Analysis of Plume Backflow From a Lithium Magnetoplasmadynamic Thruster

IEPC-2005-014

Presented at the 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005

Iain D. Boyd,* Kevin Scavezze†, and Chunpei Cai‡
University of Michigan, Ann Arbor, Michigan, 48109, USA

James E. Polk§
NASA Jet Propulsion Laboratory, Pasadena, California, 91109, USA

and

Edgar Y. Choueiri**
Princeton University, Princeton, New Jersey, 08544, USA

Abstract: The primary goal of this study is to estimate the spacecraft contamination potential due to plume back flow from a lithium magneto-plasma-dynamic thruster. An approximate assessment is first made of the maximum allowable rate of lithium deposition onto radiators associated with the assumed nuclear power plant of a typical host spacecraft. Contamination assessment then involves modeling the plume from the thruster using a hybrid particle-fluid approach to determine the lithium flux behind the thruster. It is anticipated that backflow can be significantly reduced through deployment of a plume shield that is included in the plume simulations. The plume results indicate a strong sensitivity to the fraction of mass emitted by the thruster in the form of cold, slow atoms created by ions recombining on the anode. Contamination is assessed for an example spacecraft geometry. It is found that some backflux occurs even in the absence of charge exchange collisions. It is also found that the spacecraft can be protected from backflow contamination by appropriate sizing of the plume shield.

I. Introduction

Lithium-fed magneto-plasma-dynamic (MPD) thrusters offer the prospects for high power, high flow-rate electric propulsion devices for interplanetary exploration. An important concern with deployment of an MPD thruster involves spacecraft integration due to the possibility of lithium becoming incident on surfaces of the spacecraft. The main concern is that such interactions may lead to deposition of lithium on thermal radiators that may decrease their functionality. Significant flux into the back flow region behind the thruster may result from several physical mechanisms: (1) ions pushed into the back flow region by electrostatic fields; (2) neutral atoms that predominate at the edge of the thruster exit due to recombination of ions on the anode, and (3) the charge exchange plasma also formed in this region. Accurate assessment of these effects is required at the design stage of the thruster technology

* Professor, Department of Aerospace Engineering, iainboyd@umich.edu.
† Graduate Research Assistant, Department of Aerospace Engineering, kscavezz@umich.edu
‡ Graduate Research Assistant, Department of Aerospace Engineering, ccai@umich.edu
§ Technical Group Leader, Advanced Propulsion Technology Group, james.e.polk@jpl.nasa.gov.
** Associate Professor, Department of Mechanical & Aerospace Engineering, choueiri@princeton.edu

to try and minimize the effects as a component of the overall design philosophy. The prediction of plume back flow requires physically accurate and numerically efficient simulation of collision and plasma phenomena in a complex geometric configuration. It is significant to note that no comprehensive simulations of MPD plume flow fields have ever been performed.

The approach adopted in the present study is to simulate the plasma plume from a lithium MPD thruster using a hybrid particle-fluid approach. A key aspect of these simulations is the amount of cold atoms assumed to exit the thruster. This property is estimated partly through the use of detailed computations of the plasma flow in a similar MPD thruster. An analysis is also conducted to estimate the maximum flux of lithium that can be tolerated by the thermal radiators. The plume simulation results include a shield to partially reduce the lithium back flux to the radiators. Assessment of the contamination potential of the thruster is finally performed using the results of the plume simulation in conjunction with the tolerable levels of lithium fluxes.

First, the MPD thruster and an example host spacecraft are described. Next, the analysis to establish the maximum tolerable levels of lithium flux to the radiators is performed. The plume simulation is described including the analysis to estimate the fraction of mass emitted by the thruster in the form of cold atoms. Results are then presented and used to provide a final assessment of contamination potential and options for risk reduction.

