Particle Simulation of Hall Thruster Plumes in the 12V Vacuum Chamber

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Abstract: A hybrid particle-fluid method is applied to model the plasma plume from a Hall thruster operated in the 12V vacuum chamber at the Arnold Engineering Development Center (AEDC). The method uses the direct simulation Monte Carlo method and Particle In Cell method to simulate the xenon atoms and ions. A fluid electron model is employed that is based on the Boltzmann relation. The complex geometric configuration of the vacuum chamber is handled using an unstructured mesh. The effects in the simulation of omitting charge exchange and electro-static fields are investigated. The simulation results are compared with existing plasma density measurements taken in the 12V chamber for a 4.5-kW class Hall thruster. The excellent agreement obtained between simulation and measurement serves to validate the code for analysis of plasma plumes in 12V.

Nomenclature

e = electron charge
k = Boltzmann constant
n = number density
T = temperature
g = relative velocity
ϕ = plasma potential
σ = collision cross section
ω = viscosity temperature exponent

I. Introduction

HALL thrusters represent an efficient form of plasma electric propulsion for spacecraft. They offer a high specific impulse that is well suited for satellite station-keeping, repositioning, and orbit transfer. There are concerns, however, about the plumes. For instance, the plumes may contaminate spacecraft surfaces and interfere with satellite communications. Such effects need to be understood during the development of thrusters and their

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integration onto spacecraft. Successful integration of plasma thrusters onto spacecraft involves a mixture of analysis and ground-based experiments conducted in vacuum chambers. A key aspect of the vacuum chamber experiments is the desire to maintain as low a back pressure as possible. Elevated back pressures can lead to augmentation of thrust and distortion of the plasma plume, thereby complicating the process of integration assessment. The 12V vacuum chamber located at the Arnold Engineering Development Center (AEDC) is a large facility with a total pumping rate of about 3-5x10^6 litres/sec on xenon. For thruster mass flow rates of 10-20 mg/sec, it is able to maintain a back pressure on the order of 10^{-6} torr. Further details of the facility and its operation can be found in Ref. 1. In addition to providing a physical test capability, AEDC has a desire to provide computational analysis support for customers interested in using their facilities. The focus of the present work is on the development of an analysis tool that can be applied at AEDC to model the operation of different plasma thrusters in the 12V vacuum chamber. The present study is limited to investigation of Hall thruster plumes.

In general, the near plume of a Hall thruster consists of neutrals, highly energetic ions, and electrons. The particles have collisions due to their thermal velocities, and some collisions between neutrals and ions lead to charge-exchange interactions, which produce slow ions and highly energetic neutrals. Furthermore, the ions are also affected by the self-consistent electric fields. In addition, a background gas is always involved in the ground tests of thrusters. Therefore, the behavior of thruster plumes is very complicated. An efficient approach for understanding these processes is to use computer modeling[2] because the physics at different levels can be included for the plume. For instance, the direct simulation Monte Carlo (DSMC) method[3] can be used to capture the collision dynamics, and the particle-in-cell (PIC) method[4] can be applied to include the electric field effects. In addition, computer simulations can identify the relative importance of the physics involved in the plume.

In this paper, particle simulation of a Hall thruster plume in 12V is investigated using a hybrid DSMC/PIC code. The rest of the paper is organized as follows. Section II introduces the numerical method. Section III describes the plume simulation. Section IV investigates effects of different physics and compares simulation results and measurement data. Finally, some concluding remarks are given in Section V.

II. Numerical Method

Hall thrusters primarily use xenon as propellant. The plume is comprised of beam ions with velocities on the order of 20 km/s, low energy charge-exchange ions, neutral atoms from the thruster, electrons, and the background gas of the experimental facility. The interactions of these species as well as the influence of the electric fields are the important modeling issues. Computational analysis of Hall thruster plumes is regularly performed using a hybrid particle-fluid formulation. The direct simulation Monte Carlo (DSMC) method models the collisions of the heavy particles (ions and neutrals). The particle-in-cell (PIC) method models the transport of ions in electric fields.

