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14. ABSTRACT
Two dimensional ax symmetric simulations of xenon plasma plume flow fields from a D55 Anode layer Hall thruster is performed. A hybrid particle-fluid method is used for the Simulations. The magnetic field surrounding the Hall thruster exit is included in the Calculation. The plasma properties obtained from the hydrodynamic model are used as boundary conditions for the simulations. In this simulation, the Boltzmann model and a detailed fluid model are used to compute the electron properties, the direct simulation Monte Carlo method models the collisions of heavy particles, and the Particle-In-Cell method models the transport of ions in an electric field. The accuracy of the simulation is assessed through comparison with various measured data. It is found that a magnetic field Significantly affects the profile of the plasma in the Detailed model. For instance, in the case of zero magnetic field, the plasma has a potential about 80 V at 10 mm from the thruster exit, while in the case of a magnetic field included, the plasma potential is about 60 V. Results predicted by the Detailed model with the magnetic field are found to be in better agreement with experimental data.

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MODELING A HALL THRUSTER
FROM ANODE TO PLUME FAR FIELD

AFOSR GRANT FA9550-05-1-0042

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Abstract
Hall thrusters represent an efficient form of electric propulsion that is being implemented on USAF satellites for station-keeping tasks. Numerical simulation of the plasma flow inside Hall thrusters is playing an increasingly significant role in the development of the thrusters to better understand propulsion and lifetime performance. Numerical simulation of the plumes of Hall thrusters is required to accurately assess spacecraft integration issues. The work being pursued here seeks to develop *for the first time* an end-to-end Hall thruster simulation capability that begins with propellant injection at the thruster anode, and ends in the plume far field. The development of a comprehensive simulation capability is critical for a number of reasons. The main motivation stems from the need to directly couple simulation of the plasma discharge processes inside the thruster and the transport of the plasma to the plume far field. The simulation strategy will employ two existing codes, one for the Hall thruster device and one for the plume. The coupling will take place in the plume near field region that has not previously been modeled in detail. The simulation process will be assessed through application to Hall thrusters for which measured data exist.

Recent accomplishments
Significant progress has been made in improving and extending the modeling capabilities for both Hall thruster devices and Hall thruster plumes. In particular, we have focused on thruster and plume modeling of the D55 anode layer Hall thruster due to the wide availability of detailed flow field and performance measurements. In the following sections, we summarize this progress.

Hall Thruster Channel Modeling
Hall thruster device modeling efforts were focused on calculating the thruster exit condition. A model for the thruster channel is developed [1]. This model is used to simulate the flow within the channel of the D55 TAL thruster.

We consider three conditions corresponding to three different experiments. These experiments conducted at the University of Michigan [2] [3], TsNIIMASH [4], and the University of Tennessee Space Institute (UTSI) and Lockheed Martin Astronautics (LMA) [5]. It is reported [6] that some portion of the plasma plume of a D55 thruster consists of doubly charged ions. In this research, the number fraction of double xenon ions is assumed to be 0.2.

Contour plots of the plasma density and potential fields are shown in Figs. 1 and 2, respectively. The anode is on the left side of the figure, while the exit plane is at the right border. The white spaces above and below the channel in the figures represent the outer and inner wall thicknesses, respectively, in relation to the channel domain. The velocity distributions are based on the ion temperature, which can be assumed to be the same as the initial neutral temperature, which in turn is based on a wall temperature of 1000 K. The velocity distributions are used to create a distribution of ion flow angles.

The radial distribution of the ion number density and velocity at the thruster channel exit are used for the plasma plume simulation.