II. The ALFA^2 Lithium MPD Thruster

The ALFA^2 thruster is being designed under a joint program involving Princeton University, the Jet Propulsion Laboratory (JPL), NASA Glenn Research Center, NASA Marshall Space Flight Center, the University of Michigan, and Worcester Polytechnic Institute. Two different thrusters are being developed in this program: (1) a smaller laboratory thruster to be tested at Princeton University, and (2) a larger thruster to be tested at JPL that is representative of a flight model. It is the full-scale, larger thruster that is considered in this plume contamination assessment study. A schematic diagram of the thruster is shown in Fig. 1a. The basic parameters of the thruster are a specific impulse of 6,200 sec, a mass flow rate of 80 mg/sec, and a thruster exit diameter of 172 mm. The mass flow rate, specific impulse, and thruster exit area are used to determine the flow conditions at the thruster exit that are input into the plume simulation. For the purposes of determining whether plume contamination is an issue for the ALFA^2 thruster, a particular host spacecraft geometry is assumed and shown schematically in Fig. 1b. This spacecraft is representative of a planetary exploration architecture, powered by a nuclear thermal reactor. The thrusters are located at the opposite end of the spacecraft from the payload, and the entire spacecraft is shown to be protected from the plume by a near-circular disk-shaped shield. The plume contamination study performed here assumes two ALFA^2 thrusters are being operated simultaneously. Axially symmetric plume simulations are performed in which the total thruster exit area is doubled to simulate this multiple thruster total mass flow rate condition.

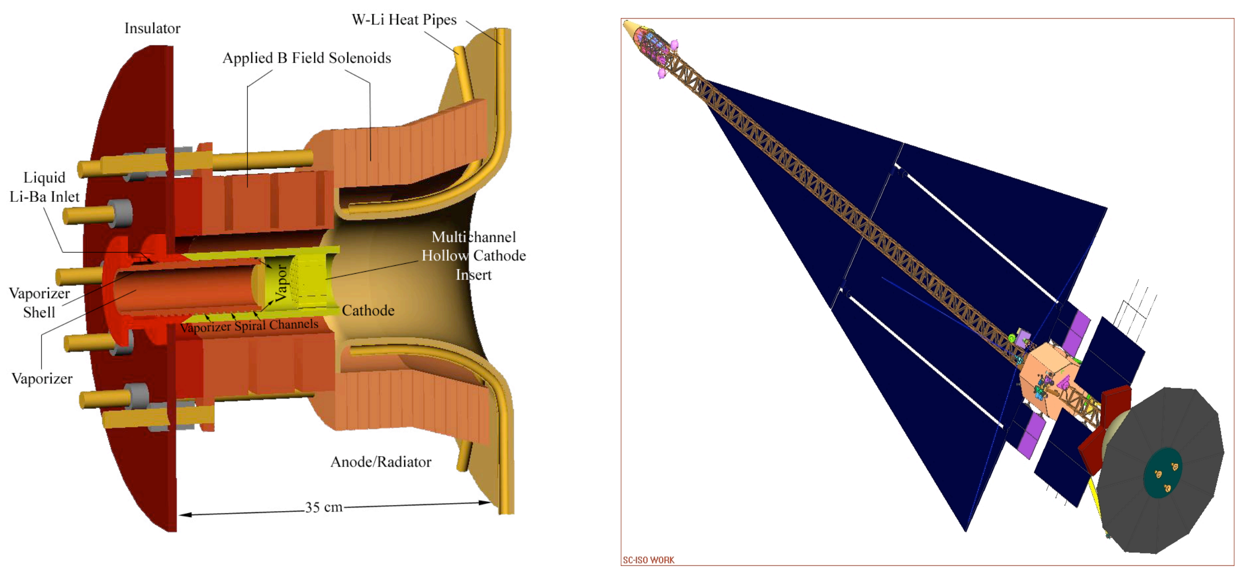

Figure 1. (a) Schematic of the ALFA^2 MPD thruster; (b) a possible host spacecraft using ALFA^2 thrusters

III. Determination of the Maximum Tolerable Lithium Flux

The primary spacecraft integration concern of MPD thruster technology concerns deposition of lithium in the backflow region of the thruster plume onto radiators used by the nuclear power system to radiate away excess heat. As illustrated in the host spacecraft shown in Fig. 1b, these thermal radiators dominate the geometric structure of the spacecraft. Even though the ALFA^2 thrusters are located at the downstream end of the spacecraft, and are fired in the direction away from the radiators, there is expected to be a finite amount of lithium propellant that flows behind the thruster in the direction of the radiators. The assessment of potential contamination from the ALFA^2 thruster onto this type of spacecraft configuration therefore requires two steps. First, there is a need to determine the maximum tolerable level of lithium deposition onto the thermal radiators that will not have any adverse effect on their radiating performance. Then, a detailed plume simulation is performed including the backflow region to determine if these maximum flux levels are exceeded at any point on the radiators.

