Cryogenic Thermal Performance of the Vacuum Insulation System for LH₂ Storage Tanks

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**INTRODUCTION**

- **Cryogenic liquids**: liquefied gases that are kept in their liquid state (boiling point below -150°C)
- Extremely cold and small amounts of liquid can expand into very large volumes of gas
- Most cryogenic liquids can be placed into Inert gases, Flammable gases, and Oxygen:
  - **Inert Gases**: They do not react chemically to any great extent (Nitrogen, Helium, Neon, Argon, and Krypton, etc.)
  - **Flammable Gases**: They produce a gas that can burn in air (Hydrogen, Methane, Liquefied natural gas, etc.)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Boiling point(°C)</th>
<th>Latent heat(kJ/kg)</th>
<th>Type</th>
<th>Volume ratio (liq→gas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG</td>
<td>-161.5</td>
<td>512</td>
<td>Flammable</td>
<td>600</td>
</tr>
<tr>
<td>H₂</td>
<td>-252.75</td>
<td>447</td>
<td>Flammable</td>
<td>800</td>
</tr>
<tr>
<td>N₂</td>
<td>-196.15</td>
<td>199</td>
<td>Inert</td>
<td>800</td>
</tr>
<tr>
<td>He</td>
<td>-268.95</td>
<td>21</td>
<td>Inert</td>
<td>700</td>
</tr>
<tr>
<td>O₂</td>
<td>-183.15</td>
<td>213</td>
<td>Reactive</td>
<td>800</td>
</tr>
<tr>
<td>Ar</td>
<td>-185.85</td>
<td>162</td>
<td>Inert</td>
<td>800</td>
</tr>
</tbody>
</table>
INTRODUCTION

➢ Hydrogen Energy

✓ Zero-emission fuel when burned with oxygen.
✓ No restriction on the energy resource because it produced from water.
✓ Current application: Vehicles, electric devices, and the propulsion of spacecraft, etc.

➢ Storage and Transport

✓ Stored and transported as a liquid state (like LNG)
✓ Liquid hydrogen requires cryogenic storage and boils around -253 °C.
✓ Necessity to develop well insulated LN2 CCS to prevent boil-off gas.

*Source) KHI(Japan) FC Expo, 2016.03
**INTRODUCTION**

Cylindrical tank for calculation of insulation thickness to achieve BOR 0.3%/day

- Gross Volume: 1,800 m$^3$ (typical fuel tank size on board)
- Diameter: 9,000 mm
- Material: 9% Nickel
- Design Pressure: 5 barg (IMO Type-C)
- Insulation: Polyurethane Foam (0.0245 W/mK)
- Target BOR: 0.3% vol./day

**BOR** = \[ \frac{\sum Q \times 3600 \times 24}{H \times V \times \rho} \times 100\% \]

\( \sum Q_i \) = Total Heat Ingress (W) \( V \) = Volume (m$^3$)
\( \rho \) = Liquid Density (kg/m$^3$) \( H \) = Latent heat (kJ/kg)
\( \sum Q_i = A_i \cdot \Delta T \cdot \frac{\lambda_i}{L_i} \)
\( \lambda_i \) = Thermal Conductivity (W/mK) \( A \) = Surface Area (m$^2$)
\( \Delta T \) = Temperature Difference \( L_i \) = Thickness of Insulation

<table>
<thead>
<tr>
<th>Liquid</th>
<th>LNG</th>
<th>LH₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latent Heat, MJ/m$^3$</td>
<td>216</td>
<td>32</td>
</tr>
<tr>
<td>BOR, %/day</td>
<td>0.309</td>
<td>0.302</td>
</tr>
<tr>
<td>Insulation Thickness, mm</td>
<td>300</td>
<td>3300</td>
</tr>
</tbody>
</table>

Over 10 times

**Liquefied Hydrogen (LH₂)**

- Density: 70.9 kg/m$^3$  
  ※ (1/7 to 1/6 compared to LNG)
- Latent heat: 32 MJ/m$^3$  
  ※ (1/7 compared to LNG)

Reduced storage due to increased insulation thickness
INTRODUCTION

LH2 Storage tank

(CCS Overview)
- Cylinder-shaped pressure tank verified as cargo hold for vessel
- Easier to manufacture than membrane type, but insulation problem exist in the curved part

(Insulation System)
- MLI and Powder type vacuum insulation system
- Strength/Thermal conductivity compared to high-performance FRP support

(Material and Structure)
- High manganese steel, Stainless steel
- Internal stiffened and vacuum ring
INTRODUCTION

