruster plumes.

In all CEX collisions, the collision dynamics assumes that there is no transfer of momentum accompanying the transfer of the electron(s). This assumption is reasonable based on the premise that these interactions are at long range.

Coulomb Interactions

Coulomb interactions involve collisions between charged species (ion–ion, electron–ion, and electron–electron). These collisions have been neglected in Hall thruster plume modeling mainly because the cross sections are only significant for very small scattering angle interactions. This behavior was confirmed for xenon flow through an ion thruster in which the inclusion of Coulomb collisions in a PIC–DSMC model was found to have no effect on the computed properties.[25]

Boundary and Auxiliary Conditions

For PIC–DSMC computations of Hall thruster plumes, boundary conditions must be specified at several locations: 1) at the thruster exit, 2) along the outer edges of the computational domain, and 3) along any solid surfaces in the computational domain. In addition, auxiliary conditions are required to simulate the plume expansion into the finite back pressure of a laboratory vacuum chamber. These aspects of PIC–DSMC models are discussed hereafter.

Several macroscopic properties of the plasma exiting the Hall thruster acceleration channel are required for PIC–DSMC computations. Specifically, the plasma potential, the electron temperature, and for each of the particle species, we require the number density, velocity, and temperature. In the real device, these properties will vary spatially across the annular face of the thruster exit plane, but also in many operating modes of the thruster these quantities vary in time. In general, the approach to determining these properties is a mixture of analysis and estimation. When ion and neutral temperatures (typically 4 eV and 1000 K, respectively) are assumed and measured properties such as thrust, mass flow rate, and current are used, it is possible to determine the species number densities and velocities. This approach gives uniform profiles of all properties across the exit plane. Generally, a small half-angle is imposed at the thruster exit plane to provide a variation in velocity vector. For the SPT-100, profiles of number density and velocity have been obtained from near-field measurements of velocity and ion current density.[18] No study has yet been made of the influence of temporally varying thruster exit boundary conditions on the plume structure, although such behavior has been observed experimentally.[26] As would be expected, the computed plume structure can be very sensitive to the boundary conditions used at the thruster exit. This is particularly true with respect to the divergence angle of the plume. The next natural step is to use output from two-dimensional models of the acceleration channel[1] as input to a PIC–DSMC plume computation.

Both field and particle boundary conditions are required at the outer edges of the computational domain. The usual field conditions employed simply set the electric fields normal to the boundary edges equal to zero. For plume expansion into vacuum, the particle boundary condition is to remove from the computation any particle crossing the domain edge.

In all configurations, the solid exterior walls of the thruster must be included in the computation. For computation of a ground-based laboratory experiment, the potential of the walls is set to zero. Any ions colliding with the thruster walls are neutralized. Both atoms and neutralized ions are scattered back into the flowfield from the surface of the thruster wall when diffuse reflection is assumed.

For simulation of a laboratory experiment, the finite back pressure of the vacuum chamber must be included in the computation. At the flow rates typical of SPT-100 Hall thrusters (about 5 mg/s), a good back pressure is on the order of 5×10^{-3} Pa. This pressure corresponds to a number density of about 10^{18} m^{-3} a room temperature, and this is of the same order as the neutral number density exiting the thruster (see Table 1). There are two methods for including the effects of the back pressure in a PIC–DSMC simulation. In one, temporary particles are created at each iteration to represent the back pressure.[15] These temporary particles may undergo collisions with and change the properties of the PIC–DSMC particles. Any change in the temporary particles is lost because new temporary particles are created at the next iteration. In the other approach, the background particles are simulated as a separate species in the full PIC–DSMC computation.[16] An example of the effect of including the facility pressure (labeled chamber + CEX) is shown in Fig. 9 for the D55 Hall thruster. In this case, the back pressure is about 2×10^{-3} Pa, which corresponds to the level in the experiment performed by Manzella and Sankovic.[4] At this level, the facility pressure generates about an order of magnitude larger ion current density in the high-angle regions due to CEX in comparison to that predicted to occur in pure vacuum (labeled vacuum + CEX). Also shown in Fig. 9 is the result of a simulation for expansion into vacuum that neglects all CEX collisions. In this case (labeled vacuum), the only spreading of the beam is due to electrostatic and thermal effects, and there is effectively no ion current beyond an angle of about 50 deg. This clearly illustrates the significant effect the CEX mechanism has on the plume structure.

