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Hall Thruster Plume Modeling

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A REVIEW OF HALL THRUSTER PLUME MODELING

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Abstract

Hall thrusters are an attractive form of electric propulsion that are being developed to replace chemical systems for many on orbit propulsion tasks on communications satellites. A major concern in the use of these devices is the possible damage their plumes may cause to the host spacecraft. In this paper, 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 model is described that can be used as a quick, engineering tool. However, accurate modeling of Hall thruster plumes requires use of kinetic 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. Through direct comparison between simulation results and detailed experimental measurements, it is demonstrated that the computer models have reached a certain level of maturity. Several areas are outlined where further work is needed.

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 1,600 sec and a thrust of about 80 mN. These characteristics make them ideally suited for spacecraft orbit maintenance tasks such as north-south station keeping. 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/sec. New classes of Hall thrusters are being developed at low power (100 W) for use on micro-spacecraft, 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 helping to understand how Hall thrusters operate, these models are useful in providing boundary conditions for plume modeling. This relates to 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

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spacecraft integration issues: (1) the divergence angle of these devices is relatively large (about 60°) 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) back flow impingement of ions caused by formation of a charge exchange plasma; and (3) 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 article, we review the physics of Hall thruster plumes that is of most relevance to the computational modeling of the first two types of spacecraft interaction effects listed above. Almost no research has been performed on the third type of problem. We first begin by considering a semi-empirical 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 short-comings are highlighted. The current status of modeling Hall thruster plumes is discussed and this is followed by consideration of areas requiring further work.

Semi-Empirical 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 has some validity since it is the impact of energetic ions on spacecraft surfaces that leads to erosion of spacecraft materials which may subsequently change their physical properties (thermal, optical, 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 SPT-100,[3,4] the D-55,[3] and the BPT-2000.[5] By making the assumptions that the velocity at some small distance away from the thruster is constant (since 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 flow field.[6]

An example of results obtained from this approach 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.[4] and the measured data at 0.5 m are used together with the above 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°. 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 plasma, and the background pressure in the experimental facility. Both of these issues are discussed in detail later in the paper. What is clear at this stage is that the simple semi-empirical model gives significant disagreement with available experimental data in the regions of the plume where spacecraft interaction effects are most likely to occur.

An additional failing of the simple approach to modeling the Hall thruster plume is the fact that it is the total ion current density that is modeled. This does not provide any 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. This 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[7] and angle of the ion. The semi-empirical 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 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. This 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, un-magnetized electrons is described by Bishaev et al..[8] The model includes charge exchange 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). While 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.

In this paper, the status of particle simulation methods for computing Hall thruster plumes is discussed. The Particle In Cell method (PIC)[9] is employed to model the plasma dynamics, and the direct simulation Monte Carlo method (DSMC)[10] 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 and Hastings[11,12] and this has formed the basis for subsequent work.[13,14] In general, the PIC method accelerates charged particles through applied and self-generated electric fields in a self-consistent manner. In Refs. 11 and 12, the ions are modeled as particles and the electrons as a fluid. The plasma potential is obtained by assuming quasi-neutrality. This allows the ion density to represent the electron density. By further assuming that the electrons are isothermal, collisionless, and un-magnetized, the Boltzmann relation can be invoked:

$$n_e = n_{ref} exp\left(\frac{\phi}{kT_e}\right) \tag{1}$$

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. Firstly, experimental evidence[15,16] 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[16] and in the far field typical values are 1 to 2 eV.[15] 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 electro-magnets 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:

$$m_e n_e \frac{d\mathbf{v_e}}{dt} = -n_e e(\mathbf{E} + \mathbf{v_e} \times \mathbf{B}) - \nabla p - n_e m_e \nu_{ei}(\mathbf{v_e} - \mathbf{v_i}) \tag{2}$$

where m_e is the electron mass, e is the electron charge, $\mathbf{v_e}$ and $\mathbf{v_i}$ are the electron and ion velocities, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field, p is the pressure, and ν_{ei} is the electron-ion collision rate. Assuming current-less 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.[13] to compute the SPT-100 plume. The variation of electron temperature was obtained by fitting a simple analytical model to available experimental measurements[16] as shown in Fig. 2. In Figs. 3a and 3b, comparisons are made between model predictions and measurements 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. 15. 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.[17] 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.[18] 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_o, 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_o=0.02 T), the D-55 (B_o=0.018 T), and a device studied by Kusamoto et al.[19] (B_o=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_o, 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_o the potential is almost constant; and (3) at high values of B_o, 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. 19.

