Neutrino Factory
Mercury Vessel: Initial Cooling Calculations

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Target Studies
Nov 15, 2012
Target System Review

- Current mechanical concept incorporates independent mercury and shielding modules
- Separates functionality, provides double mercury containment, simplifies design and remote handling
- Each vessel assumed to be cooled with Helium
  - Shielding vessel filled with tungsten beads
  - Mercury vessel cooling chambers empty
- Purpose: take an initial look at the cooling issues
## Helium Properties @ 20°C

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ($\rho$)</td>
<td>0.16674</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Dynamic Viscosity ($\mu$)</td>
<td>1.9561E-5</td>
<td>kg/m-s</td>
</tr>
<tr>
<td>Kinematic Viscosity ($\nu$)</td>
<td>1.1731E-4</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>Specific heat ($C_p$)</td>
<td>5193</td>
<td>J/kg-K</td>
</tr>
<tr>
<td>Conductivity ($k$)</td>
<td>0.14786</td>
<td>W/m-K</td>
</tr>
<tr>
<td>Prandtl number</td>
<td>0.68700</td>
<td></td>
</tr>
<tr>
<td>Thermal Diffusivity ($\kappa$)</td>
<td>1.7120E-4</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>Thermal Expansion Coefficient ($\alpha$)</td>
<td>3.4112E-3</td>
<td>1/K</td>
</tr>
</tbody>
</table>

[http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html](http://www.mhtl.uwaterloo.ca/old/onlinetools/airprop/airprop.html)
Analysis Model Simplification

- First-order cooling analysis based on simplified geometry model
- Break inner and outer regions into supply/return channels of equal areas within each region

\[ A_i^{\text{total}} = 0.1 \text{m}^2 \quad A_o^{\text{total}} = 3.6 \text{m}^2 \]
Helium Mass Flow Rates

\[ q = \dot{m}C_p \Delta T \]

- **Assumptions**
  - \( q_t = 1.5 \text{ MW} \)
  - \( q_m = 0.5 \text{ MW} \)
  - \( \rho = 0.16674 \text{ kg/m}^3 \)
  - \( C_p = 5193 \text{ J/kg-K} \)
  - Helium \( \Delta T \leq 100\degree C \)
  - Helium velocity \( \leq 100 \text{ m/s} \)

\[
\dot{m}_t = \frac{1.5E6}{5193 \times 100} \approx 3 \text{ kg/s}
\]

\[
\dot{m}_m = \frac{0.5E6}{5193 \times 100} \approx 1 \text{ kg/s}
\]

1 kg He @ STP = 6 m\(^3\)
**T2K Target Design**

- **Required flow rate 32 g/s**
- **Minimize dP (max 0.8 bar) due to high flow rate (avg = 200 m/s)**
Mercury Vessel Calculations

- Mercury cooling chamber empty (only Helium)
- Assume 4 cooling paths (8 chambers)

\[ m = \frac{m_m}{4} = 0.25 \, \text{kg} / \text{s} \]

\[ A = \frac{\dot{m}}{\rho V} = \frac{0.25}{0.16674 \times 100} = 0.015 \, m^2 \]

\[ 8A = 0.12 \, m^2 \]

\[ A_i = 0.1 \, m^2 \]

- Area may be adequate, but asymmetric heating may be problem
- Pressure drop through system needs to be calculated
Tungsten Shielding Vessel Calculations

- Shielding vessel cooling chamber not empty (Tungsten spheres)
- Assume 4 cooling paths (8 chambers)

\[ \dot{m} = \frac{\dot{m}_t}{4} = 0.75 \text{ kg/s} \]

\[ A = \frac{\dot{m}}{\rho V} = \frac{0.75}{0.16674 \times 100} = 0.045 m^2 \]

- Area adequate, may reduce helium velocity
- Pressure drop through spheres must be reviewed
Tungsten Shielding Vessel Pressure Drop

• Ergun Equation gives pressure drop through fixed beds of uniformly sized solids

\[
\frac{\Delta P}{L} = \left( \frac{\Delta P}{L} \right)_{\text{viscous}} + \left( \frac{\Delta P}{L} \right)_{\text{kinetic}}
\]

\[
\frac{\Delta P}{L} = 150 \frac{(1 - \varepsilon)^2}{\varepsilon^3} \frac{\mu u_0}{\phi_s d_p^2} + 1.75 \frac{1 - \varepsilon}{\varepsilon^3} \frac{\rho u_0^2}{\phi_s d_p}
\]

\[\Delta P = \text{pressure drop}\]

\[L = \text{bed length}\]

\[\mu = \text{fluid viscosity}\]

\[\varepsilon = \text{particle void fraction}\]

\[u_0 = \text{superficial fluid velocity}\]

\[\phi_s = \text{particle sphericity} = 1\]

\[d_p = \text{particle diameter}\]
Pressure Drop Results

- **Assumptions**
  - $\varepsilon = 0.4$
  - $d_p = 1 \text{ cm}$

- **Results indicate He pressure** ~180 bar required

- **100m/s velocity results in large amounts of stored energy within system**

- **Implies we need to limit He velocity to ~ 10 m/s**
  - Requires 10X more flow area
  - Space is available
  - If need 1 s to recool the He in a heat exchanger, need 3 kg, volume = 18 m$^3$

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[Graph showing pressure drop vs. helium velocity]

- Module length ~ 6m

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[Diagram showing module length and pressure drop graph]

Mechanical Complexities

- Non-equally distributed energy deposition
- Complicated cooling channel geometries
- Flow control hardware likely to increase space requirements
- Implement two helium systems (one for mercury cooling, one for tungsten)?
Summary

- Mercury Module now provides double-wall mercury containment with no leak path into tungsten cooling channels
- Helium cooling of the mercury and shielding vessels is not straightforward
- Initial calculations performed based on guesses for energy deposition and very simple geometry model