Lithium Vapor-Box Divertor

Rob Goldston
Princeton Plasma Physics Laboratory

Rachel Myers
University of Wisconsin, Madison

Jacob Schwartz
Princeton University

First IAEA Technical Meeting on Divertor Concepts
29 September – 2 October, 2015
Demo Needs Very High Dissipated Power
(Transport, Radiation, CX)

\[ n_{OMP} = 5 \times 10^{19} \text{ m}^{-3} \]
\[ \lambda_q = 1 \text{ mm}, \; R_0 = 6 \text{ m} \]
\[ q_{\parallel, OMP} = 18.5 \text{ GW} / \text{ m}^2 \]

\[ p_{OMP} = 6300 \text{ Pa} \]

\[ q_{\perp, \text{Target}} = 300 \text{ MW} / \text{ m}^2 \]
\[ q_{\perp, \text{Target}} = 10 \text{ MW} / \text{ m}^2 \]
Pressure Balance with Lithium Vapor

- Pressure balance achievable many ways
  - C-X and elastic collisions with $H^0$
  - Elastic collisions with Li vapor
  - Recombination at very low $T$, high $n$
- Start with very conservative approach: $\sim 1/2$ of upstream pressure is balanced by Li vapor pressure (Jaworski, PSI 2014)
  - Why $1/2$? $\lambda_{int} \sim \lambda_q + 1.64 \ S \sim 2 \ \lambda_q$
  - Vapor must be well confined to divertor chamber.
  - Much easier with a condensing vapor than a gas.
• Assume walls are coated with capillary porous material, soaked with liquid lithium, continually replenished.

• Assume each vapor box is well-mixed, at local \( n_{vap} \) and \( T_{vap} \)

• Assume Langmuir-like evaporation / condensation at walls

\[
\Gamma_{Li} \text{ (to wall)} = n_{vap} \sqrt{\frac{kT_{vap}}{2\pi m}} - n_{eq}(T_{wall}) \sqrt{\frac{kT_{wall}}{2\pi m}}
\]

• Assume ideal-gas choked nozzle flow through apertures

\[
\Gamma_{Li} \text{ (thru nozzle)} = 0.6288 \cdot n_{vap} \sqrt{\frac{kT_{vap}}{m}}
\]
Particle and Power Balance

- **Time-independent densities (particle balance)**

\[
0.6288 \left( A_{\text{noz},i-1} n_{i-1} \sqrt{k T_{\text{vap},i-1} / m} - A_{\text{noz},i} n_i \sqrt{k T_{\text{vap},i} / m} \right) \\
+ \sqrt{\frac{k}{2\pi m}} A_{\text{wall},i} \left[ n_{eq}(T_{\text{wall},i}) \sqrt{T_{\text{wall},i}} - n_i \sqrt{T_{\text{vap},i}} \right] = 0
\]

- **Time-independent temperatures (enthalpy balance)**

\[
0.6288 \left( \frac{5}{2} k T_{\text{vap},i-1} A_{\text{noz},i-1} n_{i-1} \sqrt{k T_{\text{vap},i-1} / m} - \frac{5}{2} k T_{\text{vap},i} A_{\text{noz},i} n_i \sqrt{k T_{\text{vap},i} / m} \right) \\
+ \sqrt{\frac{k}{2\pi m}} A_{\text{wall},i} \left[ \frac{5}{2} k T_{\text{wall},i} n_{eq}(T_{\text{wall},i}) \sqrt{T_{\text{wall},i}} - \frac{5}{2} k T_{\text{vap},i} n_i \sqrt{T_{\text{vap},i}} \right] = 0
\]

- **Two equations for two unknowns for box \( i \) in terms of box \( i - 1 \) (due to supersonic flow in choked nozzles).**
Solution without Plasma

- Vapor boxes are 0.4m x 0.4m, \( R_0 = 6m \)
- Apertures are 0.1m
- Initial numerical calculations indicate need for reflecting surfaces to stimulate mixing (Hakim & Hammett)
Initial 2-D Navier-Stokes Calculations are Encouraging

