Thermal Design of Vapor Cooling of Flight Vehicle Structures using LH2 Boil-off

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Background of the vapor cooling using LH2 boil-off

Vapor cooling concept considered for SLS EUS forward skirt

1D thermal model to investigate

- size of the cooling tube
- number of the cooling tubes
- entire or partial length of the skirt to be cooled

3D thermal model prediction of vapor cooling performance

- Four configurations
  a. One spiral cooling tube with 3 turns covering the entire skirt
  b. One spiral cooling tube with 2 turns covering 25% of the skirt length
  c. Two spiral tubes with one turn each covering 25% of the skirt length
  d. Axial cooling tubes (16) covering 25% of the skirt length

- Two scenarios
  ▪ on ground (steady-state)
  ▪ 5 day lunar mission (transient)

Conclusions
Background

• Using LH2 boil-off vapor to cool the flight vehicle upper stage structure can
  ✓ Reduce heat leak to the LH2 tank
  ✓ Lower the boiling-off rate such that saving mass of propellant and extending the life of the stage
  ✓ Heat up the vented gas for other purpose as a heat source (tank settling)
• In theory, the heat leaking into LH2 tank from the structure will be reduced with the boil-off vapor cooling on the structure
• However, the amount of heat leak reduction depends on
  ✓ The amount of boil-off vapor is available
  ✓ The total heat load on the structure
  ✓ Vapor cooling configurations
Vapor cooling concept

Space launch system (SLS)
Exploration Upper Stage (EUS)

Cooling loop on forward skirt

Forward skirt
LH2 tank
Aft skirt
Inter tank
Lox tank
1D analysis

- Vapor cooling configuration:
  - Upstream and downstream manifolds + axial tubes
  - Provides uniform cooling to the skirt in the circumferential direction
- Need to investigate:
  - Number of cooling tubes along axial direction (8, 16, 32, 64)
  - Length of the skirt to be cooled (100%, 75%, 50%, 25%)
  - Size of the cooling tubes (ID = 3/4”, 3/8”, 1/8”)
- Build a 1D thermal model (4 nodes along the entire skirt length)
$R_{1,2}$, $R_{2,3}$ and $R_{3,4}$: conduction resistance, $R_2$: contact resistance
1D thermal model results for axial tubing (16 tubes)

1. Baseline 1: no insulation on the skirt, top of the skirt: adiabatic
2. Baseline 2: insulate the skirt, top of the skirt: $T = 300$ K
3. Ambient: $T_a = 300$ K, radiation only

- Cooling the 25% of the skirt from the bottom is almost as effective as cooling the entire skirt.
- Using smaller tubing (1/8” diameter) provides less heat to the tank with higher pressure drop.
- Insulating the skirt will reduce significant heat leaking into the tank.
(25% of skirt length is cooled, 16 tubes)

Skirt wall temperature above cooling tubes.

Skirt wall temperature between two cooling tubes.

(1/8” diameter tube, cool 25% of the skirt length)

<table>
<thead>
<tr>
<th>No. of cooling tubes</th>
<th>Total Q2tank (W)</th>
<th>Heat reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7360</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>3847</td>
<td>47.7%</td>
</tr>
<tr>
<td>16</td>
<td>3377</td>
<td>54.1%</td>
</tr>
<tr>
<td>32</td>
<td>2765</td>
<td>62.4%</td>
</tr>
<tr>
<td>64</td>
<td>2317</td>
<td>68.5%</td>
</tr>
</tbody>
</table>
1D analysis results

Sensitivity study of the contact resistance between skirt and tank ($R_2$)

<table>
<thead>
<tr>
<th>1/8” tube, 16 tubes, 25% skirt cooled</th>
<th>1500 w/m²-k</th>
<th>3000 w/m²-k</th>
<th>6000 w/m²-k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2tank (W) (no cooling)</td>
<td>6776</td>
<td>7360</td>
<td>7680</td>
</tr>
<tr>
<td>Q2tank (W) (cooling)</td>
<td>3185.6</td>
<td>3377.7</td>
<td>3491.2</td>
</tr>
<tr>
<td>Heat leak reduction</td>
<td>53%</td>
<td>54%</td>
<td>54.5%</td>
</tr>
</tbody>
</table>