A. Collision Dynamics

The DSMC method uses particles to simulate collision effects in rarefied gas flows. The particles represent real ions and neutrals, and are grouped in cells whose sizes are less than a mean free path. Pairs of these particles are selected at random and a collision probability is evaluated that is proportional to the product of the relative velocity and collision cross section for each pair. The probability is then compared with a random number between zero and one 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 two types of collisions that are important in the Hall thruster plume: elastic (momentum exchange) and charge exchange. Elastic collisions involve only exchange of momentum between the participating particles. For the systems of interest here, this may involve neutral-neutral or neutral-ion collisions. For neutral-neutral collisions, the variable hard sphere collision model[3] is employed. The collision cross section for xenon is:

$$\sigma_{EL}(Xe, Xe) = \frac{2.12\times10^{-18}}{g^{2\omega}} m^2 \tag{1}$$

where g is the relative velocity and $\omega = 0.12$ is related to the viscosity temperature exponent for xenon. For neutral-ion elastic interactions, the following cross sections measured by Miller et al.[5] are employed:

$$\sigma_{EL}(Xe, Xe^{+}) = (175.26 - 27.2\log_{10}(g))\times10^{-20} m^2 \tag{2}$$

$$\sigma_{EL}(Xe, Xe^{++}) = (103.26 - 17.8\log_{10}(g))\times10^{-20} m^2 \tag{3}$$

Charge exchange concerns the transfer of one or more electrons between an atom and an ion. The cross sections are assumed to follow the same expressions for neutral-ion elastic collisions. In the present model, it is assumed that there is no transfer of momentum accompanying the transfer of the electron(s). This assumption is based on the premise that charge exchange interactions are primarily at long range.

B. Plasma Dynamics

The PIC algorithm uses charged particles and determines the charge density at the nodes of the mesh, based on the proximity of each particle to the surrounding nodes. The charge density is then used to calculate the potential at the nodes. The plasma potential can be described using the Boltzmann relationship that is derived by keeping only the dominant terms of the electron momentum equation and assuming isothermal electrons:

$$\phi - \phi_{ref} = \frac{kT_e}{e} \ln\left(\frac{n_e}{n_{ref}}\right) \tag{3}$$

The potential is then differentiated spatially to obtain the electric fields that are used to transport the ions.

C. Boundary Conditions

For the computations of the Hall thruster plume in 12V, boundary conditions must be specified at the thruster exit and along all solid surfaces in the computational domain.

Several macroscopic properties of the plasma exiting the thruster are required for the computations. Specifically, the plasma potential, the electron temperature, and for each species the number density, velocity, and temperature are required. These properties are determined using an approach involving a mixture of analysis and estimation.[5] Several types of surfaces are included in the computation. They are thruster walls, cryopump surfaces, baffles, and chamber walls. Along these walls, the plasma potential is set to zero. Any ions colliding with the walls are neutralized. When particles hit the cryopump surfaces, a fraction of the particles are pumped away, which is characterized by a sticking coefficient (a value of 0.8 is used in the present study). For particles scattered back into the flow field from all surfaces, a diffuse reflection is assumed characterized by the surface temperature.

III. Plume Simulation

The 12V chamber at AEDC is an Electric Propulsion (EP) test facility, whose height is about 12 m. The chamber has a relatively complex axi-symmetric geometry. As shown in Fig. 1, the thruster is mounted on the chamber axis and fired downward. There are three baffles in the "waist" area and three more near the center of the chamber bottom. Two cryopumps are employed to pump the plume away. In the present study, the plume is generated by a 4.5 kW class xenon Hall thruster (the Aerojet BPT-4000). If the vacuum chamber is assumed empty when the thruster starts to fire, simulation (Fig. 2) shows that it will take about 1 second to balance the mass in the plume due

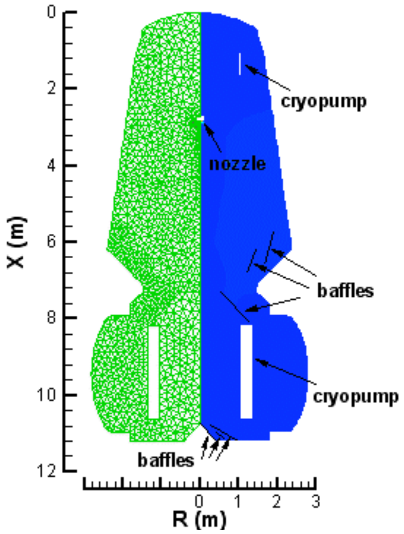

Figure 1. Mesh for the 12V chamber.