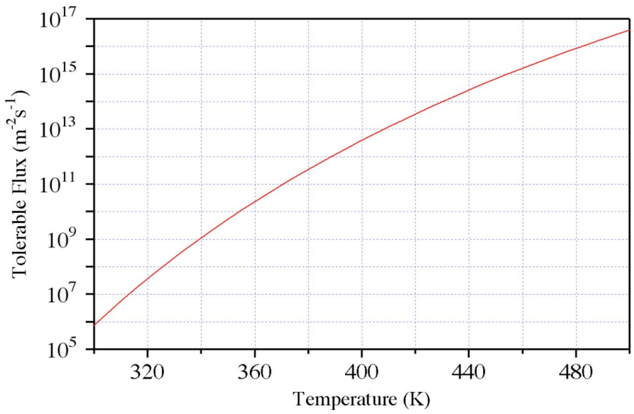

Figure 2. Tolerable flux of lithium onto thermal radiator surfaces as a function of surface temperature.

The spacecraft surfaces most at risk from lithium contamination are the radiators, because they extend furthest from the spacecraft centerline and because their radiative capability would be significantly impaired with a low emittance coating of lithium. A simple analysis can be used to obtain an estimate of the tolerable lithium flux. The condensation rate $\dot{m}_c$ of a contaminant on a spacecraft surface that is already covered by at least one monolayer of a metallic adsorbate is given by the relationship

$$\dot{m}_c = \dot{m}_i \alpha - \dot{m}_e$$

where $\dot{m}_i$ is the incident flux of contaminant to the surface, α is the condensation coefficient of the incident flux on the bulk condensate, and $\dot{m}_e$ is the evaporation rate from the bulk deposit. If the lithium flux to the hot radiator surface is less than or equal to the evaporation rate of lithium at the temperature of the radiator, then no net deposition will occur. The growth of the first monolayer is governed by a similar balance equation that includes terms describing the adsorption and desorption on surface sites free of the bulk condensate. Data on the adsorption and desorption kinetics of lithium on radiator materials are not available, so a detailed analysis of the growth of the first monolayer is not possible. However, a monolayer thickness is less than the wavelength of thermal radiation and therefore should not alter the radiative characteristics of the surface. By assuming that the condensation coefficient α is unity and that the evaporation can be described by the vapor pressure (taken from Ohse[1]) and the surface temperature, the maximum allowable flux of lithium vapor for which no further growth of the contaminant layer occurs can be calculated, as shown in Fig. 2. It is found that the allowed flux is very sensitive to the surface temperature. A detailed thermal analysis of the radiators was not conducted as part of the spacecraft conceptual design developed for the ALFA^2 program, but the temperatures are assumed to be similar to those on the radiators designed for the Prometheus 1 mission. The temperature near the tips of those radiators was about 400K, so the maximum tolerable flux to this location is about 3×10^{12} particles/m^2/sec. This is the figure of merit used to assess whether contamination from the ALFA^2 plume represents a serious issue or not. Note that any lithium that is incident on hot radiator surfaces will be re-emitted thus acting as a source of lithium that could contaminate other spacecraft surfaces. The estimation of this secondary effect lies beyond the scope of the present investigation.