Different size of skirt/tank

<table>
<thead>
<tr>
<th>1/8” tube, 16 tubes, 25% skirt cooled</th>
<th>1/8” tube, half diameter, half length</th>
<th>Baseline 1</th>
<th>Half diameter, same length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2tank (W) (no cooling)</td>
<td>2700.8</td>
<td>7360</td>
<td>2186</td>
</tr>
<tr>
<td>Q2tank (W) (cooling)</td>
<td>1209.6</td>
<td>3377.7</td>
<td>947.2</td>
</tr>
<tr>
<td>Heat leak reduction</td>
<td>55.2%</td>
<td>54.1%</td>
<td>56.7%</td>
</tr>
</tbody>
</table>

Different sink temperature

<table>
<thead>
<tr>
<th>1/8” tube, 16 tubes, 25% skirt cooled</th>
<th>Ta = 300 K</th>
<th>Ta = 200 K</th>
<th>Ta = 100 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2tank (W) (no cooling)</td>
<td>7360</td>
<td>2640</td>
<td>345.6</td>
</tr>
<tr>
<td>Q2tank (W) (cooling)</td>
<td>3377.7</td>
<td>1215</td>
<td>184.8</td>
</tr>
<tr>
<td>Heat leak reduction</td>
<td>54.1%</td>
<td>54%</td>
<td>46.5%</td>
</tr>
</tbody>
</table>

- Roughly similar percentage of heat leak reduction to LH2 tank for different size of skirt (length or diameter)
- Vapor cooling is more effective when ambient is warmer.
Vapor cooling configurations:

- Tubing along the circumferential direction (spiral, (a), (b), (c))
- Tubing along the axial direction (d)

- Tube size: ID = 0.824”, OD = 1.05”
- Tube material: Al 2219-T6
- Tube starts at 8.5” from the bottom of the skirt
3D analysis results

✓ No cooling loop:
  \( Q_{2\text{tank}} = 8013 \, \text{W} \)
  from forward skirt

Option A, one spiral tube covers the entire skirt

<table>
<thead>
<tr>
<th>Vapor mass flow rate (kg/s)</th>
<th>( Q_{2\text{tank}} ) (W)</th>
<th>( Q_{2\text{fluid}} ) (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>3627.7</td>
<td>23711</td>
</tr>
</tbody>
</table>

Option B, one spiral tube (2 turns) cover 25% of the skirt length

<table>
<thead>
<tr>
<th>Vapor mass flow rate (kg/s)</th>
<th>( Q_{2\text{tank}} ) (W)</th>
<th>( Q_{2\text{fluid}} ) (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>2346</td>
<td>12803</td>
</tr>
<tr>
<td>0.006</td>
<td>2665.6</td>
<td>11884</td>
</tr>
</tbody>
</table>
3D analysis results

Option C, two spiral tubes (1 turn) cover 25% of the skirt length

<table>
<thead>
<tr>
<th>Vapor mass flow rate (kg/s)</th>
<th>Q2tank (W)</th>
<th>Q2fluid (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>2449</td>
<td>12638</td>
</tr>
<tr>
<td>0.006</td>
<td>2817</td>
<td>11665</td>
</tr>
</tbody>
</table>

Option D: two manifolds + 16 vertical tubes, cover 25% of the skirt length
(manifold: ID = 0.824”, OD = 1.05”
Vertical tube: ID = 0.269”, OD = 0.405”)

<table>
<thead>
<tr>
<th>Vapor mass flow rate (kg/s)</th>
<th>Q2tank (W)</th>
<th>Q2fluid (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>3058</td>
<td>12960</td>
</tr>
<tr>
<td>0.007</td>
<td>3362</td>
<td>12335</td>
</tr>
</tbody>
</table>

(manifold: ID = 0.493”, OD = 0.675”,
Vertical tube: ID = 0.125”)

<table>
<thead>
<tr>
<th>Vapor mass flow rate (kg/s)</th>
<th>Q2tank (W)</th>
<th>Q2fluid (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008</td>
<td>2944</td>
<td>13348</td>
</tr>
<tr>
<td>0.007</td>
<td>3230</td>
<td>12743</td>
</tr>
</tbody>
</table>

