Modeling an Iodine Hall Thruster Plume in the Iodine Satellite (iSAT)

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Distribution Statement A: Approved for public release; distribution is unlimited.
Using Iodine for Hall-effect Thrusters (HETs)

• Iodine has been identified as an attractive alternative propellant to Xe for HETs
  – High storage density (2-3 times of Xe)
  – Efficient ionization (lower ionization potential, higher ionization cross section than Xe)
  – Similar mass for I and larger mass for I₂ than Xe
  – Comparable performance to Xe with higher T/P ratio at higher power operating condition

• A dearth of detailed knowledge of physical processes occurring in the plume

• Critical risk: High reactivity
  – Concern for spacecraft system integration
OBJECTIVE

- Simulate the iodine plasma plume generated by BHT-200 Hall thruster and its interaction with the spacecraft body/solar array in the iSAT

Busek’s BHT-200 Thruster

Basic configuration of iSAT
OVERVIEW OF NUMERICAL MODEL

• 3-D Hybrid-particle code, DRACO, developed at AFRL
  – Particle-in-cell (PIC) combined with Monte Carlo Collision (MCC)
• Quasi-neutrality
• Boltzmann relation with a polytropic temperature model:

\[
\phi = \phi_r + \frac{k_B T_{e,r}}{e} \left( \frac{\gamma}{\gamma - 1} \right) \left[ \left( \frac{n_e}{n_{e,r}} \right)^{\gamma-1} - 1 \right]
\]
Collision Cross Section Models (1)

- Neutral-neutral: Momentum-exchange (MEX)
  - Variable Hard-Sphere model
- Ion-neutral: Momentum- and charge-exchange (CEX)
  - Semi-empirical models based on measurements
- For iodine, CEX collision is also important in a Hall thruster plume
  - Consider: $I^{-}I^{+}$, $I_{2}^{-}I^{+}$, and $I_{2}^{-}I_{2}^{+}$
    - $I_{2}^{-}I^{+}$, and $I_{2}^{-}I_{2}^{+}$ available from measurement¹
    - $I^{-}I^{+}$ calculated using Sakabe’s formula²

• Verify Sakabe’s formula using Xe-Xe\(^+\) data by Miller
**Collision Cross Section Models (3)**

\[ \sigma_{\text{CEX}} = A - B \log(E) \]

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe-Xe+</td>
<td>87.3</td>
<td>13.6</td>
</tr>
<tr>
<td>Xe-Xe⁺</td>
<td>45.7</td>
<td>8.9</td>
</tr>
<tr>
<td>I₂-I⁺</td>
<td>66.0</td>
<td>4.7</td>
</tr>
</tbody>
</table>

\[ \sigma_{\text{CEX}}(I⁺,I₂) = c_1 \log^3(E) + c_2 \log^2(E) + c_3 \log(E) + c_4 \]

<table>
<thead>
<tr>
<th></th>
<th>c₁</th>
<th>c₂</th>
<th>c₃</th>
<th>c₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>I₂-I⁺</td>
<td>-0.47</td>
<td>3.5</td>
<td>-9.0</td>
<td>82.0</td>
</tr>
</tbody>
</table>

\[ \sigma(v) = [A - B \log_{10}(v)] \left( \frac{\varepsilon_I}{\varepsilon_{I₀}} \right)^{-1.5} \]

\[ A = 1.81 \times 10^{-14} \]
\[ B = 2.12 \times 10^{-15} \]
\[ \varepsilon_{I₀} = 13.6 \text{ eV} \]
Create the geometry & surface meshing in Cubit

Create the volume mesh using Volcar
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Xenon</th>
<th>Iodine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge voltage (V)</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Discharge current (A)</td>
<td>0.75</td>
<td>0.74</td>
</tr>
<tr>
<td>Anode mass flow rate (mg/s)</td>
<td>0.84</td>
<td>0.82</td>
</tr>
<tr>
<td>Cathode mass flow rate (mg/s)</td>
<td>0.098</td>
<td>0.096</td>
</tr>
<tr>
<td>Mass (propellant) utilization efficiency</td>
<td>0.981</td>
<td>0.853</td>
</tr>
<tr>
<td>Ion mass flow rate (kg/s)</td>
<td>8.24E-07</td>
<td>6.99E-07</td>
</tr>
<tr>
<td>Species temperature (K)</td>
<td>700</td>
<td>700</td>
</tr>
</tbody>
</table>

• Use HPHall source to provide particle information
• Compare with measurement by Nakles (2007)
  – Facility backpressure: $5 \times 10^{-6}$ Torr $\approx 1.6 \times 10^{17} \, m^{-3}$
Comparison with experimental data

- Generally good agreement
SIMULATION OF IODINE PLUME (1)

• Additional reactions due to molecular species ($I_2$, and $I_2^+$)
  – Including dissociative ionization, electron attachment, and inelastic energy exchange

• Accurate modeling requires these processes to be implemented in the model
  – However, the goal is to provide a first-order approximation of the iodine particle flux on spacecraft surfaces using the numerical tools available to us at this stage

• Atomic iodine species ($I$, $I^+$, and $I^{2+}$) are simulated using the HPHall

• Molecular species are introduced at the discharge channel exit assuming Maxwellian velocity distributions.
SIMULATION OF IODINE (2)

• Use iodine mole fraction measurement and mass utilization efficiency 85.3% to calculate $I_2$ and $I_2^+$ mass flow rates
  – Assumed 10% of the total neutral flow is $I_2$

<table>
<thead>
<tr>
<th>Species</th>
<th>Mole Fraction, Xe</th>
<th>Mole Fraction, I</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_2^+$</td>
<td></td>
<td>0.029</td>
</tr>
<tr>
<td>$Xe^+, I^+$</td>
<td>0.975</td>
<td>0.953</td>
</tr>
<tr>
<td>$Xe^{2+}, I^{2+}$</td>
<td>0.021</td>
<td>0.015</td>
</tr>
<tr>
<td>$Xe^{3+}, I^{3+}$</td>
<td>0.004</td>
<td>0.003</td>
</tr>
</tbody>
</table>
**Xenon vs Iodine**

- Similar result between Xe vs. I
**Estimate of Iodine Flux on Surface**

- Fluxes decrease away from the thruster in general
- Higher flux on outer edge of the front surface of s/c body and solar array
- Highest total iodine flux on the solar array: $4.5 \times 10^{16} \text{ m}^{-2}\text{s}^{-1}$
- Deposition per unit area: $0.34 \text{ mg/cm}^2$ over the entire thruster operation duration assuming 100% deposits

**Neutral Number Flux (m$^{-2}$s$^{-1}$)**

**Ion Number Flux (m$^{-2}$s$^{-1}$)**
• Verified the model using Xe data
• Simulated iodine plume with the mass flow rates based on experimental data
• Deposition per unit area: 0.34 mg/cm² over the entire thruster operation duration assuming 100% deposits
• In reality, only some portion of iodine colliding with the surface may chemically react with the surface
• How many particles actually react to or reflect off the surface will depend on the surface properties of the solar panel
• For more physically accurate simulation of iodine plasma plume, one needs to model the detailed reactions, especially the dissociative ionization
ACKNOWLEDGEMENT

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