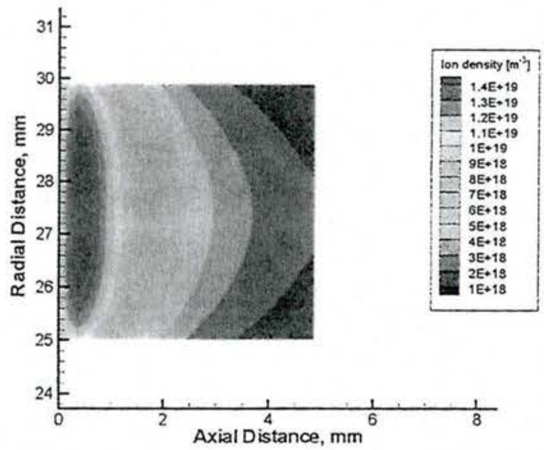


Figure 1: The simulated plasma density field within the D55 TAL thruster

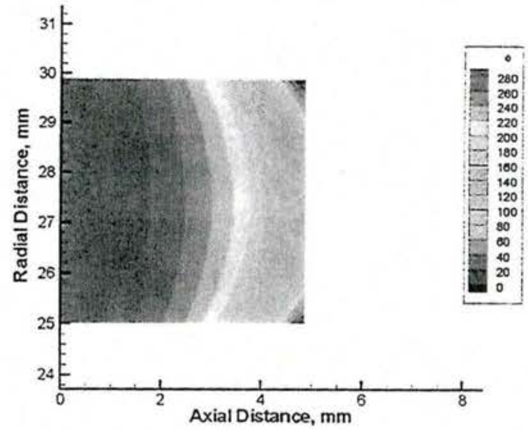


Figure 2: The simulated plasma potential field within the D55 TAL thruster

Hall Thruster Plume Field Modeling

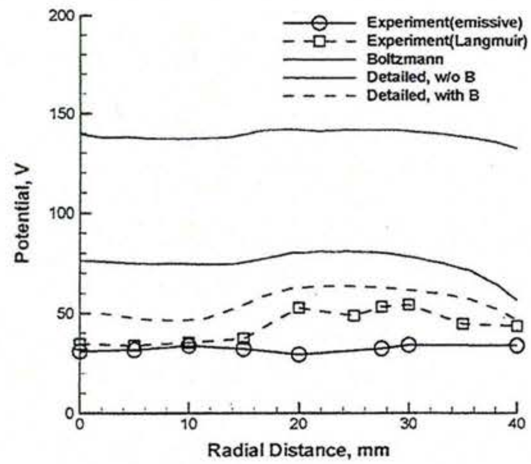
Our recent studies have focused on careful assessment of our existing Hall thruster plume models using the plume data measured for a D55 TAL thruster [2][3][4][5]. Experimental investigation of the magnetic field distribution near a Hall thruster shows that the radial magnetic field component is much larger than axial component [2]. Thus for simplicity, only the radial component of the magnetic field is considered.

Plasma Potential

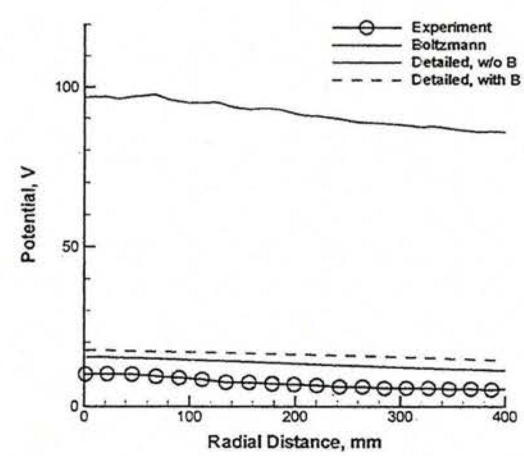
Figures 3a and 3b show radial profiles of plasma potential at axial distances of 10mm and 500mm from the thruster exit plane, respectively. At 10mm, the Boltzmann model overpredicts the potential. The Detailed model captures the shape quite well although it overpredicts the potential too. However, the result is better than the Boltzmann model and if the magnetic field is considered the improvement is much better. At a distance of 500mm from the thruster, the Boltzmann model again greatly overpredicts the potential whereas the Detailed model reproduces fairly well the measured profiles.

Ion Current Density

Ion current density profiles predicted by the simulation are compared with the experimental data in Figs. 5a and 5b along radial lines located at 10 and 500mm from the thruster exit plane, respectively. Both the Boltzmann model and the Detailed model give good prediction at 10mm. At 500mm, the Detailed model shows better agreement with measurements though both models underpredict the measured values. This underprediction of ion current density over the entire domain suggests that the simulation may over accelerate ionized particles in the radial direction. This feature is consistent with the comparisons of electron number density shown in Figs. 6.