Low Vacuum System

- Vacuum Pressure: 1,000 millitorr <
- Effective Thermal Conductivity: 10mW/m-K
- SOFI + Vacuum Insulation System
  - Spray on the foam insulation + MLI system
  - Prevent conduction with polyurethane foam
  - Advantages for large size due to low vacuum

Mid Vacuum System

- Vacuum Pressure: 1 – 1,000 millitorr
- Effective Thermal Conductivity: 1mW/m-K
- Filler + Vacuum Insulation System
  - MAT and powder type material as inner filler
  - Radiant heat shielding effect by the material itself
  - High thermal insulation performance at low vacuum

High Vacuum System

- Vacuum Pressure: < 1 millitorr
- Effective Thermal Conductivity: 0.1mW/m-K
- MLI + Vacuum Insulation System
  - Highest thermal insulation performance
  - Prevent conduc. and convect. heat by high vacuum
  - Suitable for small and medium LH2 storage tank

Radiation
Conduction
Convection
INTRODUCTION

✓ High vacuum system is the best in terms of thermal conductivity, but exist limitation of technology & expense cost

✓ Applying the low - medium vacuum system for ships cargo tank is realistic in large amount of LH2 storage

<table>
<thead>
<tr>
<th>Method</th>
<th>Type</th>
<th>Sample</th>
<th>Delta Temp</th>
<th>Temp Range (K)</th>
<th>k-value (mW/mK)</th>
<th>Heat Flux Range (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM C518</td>
<td>Comparative, Heat Flow Meter</td>
<td>Flat, square</td>
<td>Small</td>
<td>273 to 383</td>
<td>5 to 500</td>
<td>---</td>
</tr>
<tr>
<td>ASTM C177</td>
<td>Absolute, Guarded Hot Plate</td>
<td>Flat, disk</td>
<td>Small</td>
<td>93 to 773</td>
<td>14 to 2000</td>
<td>---</td>
</tr>
<tr>
<td>ASTM C745</td>
<td>Absolute, Boil off Calorimeter</td>
<td>Flat, disk</td>
<td>Large</td>
<td>250 to 670</td>
<td>---</td>
<td>0.3 to 30</td>
</tr>
<tr>
<td>Cryostat-1</td>
<td>Absolute, Boil off Calorimeter</td>
<td>Cylindrical</td>
<td>Large</td>
<td>77 to 350</td>
<td>0.03 to 30</td>
<td>0.8 to 120</td>
</tr>
<tr>
<td>Cryostat-2</td>
<td>Comparative, Boil off Calorimeter</td>
<td>Cylindrical</td>
<td>Large</td>
<td>77 to 350</td>
<td>0.1 to 50</td>
<td>2 to 400</td>
</tr>
<tr>
<td>Cryostat-4</td>
<td>Comparative, Boil off Calorimeter</td>
<td>Flat, disk</td>
<td>Large</td>
<td>77 to 350</td>
<td>0.5 to 80</td>
<td>6 to 900</td>
</tr>
</tbody>
</table>

**Note:** The Cryostat-4 method uses a Comparative, Boil off Calorimeter with a flat, disk sample for testing.
INTRODUCTION

✓ Specimen Type

Cylindrical
- Sample type: Film, Powder, Foam

Spherical
- Sample type: Powder

Flat Plate
- Sample type: Film, Powder, Foam

※ Calculated heat flow rate (Q)

\[
k_e = \frac{Q \ln \left( \frac{d_0}{d_i} \right)}{2\pi L_e \Delta T}
\]

\[
k_e = \frac{Q x}{\pi d_0 d_i \Delta T}
\]

\[
k_e = \frac{4Q x}{\pi d_e^2 \Delta T}
\]

\[
Q = V_{g_{STP}} \rho_{g_{STP}} h_f g \frac{\rho_f}{\rho_{fg}}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_g )</td>
<td>Volumetric Flow Rate of Gas</td>
<td>m³/s</td>
</tr>
<tr>
<td>( P_g )</td>
<td>Density of Gas</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>( H_g )</td>
<td>Heat of Vaporization</td>
<td>J/g</td>
</tr>
<tr>
<td>( X )</td>
<td>Insulation thickness</td>
<td>m</td>
</tr>
<tr>
<td>( d_e )</td>
<td>Diameter, effective heat transfer</td>
<td>m</td>
</tr>
</tbody>
</table>
## TEST SCENARIO

- Verification of Previous studies for data of manufacturing facility
- High Vacuum application material: MLI, Glass Bubble
- Medium vacuum application materials: MLI, Glass Bubble, Aerogel Blanket
- Low vacuum application materials: Glass Bubble, Aerogel Blanket

