**Thermodynamic modelling of the warm-up of cryogenic tank at low fill levels for LH2 storage**

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**Introduction**

Rationale: During their return voyage, LNG carriers retain a “small” quantity of liquid (heel) in one or all tanks, to mitigate tank warm-up over the duration of the voyage. This heel can be sprayed onto the tank walls prior to arrival, partially cooling the tanks and reducing excessive boil-off during loading.

Simple lumped mass models (vapour, liquid, interface) have been demonstrated to predict rate of self-presurisation with 2 tuning parameters. However, these models are unable to directly predict vapour thermal stratification and subsequently, cumulative heat gain in the tank.

Aims:
- Develop a lumped-sum analytical model to estimate vapour stratification and tank heat gain at moderate-to-low fill levels.
- Understand the differences between heel management in existing LNG membrane-type tanks and LH2 Type-B (double walled) storage tanks.
- Investigate self-presurisation as a method to reduce heel boil-off.

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**Problem Overview**

- **Figure 1**: Cumulative Heat Transfer
- **Figure 2**: Methods
- **Figure 3**: Results & Comparison to LNG case

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**Rationale**

Considering a tank at ~100% fill, immediately after unloading. Prior to unloading, tank heat transfer is in a quasi-steady state.

Defining residual heat as:

\[ Q_{\text{residual}} = \int_0^t (Q_{\text{environmental}} - Q_{\text{heat}}) \, dt \]

The maximum quantity of heel required under continuous spraying of the inner wall:

\[ m_{\text{heat, spray}} = \frac{Q_{\text{residual}} \cdot \text{heat requ.}}{\text{heat rate}} \]

Defining dimensionless environmental heat gain as:

\[ \theta_1 = \frac{Q_{\text{environmental}}}{Q_{\text{steady state}}} \]

Defining dimensionless environmental heat gain as:

\[ \theta_2 = \frac{Q_{\text{environmental}}}{Q_{\text{residual}}} \]

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**Methods**

Assuming a linear vapour temperature profile, all is divided into ‘n’ sublayers of volume \( V_i \). Thermal gradient can then be solved by minimising the mass and energy residuals:

\[ \Delta m_i = m_i - \sum_{j=1}^{n-1} W_i \rho_i \Delta h_i \]

Convergence criteria set to 0.01 for normalised residuals. Two empirical tuning parameters \( C_1 \) and \( C_2 \) are required:

\[ \theta_1 = C_1 \theta_2 \]

\[ \theta_2 = C_2 \theta_1 \]

Where \( \theta_i \) is time since pressurisation, \( \alpha_i \) is thermal diffusivity, \( \theta_i \) is vapour thermal gradient and \( \theta_i \) is thermal conductivity (all in SI units).

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**Results & Comparison to LNG case**

Considering 3 cases for 40,000 m³ storage tanks at 5% fill:

<table>
<thead>
<tr>
<th>Case</th>
<th>Insulation Type</th>
<th>Insulation thickness (m)</th>
<th>Inner wall thickness (mm)</th>
<th>Inner wall material</th>
<th>Steady State Heat Transfer (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical, LH2</td>
<td>Perfor (100 mTorr)</td>
<td>0.75</td>
<td>85</td>
<td>304 Stainless</td>
<td>6.74</td>
</tr>
<tr>
<td>Spherical, LH2</td>
<td>PUF (non-vacuum)</td>
<td>0.75</td>
<td>85</td>
<td>Steel</td>
<td>46.1</td>
</tr>
<tr>
<td>Spherical, LH2</td>
<td>PUF (non-vacuum)</td>
<td>0.5</td>
<td>7</td>
<td>304 Stainless</td>
<td>78.7</td>
</tr>
</tbody>
</table>

**Key Observations**

- For the LH2 insulated tanks over 3 weeks, 3.6% and 8.7% decrease in environmental-to outer shell for perite and polyurethane foam (PUF) respectively.
- In comparison, estimated 30% decrease in environmental-to outer shell heat transfer for LNG tank over 3 weeks. Comparatively lower portion of cumulative heat transferred retained within tank for LNG tank.

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**Conclusion**

- New approach proposed for modelling self-presurisation and vapour stratification using lumped mass methods, using two empirical tuning parameters.
- Self-presurisation predicted to result in additional net heat gain. However, this may be offset by significant boil-off reductions.
- Significantly differences in heat transfer evolution between LNG and LH2 cases, primarily due to differences in thermophysical properties of steel at ~20 and ~110K and inner wall thickness.

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