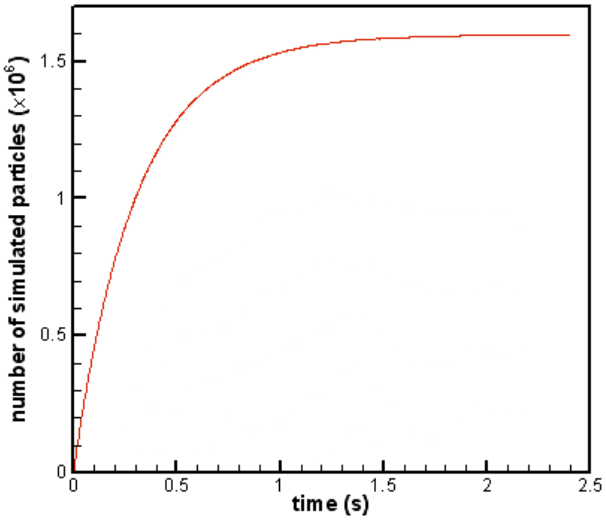

Figure 2. Approach to steady state in the simulation

to the thruster firing and the pumping. There is one main reason for taking a long time to reach a steady state for this high-speed plume. The cryopump panels are at very low temperature (20K) so that the thermal velocity of particles reflected from the panels is very small, which indicates that the characteristic speed of background particles (reflected neutrals) is about one order of magnitude smaller than the neutral velocity in the near plume and three orders of magnitude smaller than the ion velocity in the nozzle exit.

The relatively large speed at the thruster exit establishes a near field plume in a very short time whereas the far field plume requires a much longer time, which can be illustrated by showing the total number density at two different times (Fig. 3). The ions establish themselves much more rapidly as indicated by the relatively minor changes observed in Fig. 4 for these two times. The more rapid convergence of the plasma component is further illustrated in Fig. 5 that shows the behavior of plasma potential. The different behavior of neutrals and ions is also illustrated in Fig. 6 by showing the streamlines of the individual species. Specifically, the ions are emitted from the thruster exit and are lost on any surfaces, whereas the neutrals come from both the thruster exit and the surfaces of baffle and chamber, and are only removed by the cryopumps.

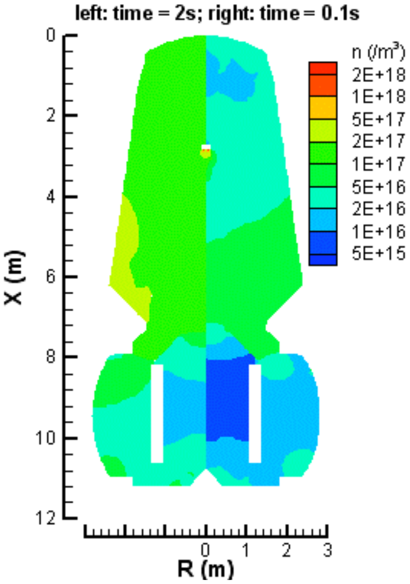

Figure 3. Total number density at different times.

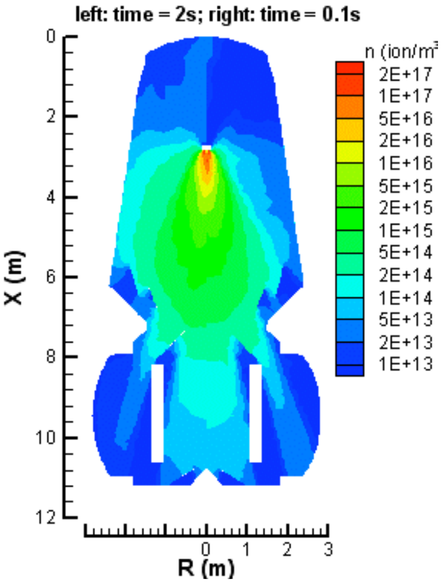

Figure 4. Ion number density at different times.