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 plume, rather than imposing a measured profile, an electron energy equation can be solved, as has been performed by Samanta Roy et al.[20] for an ion thruster plume. For magnetic effects, it is reasonable to impose the magnetic field (obtained from measurements or from a separate computation) as the self-induced magnetic fields are negligible under the conditions found in Hall thruster plumes. This has not yet been performed in the framework of a PIC-DSMC simulation.

Collision Dynamics

The DSMC method uses particles to simulate collision effects in rarefied gas flows. This is performed 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 if 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 that charge exchange 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 (VHS)[10] collision model is employed. For xenon, the collision cross section is:

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

where g is the relative velocity, and ω=0.12 is related to the viscosity temperature exponent. For atom–ion elastic interactions, the following cross section of Dalgarno et al.[21] is employed:

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

The model of Ref. 21 predicts that there is no difference in the elastic cross section for interaction between an atom and a singly charged and for an atom and a doubly charged ion. In all elastic interactions, the collision dynamics employs isotropic scattering together with conservation of linear momentum and energy to determine the post-collision velocities of the colliding particles.[10]

Charge Exchange Collisions

Charge exchange 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). While the ions have been accelerated electrostatically, the atoms remain at thermal speeds. Thus, charge exchange 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 charge exchange plasma is formed near the thruster exit. It is because we need to model the charge exchange 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[22] has been widely used:

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

An alternative cross section is based on an empirical curve-fit to several sets of experimental data for a variety of atomic species performed by Sakabe and Izawa:[23]

$$\sigma_{CEX}(Xe, Xe^+) = (-21.2 log_{10}(g) + 140)(I/I_o)^{-1.5} \times 10^{-20} \mathrm{m}^2 \tag{7}$$

where I is the ionization potential of the atom, and I_o is the value for hydrogen. These two cross sections are almost identical and Eq. (7) is used here. For doubly charged xenon ions exchanging two electrons with a xenon atom, the following curve fit to the experimental measurements of Hasted and Hussein[24] is employed:

$$\sigma_{CEX}(Xe, Xe^{2+}) = (-2.7038 log(g) + 35.006)^2 \times 10^{-20}\text{m}^2 \tag{8}$$

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 charge exchange collisions, the collision dynamics assumes that there is no transfer of momentum accompanying the transfer of the electron(s). This is a reasonable assumption 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 has been confirmed for xenon flow through an ion thruster in which the inclusion of Coulomb collisions in a PIC-DSMC model were 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 below.

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. By assuming ion and neutral temperatures (typically 4 eV and 1,000 K, respectively) and using measured properties such as thrust, mass flow rate, and current, 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.[13] 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 flow field from the surface of the thruster wall assuming diffuse reflection.

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} at 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.[13] 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 back ground particles are simulated as a separate species in the full PIC-DSMC computation.[14] 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.[3] At this level, the facility pressure generates about an order of magnitude larger ion current density in the high angle regions due to charge exchange 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 charge exchange 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°. This clearly illustrates the significant effect the charge exchange mechanism has on the plume structure.

For simulation of the operation of a Hall thruster in space, there is no requirement for back pressure, but several other difficulties 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, and the distribution of potential over the spacecraft plays an important role in determining the impact energy of ions, particularly in the back flow 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 (LEO) 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]

Current Status and Future Work

It is recommended that computer models of Hall thruster plumes include the following: (1) charge exchange collisions; (2) variable electron temperature; and (3) effects of the back ground 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.[4] in a vacuum chamber at the University of Michigan. The PIC-DSMC computations[13] included the full chamber geometry. Note the excellent agreement between experiment and simulation all the way into the extreme back flow (which begins at angles of ± 90°). 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° (well into the back flow 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° 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[20] 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. The most important collision model concerns the charge exchange interactions. There is uncertainty here both in the magnitude and energy dependence of the cross section, and in the nature of scattering following the interaction. Recent experimental work[31] may clarify some of these issues. 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 will certainly require inclusion in the plume simulation of non-isothermal and partially magnetized electrons.

While three-dimensional modeling of Hall thruster plumes interacting with a representative satellite configuration was performed by Oh and Hastings,[12] 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.