- Reflecting surfaces create shocks
- Density drops by 1500 vs. 3400 in simple calc.
- Just beginning optimization, e.g. multiple baffles
Entrain Lithium Flux to Plasma Sheet and Eject with 200 MW into Bottom Box

End Box

<table>
<thead>
<tr>
<th>T (wall) (C)</th>
<th>950</th>
<th>787.5</th>
<th>625</th>
<th>462.5</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (vapor) (C)</td>
<td>2443.9</td>
<td>1756.5</td>
<td>1533.9</td>
<td>1499.1</td>
<td>1498.6</td>
</tr>
<tr>
<td>n (vapor) (m(^{-3}))</td>
<td>1.15E+23</td>
<td>1.80E+22</td>
<td>1.74E+21</td>
<td>1.23E+20</td>
<td>8.21E+18</td>
</tr>
<tr>
<td>Mass flow (kg/s)</td>
<td>5.3605</td>
<td>0.7124</td>
<td>0.0643</td>
<td>0.0045</td>
<td>0.00037</td>
</tr>
<tr>
<td>Latent heat flow (W)</td>
<td>1.05E+08</td>
<td>1.40E+07</td>
<td>1.26E+06</td>
<td>8.81E+04</td>
<td>5.89E+03</td>
</tr>
<tr>
<td>Enthalpy flow (W)</td>
<td>3.92E+07</td>
<td>3.75E+06</td>
<td>2.95E+05</td>
<td>2.02E+04</td>
<td>1.35E+03</td>
</tr>
<tr>
<td>Wall heat flux (W/m(^2))</td>
<td>9.85E+05</td>
<td>2.40E+06</td>
<td>3.06E+05</td>
<td>2.74E+04</td>
<td>1.91E+03</td>
</tr>
</tbody>
</table>

NSTX thrives on 0.22g/sec from dropper
Control D/T pumping by varying front boxes’ T(wall)
If we take radiation losses only, solid lines include power committed to ionization. We have evaluated the results shown in Figure 3 with ADAS Collisional-Radiative Model being satisfactory in the regime studied here.

In order to address non-linear density effects such as three-body ionization, in this case, we will find that the extracted energy rate of particle introduction, in #/sec, is committed to ionization. Most lithium has been mitigated by a factor of ~10~4.

Solid lines: total cooling
Dashed: radiation only

\[ \frac{\Delta E}{\text{ptcl.}} = \frac{p_{\text{cool}} V}{S} = \frac{n_e n_z L_z V}{S} = n_e \tau_z L_z \sim 6.2eV/\text{ptcl.} \quad (L_z/n_e \tau_z \sim \text{const.}) \]
Radiated Power @ 10 eV / Atom Injected (using previous solution)

- Previous solution was very conservative, assuming upstream pressure balanced against Li vapor pressure.
- Now considering that 100% dissipated power implies recombination; $H^0 + Li^0$ flow balances upstream pressure.
- Might not need the end 2 boxes.
To Do List

- Optimization using fluid mechanics calculations
  - Now started by Hakim and Hammett
- Proper plasma calculations.
  - Thermal force? Flow reversal in outer layers?
  - Self consistent combination with fluid solution.
- Concept for how to recirculate the lithium.
  - Can we use passive or active heat-pipe technology?
  - Clean-up D/T and impurities.
  - How to recover lithium that escapes?
- Design and testing of a water/steam-based prototype?
- Design and testing of a lithium-based prototype.
- Add plasma in a test stand?
- Install in a tokamak.
Foundational Work

Energy Exhaust through Neutrals in a Tokamak Divertor

Liquid Lithium Divertor System for Fusion Reactor
Y. Nagayama et al., Fusion Eng. Des. 84 (2009) 1380

Recent Progress in the NSTX/NSTX-U Lithium Program and Prospects for Reactor-Relevant Liquid-Lithium Based Divertor Development
M. Ono, M.A. Jaworski, R. Kaita et al., Nuc. Fusion 53 (2013) 113030

Liquid-Metal Plasma-Facing Component Research on NSTX