Mars Propellant Liquefaction Modeling in Thermal Desktop

Pooja Desai¹, Dan Hauser², Steven Sutherlin³

¹Johnson Space Center, Houston, TX, 77058, USA
²Glenn Research Center, Cleveland, OH, 44135, USA
³Marshall Spaceflight Center, Huntsville, AL, 35812, USA

Space Cryogenics Workshop
7/07/2017
Agenda

• Background/Purpose for Liquefaction
• Broad Area Cooling (Method of Liquefaction) Overview
• MAV Model Overview and Results
• Overview of Zero Boil-off testing campaign at Glenn Research Center
• ZBO Model Overview (similar to MAV Model)
• ZBO Model Validation with Test Results
• Future Work
Background

- Current Mars human architectures point to using In-Situ Resource Utilization
- An ISRU plant could potentially reduce the landed mass required by 30000 kilograms
- Gaseous oxygen and methane that ISRU produces must be liquefied and stored as propellants for the Mars Ascent Vehicle (MAV)
- 23 tons (~21000 kg) of liquid oxygen needed in 500+ days
- An energy efficient liquefaction system required
Broad Area Cooling (BAC)

- Working fluid is circulated by a reverse Turbo-Brayton (RTB) cycle cryocooler through a tubing network welded over the whole surface of a cryogenic tank
- Working fluid intercepts the heat that would otherwise go into the propellant
- Interest in using BAC as cooling system for zero boil-off for storage of cryogenic rocket engine propellants
- Now also being considered as a liquefaction method
Model Scope

- Integrated model of MAV sized propellant tank with an integrated reverse Turbo-Brayton cycle cryocooler created in Thermal Desktop
- Predicts liquefaction performance and operation
- Includes Martian daily cycle heat loads and radiator temperatures
- First step: Create a MAV sized spherical propellant tank for liquid oxygen
Thermal Desktop Tank Model Details

- Tank model is a thin walled spherical aluminum tank with a liquid volume and a gas volume (twinned lump), propellant: liquid oxygen
- Heat transfer between wall and fluid is represented by pool boiling ties ($\dot{Q}_{VLB}$ and $\dot{Q}_{VLC}$)
- Heat transfer from environment to tank is represented by a given Martian daily cycle heat load
- No stratification is modeled
# Thermal Desktop Tank Model Details

<table>
<thead>
<tr>
<th>Tank Material</th>
<th>Aluminum 6061-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Outer Diameter</td>
<td>2.65 m</td>
</tr>
<tr>
<td>Tank Thickness</td>
<td>0.00635 m</td>
</tr>
<tr>
<td></td>
<td>104.33 in</td>
</tr>
<tr>
<td></td>
<td>0.25 in</td>
</tr>
<tr>
<td></td>
<td>based on MAV tank estimates</td>
</tr>
</tbody>
</table>

## Starting Conditions in Tank

- Liquid oxygen temperature: 90 K
- Vapor Temperature: 273.15 K
- Pressure: 101,325 Pa
- Void Fraction: 0.99
- Initial Tank and Pipe Wall Temperature: 90 K

## Flow into Tank

- Mass Flow: 2.2 kg/hr
- Temperature: 273.15 K
- Pressure: 101,325 Pa
- 1 atm

## Heat Load

- 9 to 15 W/m²
- Modeled as a sine curve

## 3 pipe loops

<table>
<thead>
<tr>
<th>Material</th>
<th>Aluminum 6061-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Diameter</td>
<td>0.009525 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.00889 m</td>
</tr>
<tr>
<td>Coolant</td>
<td>Neon</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>0.375 in</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.015 in</td>
</tr>
</tbody>
</table>
Tank Model integration with Creare Cryocooler Model

- Between 7-8 is the tank model
- Rest of the system is represented by equations for the Creare 90 K and 500 W cryocooler (given by Creare)
- Integrated system modeled in Thermal Desktop