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

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

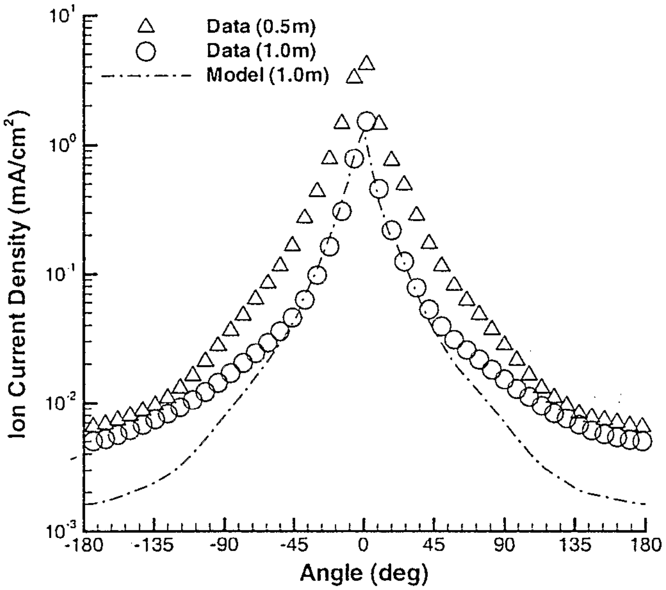

Fig. 1. Angular profiles of ion current density in the plume of the SPT-100.

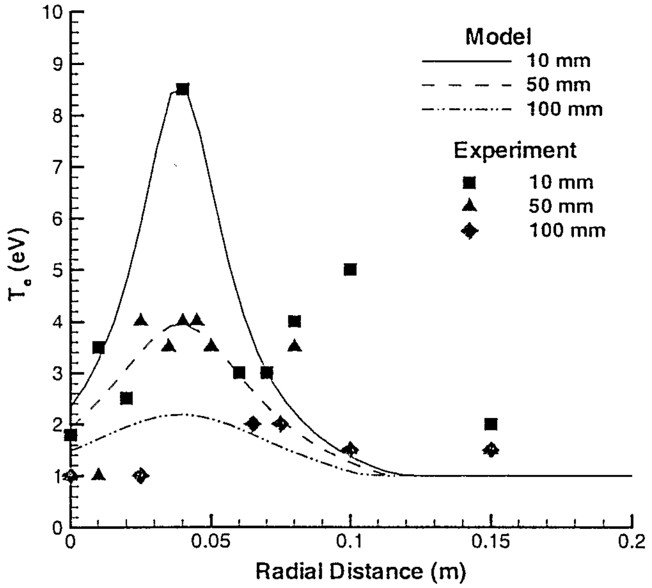

Fig. 2. Radial profiles of electron temperature in the near field of the SPT-100.

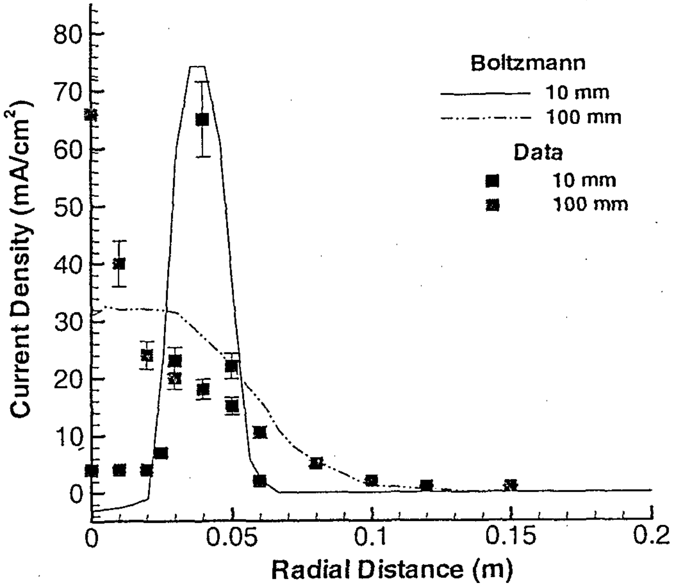

Fig. 3a. Radial profiles of ion current density in the near field of the SPT-100: comparison of measured data[16] with Boltzmann PIC-DSMC model.