IV. Plume Analysis

A. Numerical Approach

The primary mechanisms creating plume backflow from plasma thrusters are electro-static fields and collisions. The number density at the exit of the ALFA^2 thruster is of the order of 10^{18}-10^{19} m^{-3}. This indicates that the flow is not in the hydrodynamic regime. However, there will be some collisions that need to be taken into account. The numerical approach employed in the present work employs a hybrid particle-fluid approach. The lithium ions (only singly charged) and atoms are simulated as particles using the direct simulation Monte Carlo (DSMC) method[2] to model collisions, and the Particle-In-Cell (PIC) method[3] to accelerate the ions self-consistently in electrostatic fields. Due to their significantly smaller length and time scales, electrons are simulated using a hydrodynamic fluid approach. In the present work, the electron fluid model simply uses the Boltzmann relation that provides the plasma potential based on the plasma number density that is obtained directly from the spatial distribution of the ions along with an assumption of charge neutrality. While more advanced electron fluid models have been developed recently for xenon plasma plumes,[4] the Boltzmann relation is considered a sufficient approach for this preliminary study. A critical aspect of these simulations concerns the cross sections for charge and momentum exchange as these are important mechanisms leading to plume backflow. In the present work, the charge exchange cross sections are evaluated using the semi-empirical general model of Sakabe and Isawa.[5] When a charge exchange event occurs between a lithium ion and a lithium atom, it is assumed that no collisional scattering occurs. Based on conclusions drawn for a xenon plasma,[6] it is assumed that the momentum exchange cross section between an ion and an atom is identical to that for charge exchange. For momentum exchange between two atoms, the Variable Hard Sphere (VHS) collision model of Bird[2] is employed. Coulomb collisions are omitted from the present analysis. All momentum exchange collisions are assumed to follow isotropic scattering. The hybrid DSMC-PIC-fluid code employed in the present study is based on a general unstructured mesh implementation of these algorithms.[7]

B. Boundary Conditions

The properties assumed at the thruster exit will largely determine the resulting plume. As mentioned earlier, bulk properties of the thruster, including mass flow rate, specific impulse, and exit area, are employed to determine most of the flow properties input to the plume simulation. Based on computational analysis of a similar MPD thruster,[8] ions are assumed to have a temperature of 4 eV at the thruster exit where the plasma potential is assumed to be 10 V. An average electron temperature of 1 eV is assumed for the entire plume.

A key parameter that cannot be obtained from such information is the fraction of mass exiting the thruster in the form of cold atoms that have recombined from ions incident on the thruster anode. These atoms may play a critical role in determining the plume backflow due to their participation in charge exchange events. In such events, the low energy atom is converted into an ion that becomes very mobile in the electro-static fields generated in the plume by significant gradients in plasma density. These are the ions most likely to be pushed into the backflow region of the plume. This phenomenon is characterized in the present work by a parameter called the atom leakage fraction, γ. To estimate the value of this parameter, results are again employed from the computer analysis of the plasma flow in a similar, self-field MPD thruster.[8] While the plasma streamlines are not expected to intersect with the anode surface, there will be some finite flux of ions to the wall due to thermal and sheath effects. The mass flow rate of ions attracted by the sheath to the anode is given by:

$$\dot{m}_{ia} = n_{ia} v_B 0.6 m_i 2\pi r l$$

where n_{ia} is the average ion number density along the anode wall, v_B is the Bohm velocity, m_i is the ion mass, r is the average anode radius, and l is the anode length. The factor of 0.6 accounts for the reduction in number density in the pre-sheath due to ion acceleration to the Bohm velocity. It is assumed that every ion that is incident onto the anode wall is reflected as a neutralized atom. However, many of these atoms can be subsequently re-ionized due to the relatively high electron temperatures in the thruster. The average ionization distance (λ_i) is estimated to be about 3 cm based on an average plasma density of 10^{20} m^{-3} and a lithium ionization cross section of $3\text{x}10^{-19}$ m^2 at the average thruster electron temperature of 5 eV. The atom mass leakage fraction is then evaluated as

$$\gamma = \frac{\dot{m}_{na}}{\dot{m}} \frac{[\pi(r^2 - (r-\lambda_i)^2]}{2\pi r l}$$

where $\dot{m}$ is the total mass flow rate from the thruster. The final value obtained is γ=0.01 which means that 1% of the mass flow out of the thruster is in the form of cold atoms. These atoms are assumed to exit the thruster at the local sound speed at the temperature of the anode, about 2400 K. This value of γ is considered an upper bound. However, due to the uncertainty in determining its value, results are presented in the following for simulations that employ several different values of γ.

Boundary conditions are also required for the plume shield surface. Any heavy particles incident on the plume shield are assumed to stick to the surface. For most simulations, the potential of the shield surface is allowed to float.

C. Results

Two sizes of simulations are performed. Relatively small simulations are first performed to analyze a region of a few meters surrounding the thruster that includes the plume shield. These simulations typically employ over 600,000 particles, on a mesh of 11,000 cells, running for 65,000 iterations. Larger simulations are subsequently performed that are extended back to the tip of the thermal radiators. These simulations typically employ over 600,000 particles on a mesh of 60,000 cells. Contours of total lithium flux (particles/m^2/sec) and plasma potential are shown in Figs. 3a and 3b, respectively, for the γ=0 case (no atoms at all exit the thruster). The thruster exit is located at z=0 m, and is exhausting to the right. The region downstream of the thruster is designed to be long enough to include most contributions to the backflow process. Note that a plume shield with a radius of 5 m is included in these simulations and is located about 50 cm upstream of the thruster exit.