<table>
<thead>
<tr>
<th>Tank Model</th>
<th>Creare Cryocooler Model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs from Cryocooler</strong></td>
<td><strong>Inputs from TD Model</strong></td>
</tr>
<tr>
<td>BAC inlet temperature (T7)</td>
<td>BAC outlet temperature (T8)</td>
</tr>
<tr>
<td>Coolant Mass flow Rate (mdot)</td>
<td>Pressure drop from 7 to 8</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td><strong>Outputs</strong></td>
</tr>
<tr>
<td>Tank Wall Temperatures</td>
<td>Net refrigeration</td>
</tr>
<tr>
<td>Coolant Temperatures</td>
<td>Coolant Mass Flow</td>
</tr>
<tr>
<td>Coolant Pressures</td>
<td></td>
</tr>
<tr>
<td>Liquid Temperature</td>
<td></td>
</tr>
<tr>
<td>Tank Pressure</td>
<td></td>
</tr>
<tr>
<td>Ullage Volume Fraction</td>
<td></td>
</tr>
<tr>
<td>Liquid Mass</td>
<td></td>
</tr>
</tbody>
</table>
Results - Tank Wall Temperatures (K)

(Initial condition)

(500 hours)

(1 hour)

(250 hours)

(1000 hours)
Results - Tank Wall Temperatures (K)
Results - Tank Wall Temperatures (K)
Results - Tank Wall Temperatures (K)
Results – Net Refrigeration (W) and Liquid Volume Fraction (%)
Model Case Runs

- Radiator temperature is the temperature at point 2 in the diagram (where cryocooler rejects heat)
- Two cases ran: one with a constant radiator temperature of 300 K and one with a sine curve fit from MAV thermal analysis
- Tank starts at an initial ullage volume fraction of 0.99
- Results:
  - Constant Trad – 4750 W
  - Changing Trad – 4000 W
- Mars environmental temperature cycles can potentially reduce cryocooler power and mass by 15-20% with current radiator design
ZBO Model Overview

- Assembly consists of Zero Boiloff (ZBO) test tank, with the tube-on-tank BAC system, covered with insulation
- Propellant: liquid nitrogen
- Coolant: neon
- 10 tests were performed with the ZBO tank
  - Test 1: Passive Boiloff (15 days)
  - Test 2: Passive Pressurization (1 day)
  - Test 3: Active ZBO (6 days)
  - Test 4: Active high power A (1 day)
  - Test 5: Active low power (1 day)
  - Test 6: Active de-stratification (2 days)
  - Test 7: Active high power B (1 day)
  - Test 8: Active low-fill ZBO (7 days)
  - Test 9: Active low fill and high power (1 day)
  - Test 10: Passive boiloff at 300 K (10 days)
ZBO Test Descriptions

- **Test 2: Passive Pressurization**
  - Tank fill level at 90%, tank pressure at 82 psi
  - Tank’s vent valve was closed, tank self-pressurized
  - Tank pressurization rate – 0.33 psi/hr
  - Tank heat leak - 4.64 W
  - No mixing or cooling occurred

- **Test 4: Active Zero Boiloff**
  - Cryocooler power increased from 145 W (test 3) to 272 W
  - Initial tank pressure at 82 psi
  - Cryocooler mass flow increased to 2.2 g/s
  - Pressure drop was 0.14 psi/hr (over 16 hours)

- **Test 6: Active destratification**
  - Cryocooler power on, heaters also powered on to match heat loads in Test 2
  - Compare pressure rise to Test 2

- **Test 9: Active Low Fill, High Power**
  - Cryocooler power increased to 208 W
  - Tank pressure drop was 0.11 psi/hr (over 23 hours)
ZBO Modeling Overview

- **Goal:** Compare ZBO thermal desktop model with available data
- Created a model in Thermal Desktop of the liquid nitrogen test tank and BAC cooling loops
  - Tank and pipe walls are modeled with MLI insulation attached
  - No stratification modeled in tank (liquid lump and vapor lump each at one temperature)
  - Strut heat load included as heat loads on 3 tank wall nodes
    - (0.136 W on each wall node)
  - Vent, fill, nipple, strap, and parasitic heat loads applied on tank wall nodes near top of tank
### ZBO Model Cases