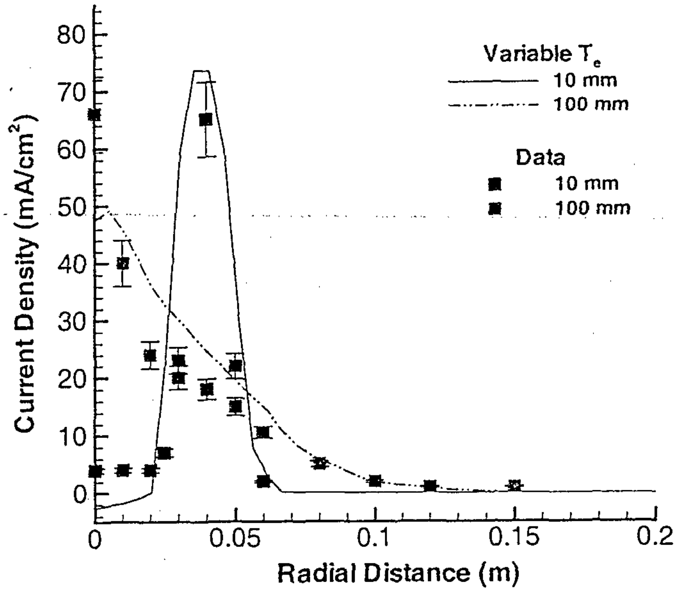

Fig. 3b. Radial profiles of ion current density in the near field of the SPT-100: comparison of measured data[16] with non-isothermal PIC-DSMC model.

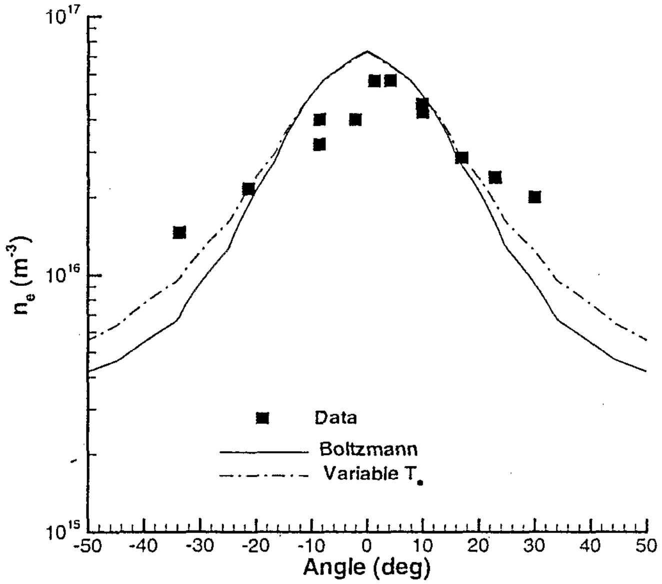

Fig. 4. Angular profiles of electron number density in the far field of the SPT-100.

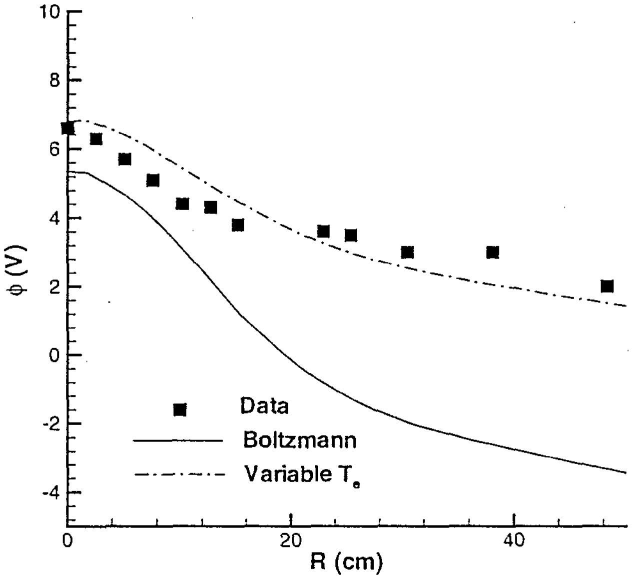

Fig. 5. Radial profiles of plasma potential in the far field of the SPT-100.

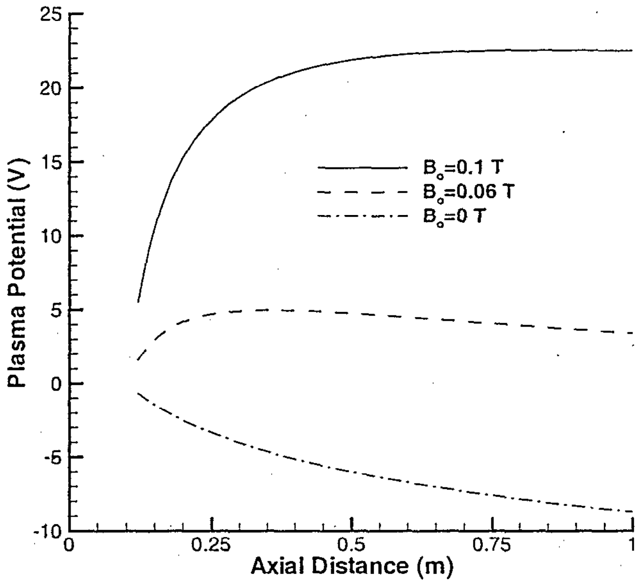

Fig. 6. Plasma potential along the axis as a function of thruster exit magnetic field strength.