For simulation of the operation of a Hall thruster in space, there is no requirement for backpressure, but several other difficulties

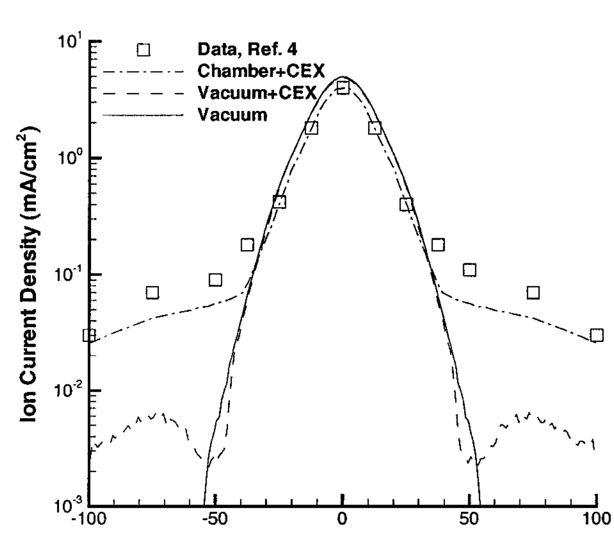

Fig. 9 Angular profiles of ion current density in plume of D-55.

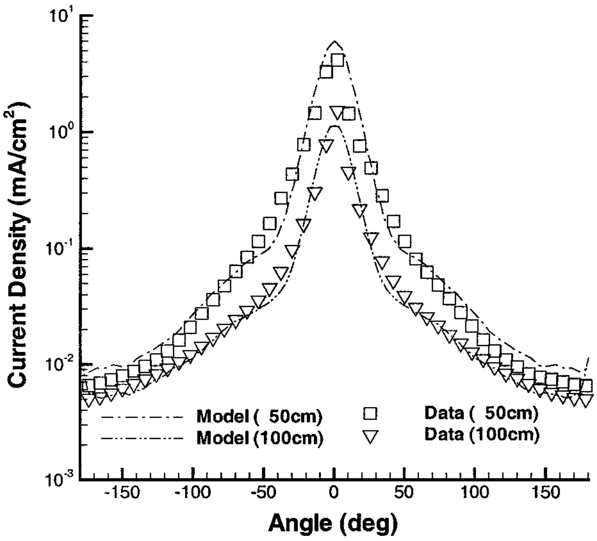

Fig. 10 Angular profiles of ion current density in plume of SPT-100.

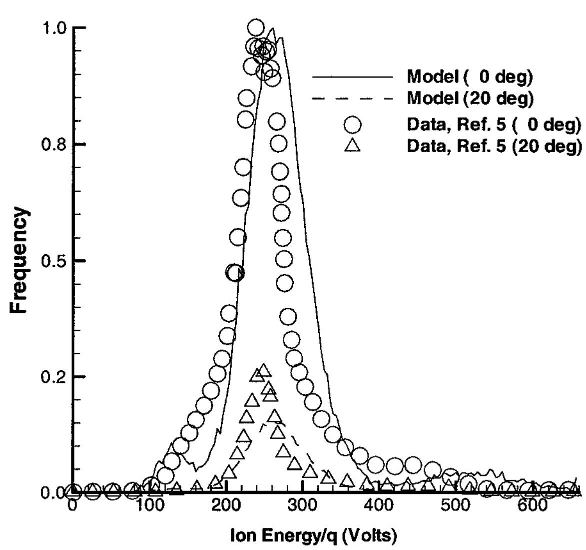

Fig. 11a Ion energy distribution functions at 0.5 m from SPT-100.

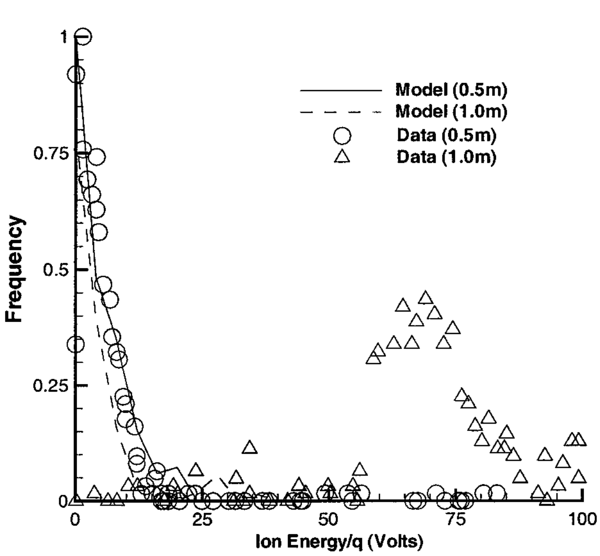

Fig. 11b Ion energy distribution functions at 150 deg from plume axis for SPT-100.