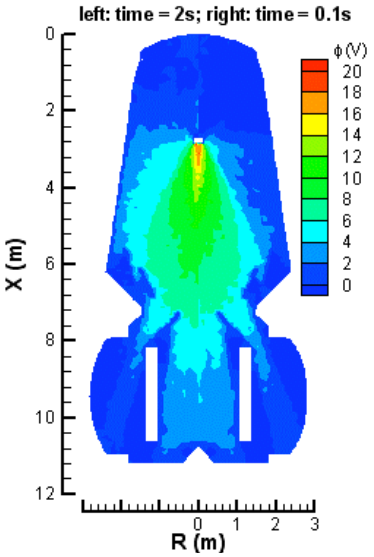

Figure 5. Plasma potential at different times.

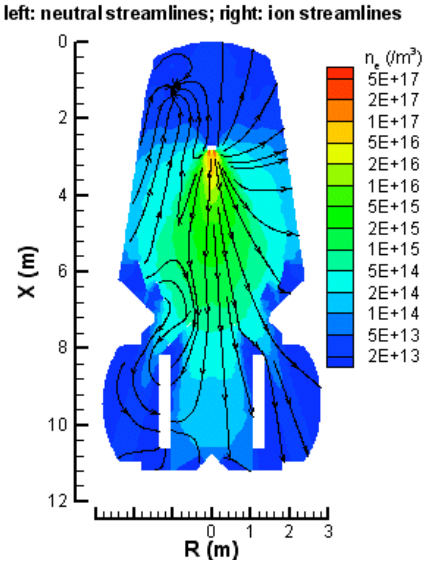

Figure 6. Streamlines of atoms and ions.

IV. Physics Modeling

A series of plume simulations are conducted to quantify the effects of different physical mechanisms on the plasma plume structure. Specifically, three simulations are performed: (1) with charge exchange and electro-static fields (DSMC, PIC, CEX); (2) with electro-static fields and no charge exchange (DSMC, PIC), and (3) with charge exchange and no electro-static fields (DSMC, CEX). Results from these simulations are compared in Figs. 7a and 7b for the total number density. In Fig. 7a, the full simulation result is shown on the left, and the simulation omitting charge exchange and including electro-static fields is shown on the right. In Fig. 7b, the right hand solution includes charge exchange collisions but now omits the electric fields. There are relatively minor differences between these three solution results indicating that the overall pressure distribution in the 12V chamber is largely unaffected

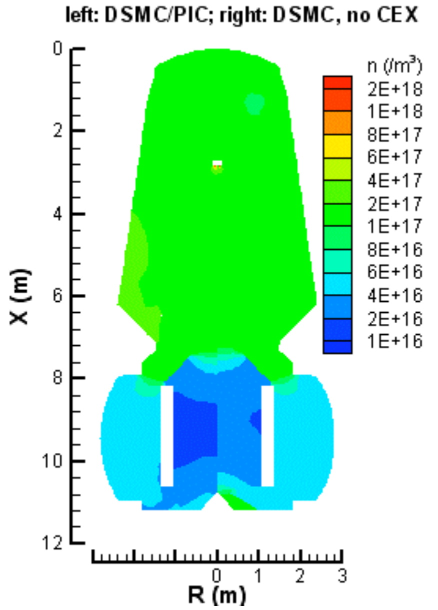

Figure 7a. Total number density obtained with different physical models.