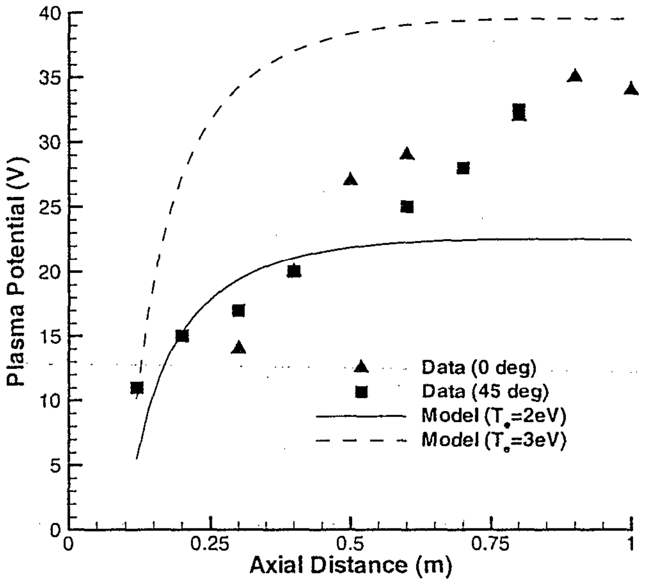

Fig. 7. Plasma potential along the axis for the Hall thruster of Ref. 19 with B_o=0.1 T.

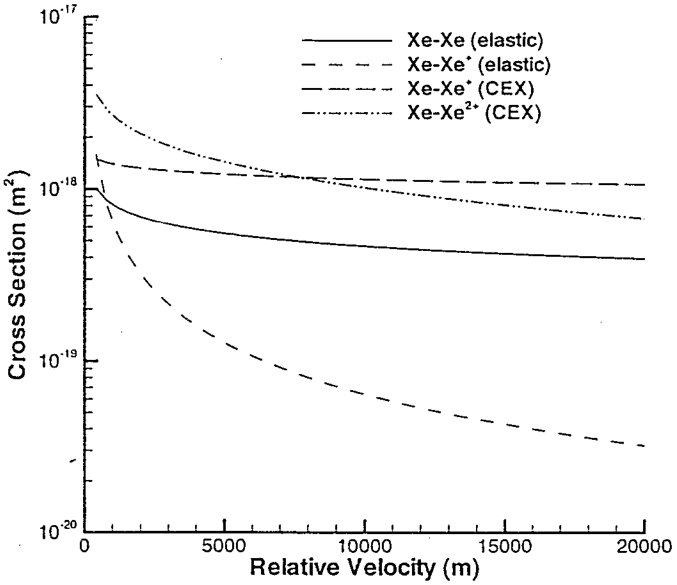

Fig. 8. Various collision cross sections as a function of relative velocity.

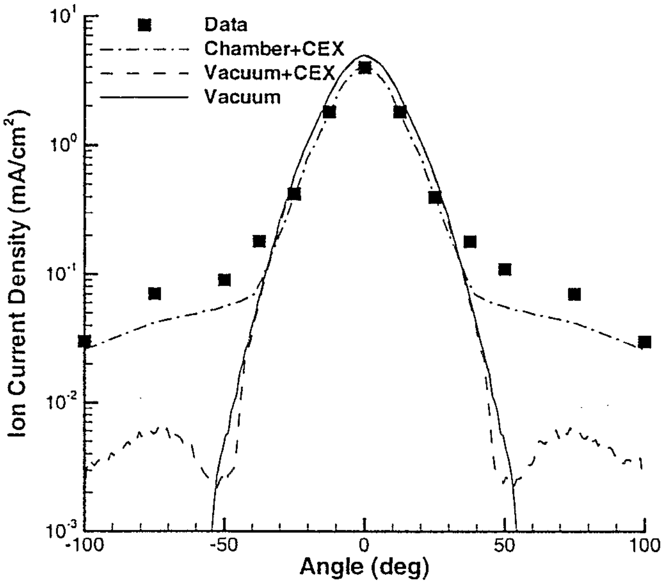

Fig. 9. Angular profiles of ion current density in the plume of the D-55.