1D model prediction: mass flow rate: 0.00786 kg/s, Q2tank = 3377 W
(16 vertical tube of 1/8” ID covers 25% of the skirt length, no manifold)
### Summary of the 3D TD results

#### Tube size: ID = 0.824” OD = 1.05”

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Vapor mfr (kg/s)</th>
<th>Q2tank (W)</th>
<th>Q2fluid (W)</th>
<th>Pdrop (psi)</th>
<th>Texit (K)</th>
<th>Heat leak reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.008</td>
<td>3627.7</td>
<td>23711</td>
<td>11.8</td>
<td>229.8</td>
<td>59.7%</td>
</tr>
<tr>
<td>B</td>
<td>0.006</td>
<td>2665.6</td>
<td>11884</td>
<td>3.35</td>
<td>169.1</td>
<td>66.7%</td>
</tr>
<tr>
<td>C</td>
<td>0.006</td>
<td>2817</td>
<td>11665</td>
<td>0.14</td>
<td>167.8</td>
<td>64.8%</td>
</tr>
<tr>
<td>D</td>
<td>0.007</td>
<td>3362</td>
<td>12335</td>
<td>0.89</td>
<td>185.3</td>
<td>58%</td>
</tr>
</tbody>
</table>

#### Tube size: ID = 0.493” OD = 0.675”

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Vapor mfr (kg/s)</th>
<th>Q2tank (W)</th>
<th>Q2fluid (W)</th>
<th>Pdrop (psi)</th>
<th>Texit (K)</th>
<th>Heat leak reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.008</td>
<td>3732.6</td>
<td>23666</td>
<td>64.8</td>
<td>226.2</td>
<td>53.4%</td>
</tr>
<tr>
<td>B</td>
<td>0.006</td>
<td>2663.5</td>
<td>12849</td>
<td>28.7</td>
<td>144.1*</td>
<td>66.8%</td>
</tr>
<tr>
<td>C</td>
<td>0.006</td>
<td>2785</td>
<td>11714</td>
<td>6.5</td>
<td>169.0</td>
<td>65.2%</td>
</tr>
<tr>
<td>D</td>
<td>0.007</td>
<td>3230</td>
<td>12743</td>
<td>8.0</td>
<td>196.3</td>
<td>59.7%</td>
</tr>
</tbody>
</table>

- Configurations B and C results in the least heat to the LH2 tank.
- Tube size of 0.5” ID will have much higher pressure drop.
- For the tube along the axial direction, more vertical tubes are necessary if heat leak to LH2 needs to be further reduced. (* convergence problem)
• 5 day lunar mission is considered for vapor cooling configuration performance
  • Lunar orbit rendezvous (lander)
    • On ground: 300 K sink temperature
    • Low Earth Orbit (LEO): 3 hr (2 orbits)
  • Trans lunar Cruise (TLC): 5 days
    • Nose to Sun
    • Broadside to Sun
    • Broadside to Sun with spin
LEO and TLC orbits

**LEO**, altitude = 240 km, beta = 52°, +Z to Nadir, period = 1.488 hr

**TLC**, broadside to sun, inclination angle = 90°, period is 10 days
Sink temperature at different locations on the forward skirt

LEO

TLC nose to sun

TLC broadside to Sun

TLC broadside to Sun with spin
For TLC,
- Nose to Sun is the coolest environment.
- Broadside to Sun with spin is the warmest.
- Broadside to Sun is considered for vapor cooling configurations performance.
- A constant vapor mass flow rate of 0.006 kg/s is used for all configurations.
Temperature distribution at different time

end of LEO

end of TLC
Conclusions

- 3D model results showed similar cooling benefit to that indicated by 1-D model results
- Concentrating the cooling closer to skirt/tank connection appears to be more effective
- Multi-tube axial configuration not as effective as spiral tube
- Configurations B and C result in the least heat leak to the LH2 tank. Configuration C has lower pressure drop
- Vapor cooling will be more effective when the heat load is high on the structures
- For LEO, vapor cooling can reduce heat leak to the LH2 tank significantly
- For TLC nose to sun, vapor cooling might not save much heat leak to the LH2
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– Justin Elchert at GRC: valuable help on the TD model
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