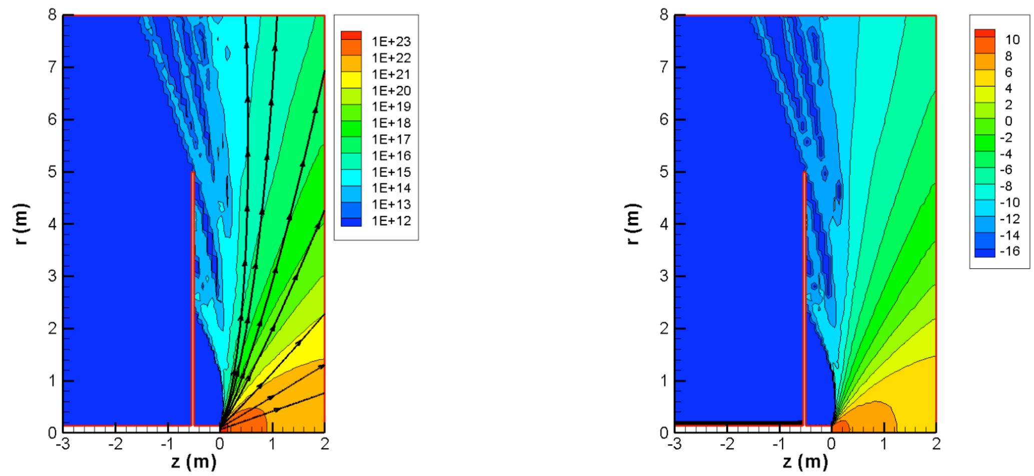

Figure 3. Contours for the γ=0 case: (a) total lithium particle flux (m^{-2} s^{-1}); (b) plasma potential (V).

It is clear in this case that only a tiny fraction of the particle flux exiting the thruster is distributed into the backflow region. The streaks at the edge of the backflow region represent individual particle trajectories. The very small amount of backflux is explained by the axial energy distribution of ions exiting the thruster that is shown in Fig. 4. The high speed of the exiting flow (Mach 6) means that only the very lowest energy beam ions can be turned around by electro-static forces into the back flow region. Hence, in the absence of any flux of cold atoms out of the thruster, there is almost no concern over plume backflow.

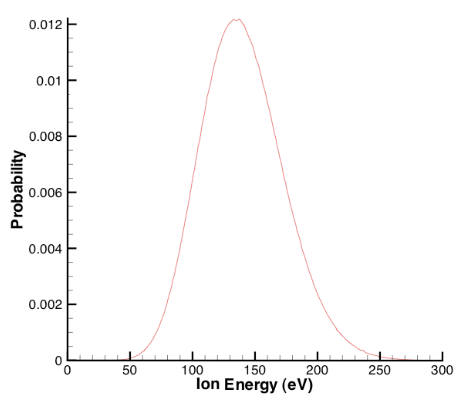

Figure 4. Distribution of the axial energy of ions exiting the ALFA^2 thruster.