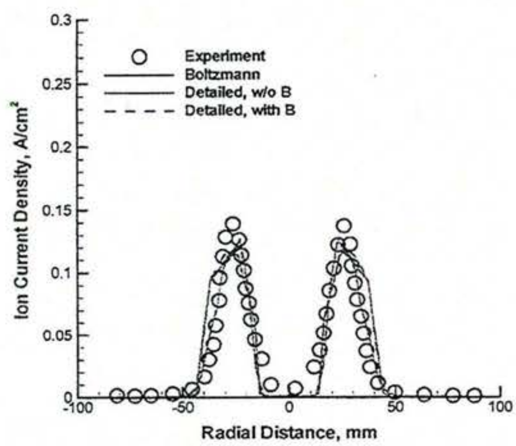


a: 10 mm from the thruster exit plane

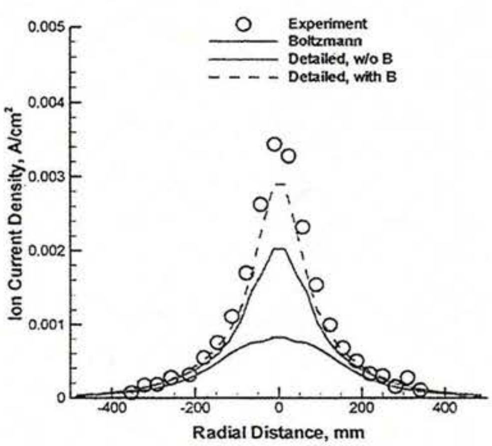


b: 500 mm from the thruster exit plane

Figure 4: Radial profiles of plasma potential



a: 10 mm from the thruster exit plane

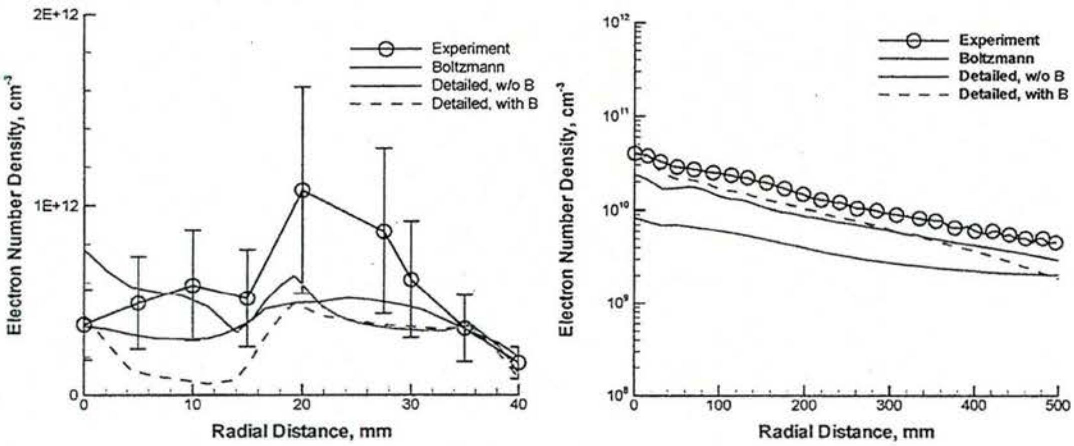


b: 500 mm from the thruster exit plane

Figure 5: Radial profiles of ion current density

Electron Number Density

Measurements of electron number density are compared with the simulations for radial profiles at 10mm and 500 mm in Figs. 6a and 6b, respectively. The simulation values represent the total charge density obtained from the number densities of the Xe_+ and Xe_{++} ions. At 10mm, most of the simulation data underpredict the measured values. The peak electron number density measured at both stations is more than double the total charge density assumed in the simulations at the thruster exit plane. One interpretation of these comparisons is that the axial component of electric fields in the simulation is so strong that the acceleration of ions is overestimated in the axial direction. One possible way to address such differences between the model and the measured data would be axial confinement of electrons caused by the magnetic field. It was shown that the axial component of the magnetic field is much smaller than the radial component in SPT-100 thrusters [7], although there is no direct evidence that it is true in D55 thrusters. Measurements of the axial component of the magnetic field are required to help resolve this issue, and no such data exist as of now. At 500mm, the Detailed model shows better agreement with the measurements though both models still underpredict the measured values over the entire radial profile.

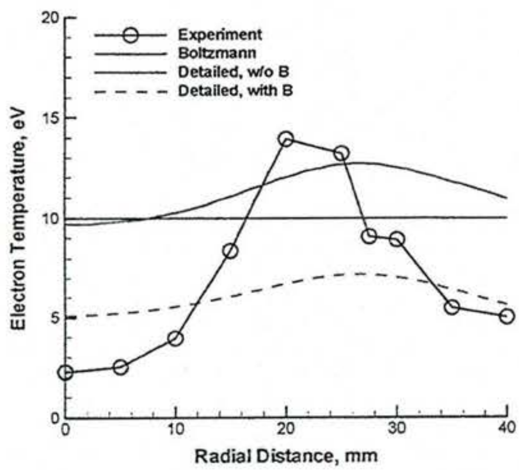


a: 10 mm from the thruster exit plane b: 500 mm from the thruster exit plane

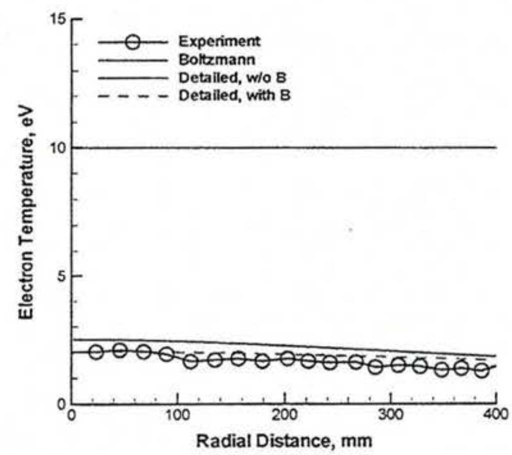
Figure 6: Radial profiles of electron number density