present themselves. First, there is the question of what value to use for the plasma potential on the thruster surface. In space, the entire spacecraft will tend to be biased to a negative potential with respect to the plasma plume, on the order of 20 V. In addition, the distribution of potential over the spacecraft may play an important role in determining the impact energy of ions, particularly in the backflow regions. Second, there is the question of how the ambient space environment may affect the Hall thruster plume. For example, it has been argued that, in low Earth orbit, the magnetic field of the Earth may distort the plume in different ways throughout the orbit of the spacecraft.[27] Also, far from the Earth, the question has been raised about the possible interaction of the solar wind with the plume of an ion thruster.[28]

Conclusions

It is recommended that computer models of Hall thruster plumes include the following: 1) CEX collisions, 2) variable electron temperature, and 3) effects of the background gas in a laboratory experiment. With these physical effects modeled, the PIC–DSMC codes are capable of producing accurate predictions of plume properties of most relevance to understanding spacecraft integration concerns. For example, the angular profile of ion current density at two different locations in the plume of the SPT-100 are shown in Fig. 10. The experiments were performed by King et al.[5] in a vacuum chamber at the University of Michigan. The PIC–DSMC computations[15] included the full chamber geometry. Note the excellent agreement between experiment and simulation all of the way into the extreme backflow (which begins at angles of ±90 deg). As stated earlier, it is not sufficient to model the total ion current density accurately. It is also important that the distribution of ion energy contained within the ion current be accurately represented. In Fig. 11a, comparison is made between the measured and predicted ion energy distribution functions at a distance of 0.50 m from the thruster at two different angles with respect to the plume axis.[29] The agreement obtained indicates that the PIC–DSMC model can be considered an accurate prediction method at small angles from the plume axis. Unfortunately, this level of agreement between experiment and computation is not maintained at higher angles. As an extreme example, in Fig. 11b, comparison is made between measured data and the PIC–DSMC computation at distances of 0.50 and 1.0 m and an angle of 150 deg (well into the backflow region). There is significant high-energy structure in the experimental data at 1.0 m that is completely missing in the computational results. Significant discrepancies between the PIC–DSMC simulation and the experimental data begin at angles of 40 deg, and their source is not yet understood.[29] Possible explanations include an effect of the thruster magnetic field, or beam ions scattering from the chamber walls. A first attempt to include this latter phenomena in Hall thruster plume modeling is reported in Ref. 30.

There are several areas where further work is required to improve the PIC–DSMC modeling described here. It has been shown that the variation of electron temperature has a significant effect on the plume structure both in the near and far fields. Solution of an electron energy equation has been successfully included in analysis of an ion thruster plume[21] and should also be performed for Hall thrusters. Depending on the magnetic field strength used in the device, inclusion of the magnetic field in the plume should also be assessed. Although the most important collision model concerns the CEX interactions, and recent measurements of cross sections have become available,[24] there is significant uncertainty in the cross sections of other possible interactions and, therefore, there is a need to consider these processes in greater detail. In terms of boundary conditions, the thruster exit plane is most problematic. It is a major goal to develop a seamless transition between detailed computations of the device acceleration channel and PIC–DSMC simulation of the external plume. This approach will certainly require inclusion in the plume simulation of nonisothermal and partially magnetized electrons.

Although three-dimensional modeling of Hall thruster plumes interacting with a representative satellite configuration was performed by Oh et al.,[14] their approach employed the Boltzmann relation. All of the physical modeling improvements discussed here need to be implemented into a numerically efficient three-dimensional model.

This paper has focused on modeling of the plasma plumes from Hall thrusters with regard to their potential to damage the host spacecraft. Discussion of the sputtering of spacecraft surfaces caused by energetic ion impact lies beyond the scope of this study. However, note that although some studies have included analysis of these phenomena,[3,7,8,14] significant uncertainty lies in the sputter yields for the impact of interest. This is another area of active ongoing research.

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