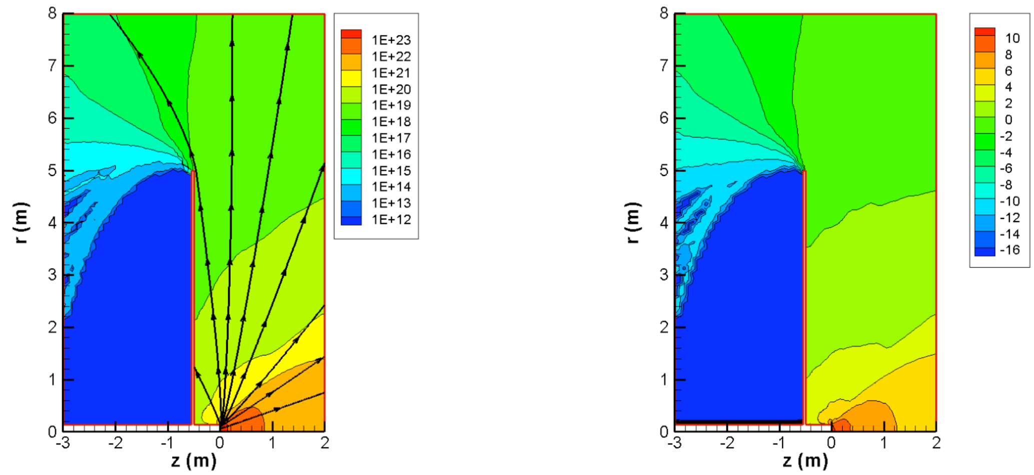

Figure 5. Contours for the γ=0.1 case: (a) total lithium particle flux (m^{-2} s^{-1}); (b) plasma potential (V).

Similar results are provided in Figs. 5a and 5b for the case of γ=0.1. This is the case in which the value of γ is an order of magnitude higher than that likely to be generated by the thruster. In this case, the flux of lithium onto the plume shield is increased significantly in comparison to the levels shown in Fig. 3a due to charge exchange collisions. Also, note how ions are pushed around the top of the plume shield due to the electrostatic fields generated by the plasma density gradients in this region of the flow. Note that the minimum plasma density assumed in the void region is 10^7 m^{-3} corresponding to the ambient plasma density in planetary exploration missions.

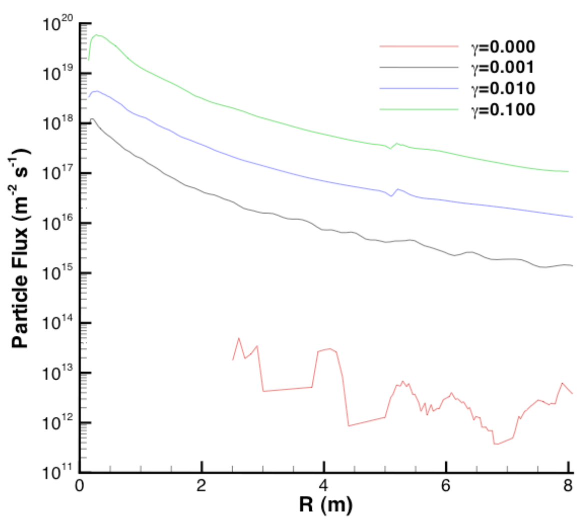

Figure 6. Radial profiles of total lithium particle flux at the axial location of the plume shield.

Radial profiles of total lithium flux at the axial location of the plume shield (50 cm upstream of the thruster exit) are shown in Fig. 6 for several different values of γ. As illustrated by the Figs. 3, there is almost zero backflux into this location for the γ=0 case. Between the cases of γ=0.001 and γ=0.100 there is an almost linear increase of backflux with increasing γ. This is expected as the charge exchange production rate, that is proportional to the product of the plasma and neutral densities at the thruster exit, is nearly linearly proportional to γ over this range.

D. Contamination Assessment

To focus the assessment of possible contamination from the ALFA^2 thruster, consideration is given to the specific case of contaminating the edge of the thermal radiators of the spacecraft shown in Fig. 1b. In this case, the radiator tips is at the coordinates (-14 m, +10 m) using the same coordinate system used in the computational results shown above. Large scale simulations are therefore performed that are extended sufficiently far into the backflow region to include the tips. Figures 7a and 7b show contours of total particle flux for the cases of γ=0 and 0.01, respectively. Recall that the maximum tolerable flux level of lithium onto the thermal radiators is 3×10^{12} particles/m^2/sec. The results in Fig. 7 indicate that the plume shield is effective if γ=0, but is not able to protect the spacecraft from the fluxes experienced at γ=0.01. A further simulation is therefore performed at γ=0.01 where a larger plume shield with a radius of 10 m is employed. The corresponding particle flux contours are shown in Fig. 8 and they clearly demonstrate that a plume shield is able to change the dynamics of the backflow region. In this case, the particle flux at the tip is almost exactly 3×10^{12} particles/m^2/sec. It is therefore concluded that a spacecraft can be protected from contamination from the plume of the ALFA^2 thruster through use of an appropriately sized plume shield.