Electron Temperature

Figures 7a and 7b show radial profiles of electron temperature at distances of 10mm and 500mm from the thruster, respectively. Electron temperature is constant in the Boltzmann model and here we show the value of 10eV which is used in the simulation. At 10 mm, it is clear from the measurement that there is significant spatial variation in the electron temperature caused by the dynamics of the plasma as it enters the acceleration channel. In general, although the Detailed model provides reasonable agreement with the measurements, the radial gradients predicted by the model are smaller than the measured data indicate. These disparities between the models and the measurement indicate that more elaborate thruster exit boundary conditions are needed. In fact, it is known that the Detailed model is relatively more sensitive to boundary conditions than the Boltzmann model. Fig. 7a shows that the electron temperature decrease if the magnetic field is considered. If the magnetic field is considered, the resulting thermal conductivity coefficient is decreasing [8]. Therefore, the electrons' motion is confined and the electron temperature decreases. Fig. 7a shows that the Detailed model with a magnetic field underpredicts electron temperature. This suggests that we need more accurate physical models. Fig. 7b. clearly shows that the Detailed model gives good agreement with the measured data in the far field.



a: 10 mm from the thruster exit plane



b: 500 mm from the thruster exit plane

Figure 7: Radial profiles of electron temperature

Axial Velocity of Xe+

Figure 8 shows the axial velocity profiles at a radial position of 27.5 mm which is along the thruster channel center.

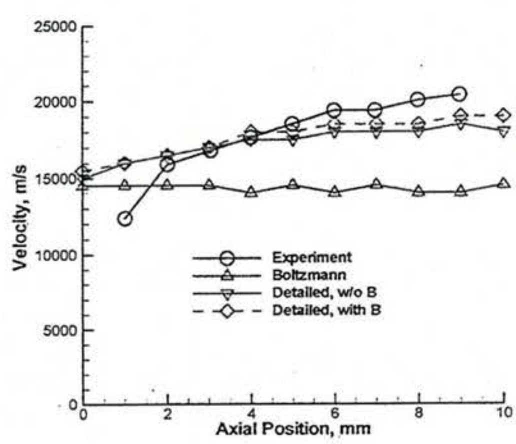


Figure 8: Axial components of ion velocity at a radial position of 27.5mm

It is clear that the Boltzmann model fails to produce sufficient ion acceleration in the near field of the plume. This is an expected result because the plasma potential gradient shown in Fig. 3 is not enough to give ions significant acceleration. The Detailed model predicts strong ion acceleration in the near field region and rapidly accelerates the ions from the thruster exit velocity of 15 km/s to a value of about 18 km/s that corresponds to the measured data and the results becomes slightly better when the magnetic field is considered. The simulation result, however, overestimates the axial velocity at z=1 mm. One possible explanation is that there would be a lot of CEX collisions in front of the thruster. Because of CEX collision, slow ions are created, and these slow ions would make lower the central value of the ion velocity distribution function.

Relevance/Transitions

The plasma plume code MONACO-PIC used in this research is distributed to Ken Tatum of AEDC where it is used to model Hall thruster plume expansions created in the 12V vacuum facility at AEDC.

Acknowledgment / Disclaimer

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Page One

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9. Archival Publications (published) during reporting period:

Choi, Y., Boyd, I.D., and Keidar, M, "Effect of Magnetic Field in Simulating the Plume Field of an Anode layer Hall Thruster," Journal of Applied Physics, Vol. 105, 2009, Article 013303.

Choi, Y., Keidar, M., and Boyd, I.D., "Particle Simulation of Plume Flows From an Anode-Layer Hall Thruster," Journal of Propulsion and Power, Vol. 24, 2008, pp. 554-561.

Keidar, M., Choi, Y. and Boyd, I.D., "Modeling a Two-Stage High-Power Anode Layer Thruster and its Plume," Journal of Propulsion and Power, Vol. 23, 2007, pp. 500-506.

Boyd, I.D., "Numerical Simulation of Hall Thruster Plasma Plumes In Space," IEEE Transactions on Plasma Science, Vol. 34, 2006, pp. 2140-2147.

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