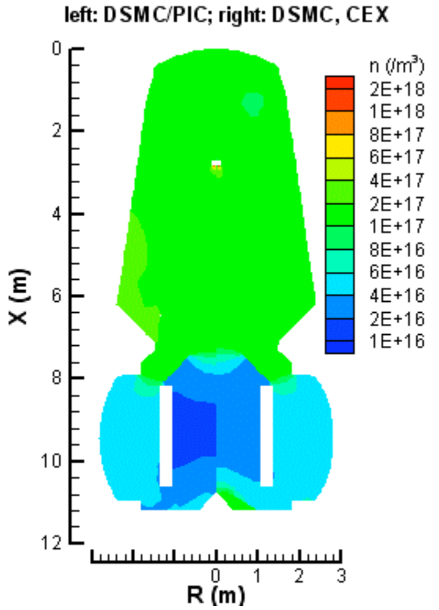

Figure 7b. Total number density obtained with different physical models.

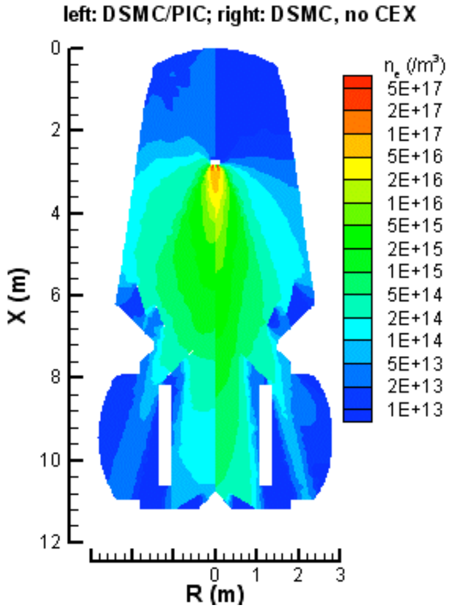

Figure 8a. Plasma number density obtained with different physical models.

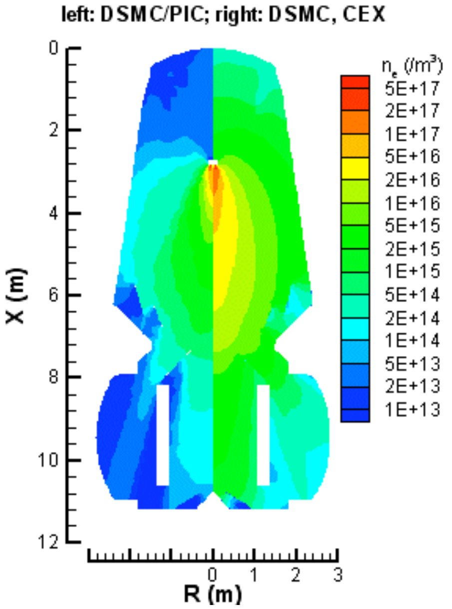

Figure 8b. Plasma number density obtained with different physical models.

by the additional physics. The same comparisons are made in Figs. 8a and 8b for the plasma density. Figure 8a indicates that charge exchange has a relatively weak effect on the plasma distribution except for the backflow region behind the thruster. By contrast, Fig. 8b shows that omitting the electric fields creates a significantly different plasma plume structure

Comparison is also made between the simulation results and measurement data. In Ref. 7, the application is reported of a microwave interferometry diagnostic for measurement of plasma density in 12V in the plume of the BPT-4000 Hall thruster. Raw data and best curve fits are presented in Ref. 7 of the plasma density distributions. In our use of these data sets, the error bar is set as 50% of the curve fitted value based on our observations of the effectiveness of the curve fit. In Fig. 9a, comparisons between the three different simulations are shown for the radial plasma density profiles at five different axial distances from the thruster exit plane. These profiles show quantitatively the same trends illustrated in Figs. 7-8. Namely, that omitting the electric fields has a much greater effect on the plume structure than omitting the charge exchange collisions. In Fig. 9b, the full DSMC/PIC simulation results (including both charge exchange and electric fields) are compared with the curve-fits provided by Meyer et al.[7] The simulation and measurement profiles are in remarkably good agreement at all locations in the plume considered The two data sets lie within the uncertainty level of the curve-fit data at all points. For reference, Fig. 9c is taken directly from Ref. 7 and compares the curve fits with the raw measurement data. Comparison of the raw measurement data in Fig. 9c with the DSMC/PIC results in Fig. 9b shows even better agreement than with the curve-fit data. The excellent levels of agreement obtained in these comparisons serves as a strong validation of the DSMC-PIC code developed for analysis of plasma plumes in the 12V facility.