<table>
<thead>
<tr>
<th>Test Number and Type</th>
<th>Test Description</th>
<th>Test Duration</th>
<th>dP/dt (psi/hr)</th>
<th>Qfluid (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – Passive Pressurization</td>
<td>Tank fill level at 90%, vent valve closed, tank self-pressurized</td>
<td>1 day</td>
<td>0.33</td>
<td>3.80</td>
</tr>
<tr>
<td>4 – Active High Power at High Fill</td>
<td>Tank fill level at 90%, cryocooler power on at 272 W</td>
<td>1 day</td>
<td>-0.096</td>
<td>-7.13</td>
</tr>
<tr>
<td>6 – Active Destratification</td>
<td>Tank fill level at 90%, cryocooler on to homogenize liquid temperature, heat added to tank to compare with test 2</td>
<td>1 day</td>
<td>0.024</td>
<td>2.75</td>
</tr>
<tr>
<td>9 – Active High Power at Low Fill</td>
<td>Tank fill level at 27%, cryocooler power on at 208 W</td>
<td>1 day</td>
<td>-0.11</td>
<td>-2.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cases</th>
<th>Test to Compare</th>
<th>Time Duration (hr)</th>
<th>Fill Volume (%)</th>
<th>Initial Tank Vapor Wall Temperature (K)</th>
<th>Initial Tank Liquid Wall Temperature (K)</th>
<th>Initial Tank Vapor Temperature (K)</th>
<th>Initial Tank Pressure (psi)</th>
<th>Coolant Mass Flow (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>20</td>
<td>95%</td>
<td>105.2</td>
<td>95.3</td>
<td>95.4</td>
<td>98.3</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>20</td>
<td>95%</td>
<td>98.7</td>
<td>95</td>
<td>95.3</td>
<td>96.1</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>20</td>
<td>95%</td>
<td>98.7</td>
<td>95.1</td>
<td>95.4</td>
<td>96.2</td>
<td>82</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>20</td>
<td>27%</td>
<td>98.9</td>
<td>95.3</td>
<td>95.4</td>
<td>96.5</td>
<td>82</td>
</tr>
</tbody>
</table>
ZBO Model Results – Net Heat Addition Positive

Test 2: Propellant Stratified

Test 6: Propellant Behaved De-Stratified

<table>
<thead>
<tr>
<th></th>
<th>Model (Test 2)</th>
<th>Data (Test 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure rise</td>
<td>0.026</td>
<td>0.33</td>
</tr>
<tr>
<td>Temperature rise</td>
<td>0.0031</td>
<td>0.0043</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Model (Test 6)</th>
<th>Data (Test 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure rise</td>
<td>0.0259</td>
<td>0.024</td>
</tr>
<tr>
<td>Temperature rise</td>
<td>0.0047</td>
<td>0.0043</td>
</tr>
</tbody>
</table>
ZBO Model Results – Cryocooler on, Net Heat Addition Negative

Test 4:
95% Fill Level

Test 9:
27% Fill Level

<table>
<thead>
<tr>
<th>Test</th>
<th>Fill Level</th>
<th>Pressure rise (psi/hr)</th>
<th>Temperature rise (K/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 4</td>
<td>95% Fill Level</td>
<td>-0.068</td>
<td>-0.096</td>
</tr>
<tr>
<td>Test 9</td>
<td>27% Fill Level</td>
<td>-0.093</td>
<td>-0.011</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Data (Test 4)</th>
<th>Model</th>
<th>Data (Test 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure rise (psi/hr)</td>
<td>-0.068</td>
<td>-0.093</td>
<td>-0.011</td>
</tr>
<tr>
<td>Temperature rise (K/hr)</td>
<td>-0.096</td>
<td>-0.011</td>
<td>-0.015</td>
</tr>
</tbody>
</table>
Future Work

• Further testing on ZBO test tank
• Validate test matrix by running simulations of planned tests with ZBO model
  • Look at constant versus batch liquefaction
• Look at effects of non-condensable gases on liquefaction performance
• MAV model – also look at constant versus batch liquefaction
  • Cryocooler 12 hours on/12 hours off