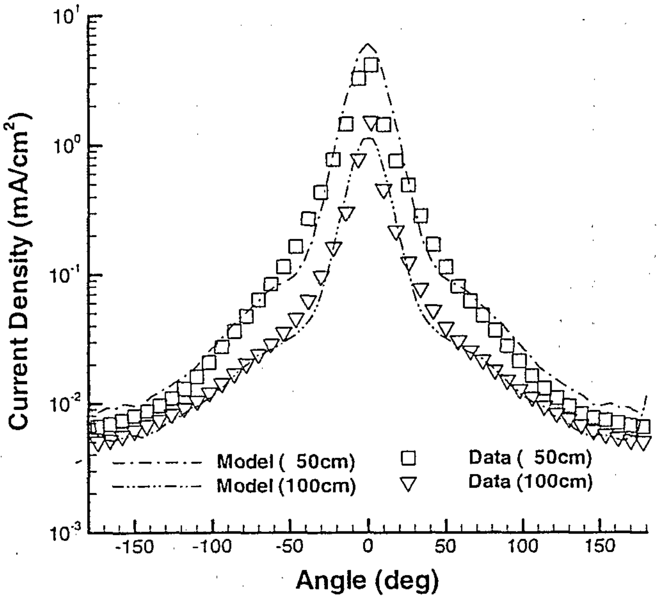

Fig. 10. Angular profiles of ion current density in the plume of the SPT-100.

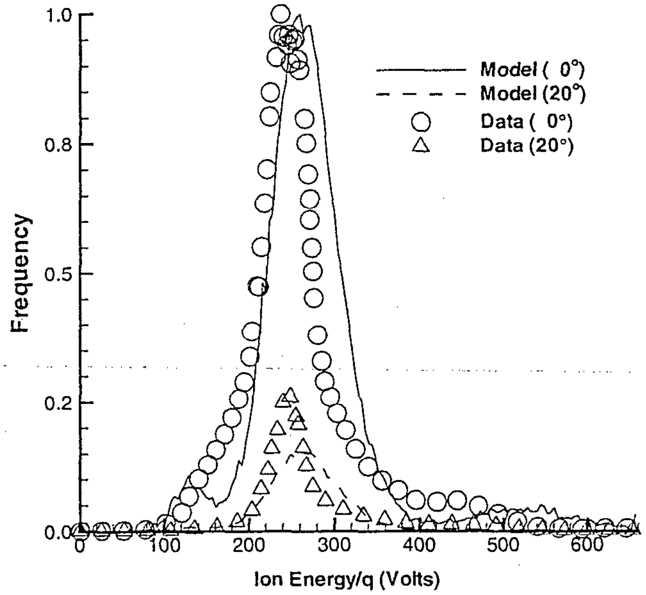

Fig. 11a. Ion energy distribution functions at 0.5 m from the SPT-100.

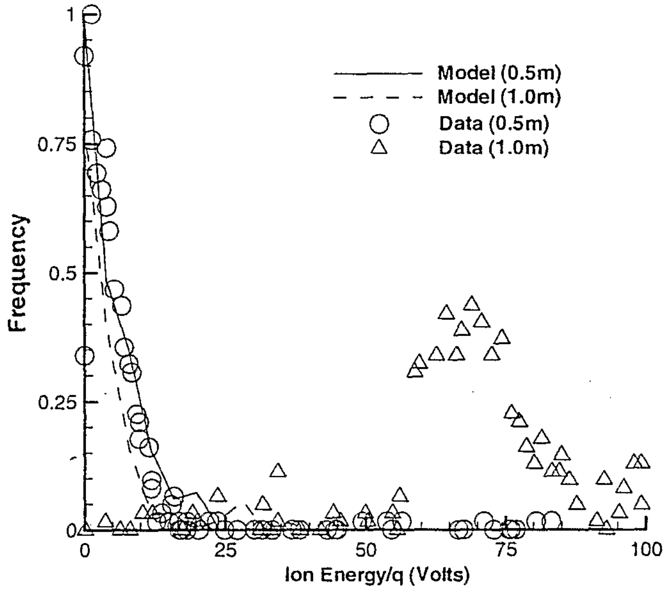

Fig. 11b. Ion energy distribution functions at 150° from the plume axis for the SPT-100.