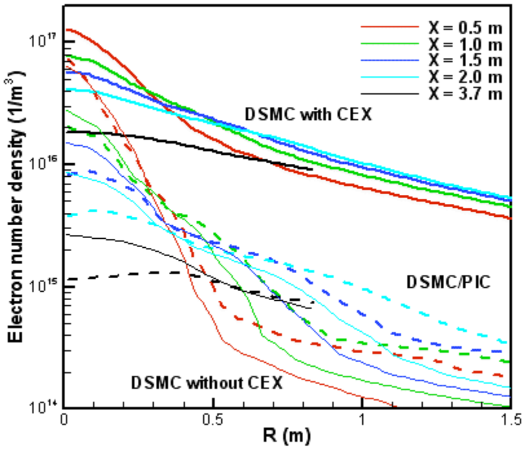

Figure 9a. Radial Profiles of plasma number density

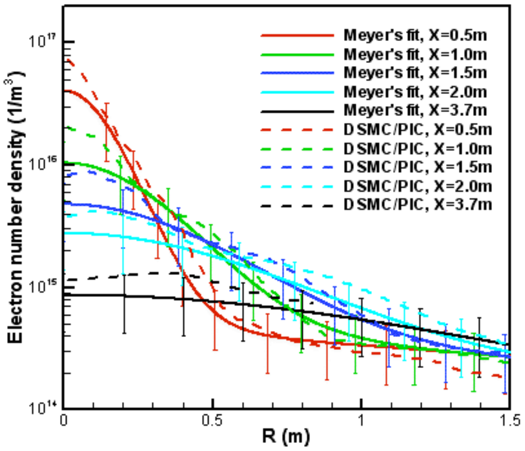

Figure 9b. Radial Profiles of plasma number density

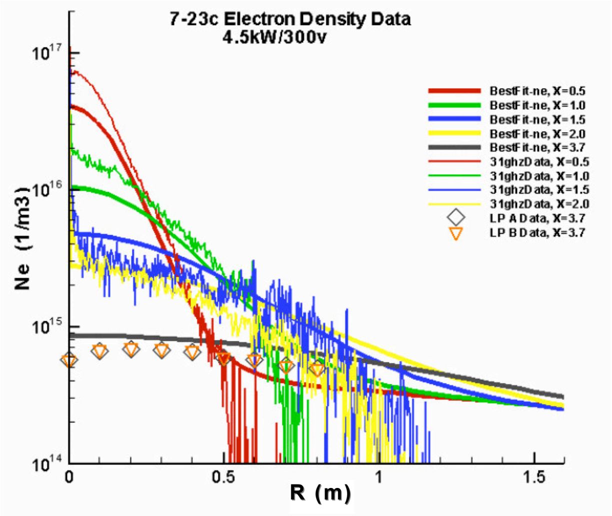

Figure 9c. Radial Profiles of plasma number density (taken from Ref. 7).

V. Conclusions

A general purpose, hybrid DSMC-PIC-fluid code has been developed for simulation of plasma plumes from thrusters operated in the 12V electric propulsion facility at AEDC. The code was applied to model the plasma plume structure from the BPT-4000 Hall thruster. A series of simulations was performed in order to assess the sensitivity of the computed results to inclusion of different levels of physical modeling fidelity. Comparison of these results indicated that the electric fields have a significantly stronger impact on the plasma plume structure than charge exchange collisions. The physical accuracy of the full plume simulation was assessed through comparisons of previous measurements of plasma number density in the thruster plume obtained with a microwave interferometer. Excellent agreement was obtained between simulation and measurement for all plume locations considered. The simulation tool is therefore considered validated for application to this class of Hall thruster.

Acknowledgments

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