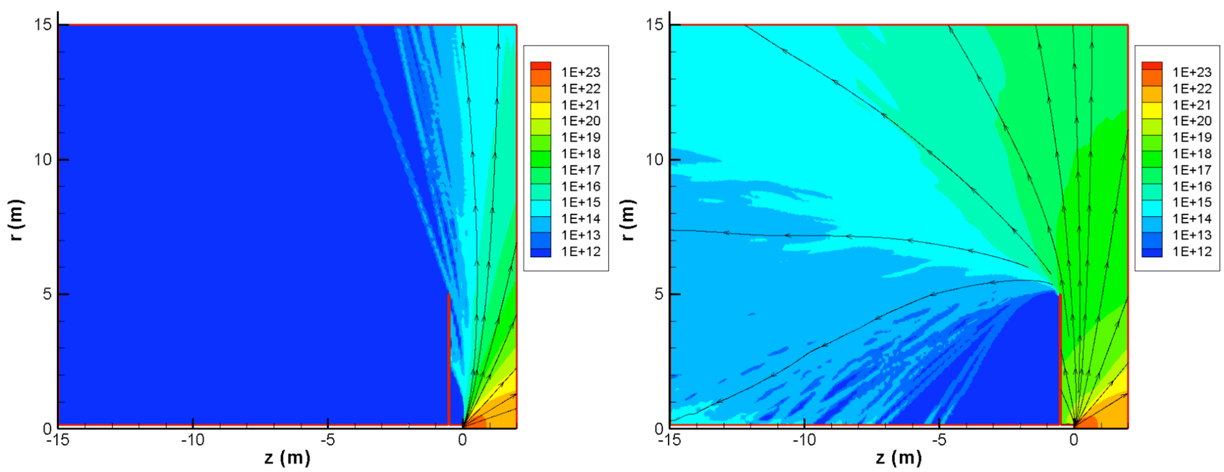

Figure 7. Particle flux contours ($m^{-2}\ s^{-1}$) for: (a) γ=0; and (b) γ=0.01.

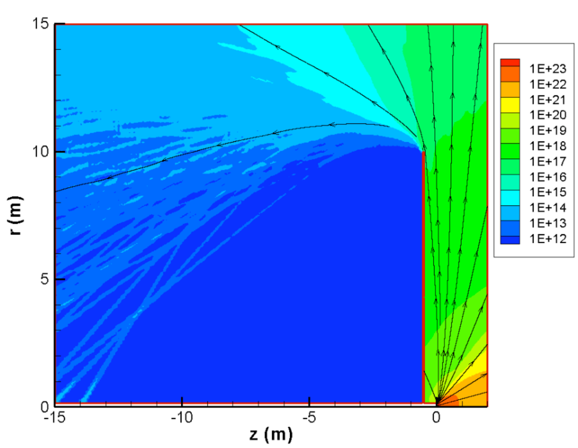

Figure 8. Particle flux contours ($m^{-2}\ s^{-1}$) for γ=0.01 and a plume shield radius of 10 m.

V. Conclusion

The potential for spacecraft contamination from a lithium-fed magneto-plasma-dynamic thruster was assessed. First, an analysis was conducted to determine the maximum tolerable lithium flux to thermal radiators on a spacecraft employing MPD thrusters. The maximum flux was obtained by setting it equal to the evaporation rate of lithium for typical radiator temperatures. Then, detailed plume simulations were performed using a hybrid particle-fluid approach. The simulations included a plume shield and a significant portion of the backflow region. An important property of the plasma exiting the thruster is the atom mass leakage fraction, γ, which is determined by the flux of cold atoms from the anode wall. This parameter was estimated at 1% based on a prior computational analysis of a similar thruster. To understand the sensitivity of the backflow results, plume simulations were conducted for a variety of values of γ. Contamination was assessed for a representative spacecraft geometry. Using a 5 m radius plume shield, it was found that the γ =0.01 case led to contamination levels of the thermal radiator tips that were too high. For the same plume shield, the case at γ=0 yielded safe levels of contamination. Further, use of a larger 10 m radius plume shield also provided safe levels of contamination. It is therefore concluded that a spacecraft can be effectively protected against backflow contamination from a lithium MPD thruster by suitable sizing of a plume shield.

Acknowledgments

This work is funded by NASA through contract NNM05AA23C administered by NASA Marshall Space Flight Center.

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