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

Xiao-Yen Wang
&
Joseph Zoeckler

NASA Glenn Research center
08-03-2015
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
• 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

- Cooling loop on forward skirt
- Forward skirt
- LH2 tank
- Aft skirt
- Inter tank
- Lox tank

Space launch system (SLS)
Exploration Upper Stage (EUS)
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)
1D thermal circuit for tubing along axial direction

\[ R_{1,2}, R_{2,3} \text{ and } R_{3,4} : \text{conduction resistance}, R_2 : \text{contact resistance} \]
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.
1D analysis results

(25% of skirt length is cooled, 16 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>

Skirt wall temperature above cooling tubes.

Skirt wall temperature between two cooling tubes.

TFAWS 2015 – August 3-7, 2015
# 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>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)

- (a) 1 loop with 3 turns, on entire skirt length
- (b) 1 loop, 2 turns, on 25% of skirt length
- (c) 2 loops, 1 turn/loop, on 25% of skirt length
- (d) Tubing along the axial direction, on 25% of skirt length

- 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 thermal modeling using Thermal Desktop (TD):
3D analysis results

✓ No cooling loop:

Q2tank = 8013 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>Q2tank (W)</th>
<th>Q2fluid (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>Q2tank (W)</th>
<th>Q2fluid (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>
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

<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>

<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, 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

Configuration (a)

Configuration (b)

Configuration (c)

Configuration (d)

end of LEO

end of TLC

7/27/2015

TFAWS 2015 – August 3-7, 2015
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
Acknowledgements

– Justin Elchert at GRC: valuable help on the TD model
– Douglas Bell at C & R tech: super tech support all the time
– Wesley Johnson and Lauren Best at GRC: review and technical input
– eCryo project: support of the work and travel to TFAWS