<table>
<thead>
<tr>
<th>Classification</th>
<th>Insulation</th>
<th>Deg. of vacuum</th>
<th>$K_{eff}$ (mW/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vacuum</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High vacuum</td>
<td>MLI</td>
<td>0.001</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>Vacuum only</td>
<td>0.003</td>
<td>10.44</td>
</tr>
<tr>
<td></td>
<td>Glass bubble</td>
<td>0.003</td>
<td>0.69</td>
</tr>
<tr>
<td>Soft vacuum</td>
<td>MLI</td>
<td>1</td>
<td>0.082</td>
</tr>
<tr>
<td></td>
<td>Vacuum only</td>
<td>1</td>
<td>12.52</td>
</tr>
<tr>
<td></td>
<td>Glass bubble</td>
<td>1</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>Aerogel blanket</td>
<td>1</td>
<td>1.64</td>
</tr>
<tr>
<td><strong>No-Vacuum</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vacuum only</td>
<td>760000</td>
<td>62.37</td>
</tr>
<tr>
<td></td>
<td>Glass bubble</td>
<td>760000</td>
<td>25.61</td>
</tr>
<tr>
<td></td>
<td>Aerogel blanket</td>
<td>760000</td>
<td>11.24</td>
</tr>
</tbody>
</table>
INTRODUCTION

Thermal conductivity for various material and fitted results

Markers: Experimental Solid lines: Dual pore

\[
\begin{align*}
\text{Therm. Cond. (mW/m-K)} \\
\end{align*}
\]

Notes:
1. Boundary Temperatures approximately 78 K & 293 K.
2. Residual gas nitrogen.
3. Legend data (25, 40, 55) means: 25 mm thickness, 40 layers, and 55 kg/m³ bulk density \([\chi, n, \rho]\).

(Fesmire, 2015)

(Ram, 2023)
TEST PROCEDURE
Method by C1774 (Cryostat) – Flat plate

- Mounting part of thermal insulation test specimen: Atmospheric to 10-5 torr pressure environment implementation
- Measuring and analyzing thermal insulation performance at wider temperature range (4K to 293K) than existing temperature (78K to 293K) in NASA Data
- Calculate effective thermal conductivity \( k_e \) by measuring heat flux \( Q \) according to temperature gradient through cold and hot plates

Equation of \( K_{eff} \) (ASTM C1774)

\[
Q = V_{g STP} \rho_{g STP} h_f g \left( \frac{\rho_f}{\rho_{fg}} \right)
\]

\[
k_e = \frac{Q \ln \left( \frac{(d_i + 2x)}{d_i} \right)}{2\pi L_e \Delta T}
\]
TEST APPARATUS

- Dimension of specimen: diameter (280 mm~300 mm) / thickness (max. 100 mm)
- Applied filling material: MLI (RUAG社, Polyester foil) / Glass Bubble (3M社, K1) / Aerogel Mat
- In case of glass bubble powder, sample container is prepared for specimen mounting

MLI & Aerogel Mat

Glass Bubble

MLI  Aerogel Mat  Heat flux sensor  Glass bubble  Filter

Specimen installation  Sample container with glass bubble
TEST APPARATUS

TEST RESULT
Results and Discussion

- Vacuum deterioration due to lowering molecular motion of the remaining air inside when LN2 is injected
- Through vacuum pumps and oil diffusion pumps, implement various Cold Vacuum Pressures (CVPs)
- In the condition of CVP, measure heat flow rate Q and calculate $k_{eff}$ for applied filling materials

![Graph showing Cold Vacuum Pressure (CVP) over time with different vacuum levels: High, Medium, Low.](image)

- Only Vacuum #1
- Only Vacuum #2
- Only Vacuum #3

- Boil-off Flow Rate
- Thermal equilibrium
- Both side boil off
- One direction boil off
- Thermal equilibrium point
- Sampling stage

![Diagram showing Guard Chamber, Test Chamber, Insulated Space, and Hot Plate with flow rate history](image)
Results and Discussion

- Vacuum deterioration due to lowering molecular motion of the remaining air inside when LN2 is injected
- Through vacuum pumps and oil diffusion pumps, implement various Cold Vacuum Pressures (CVPs)
- In the condition of CVP, measure heat flow rate $Q = \text{heat leakage}$ and calculate $k_{\text{eff}}$ for applied filling materials

Flow rate time history of Vacuum Only

$$Q = (\text{mass flow rate})(h_{fg})$$

$$k_e = \frac{Q \ln((d_i+2x)/d_i)}{2\pi L_e \Delta T}$$
**Results and Discussion**

- Verification of comparison with previous research NASA data through only vacuum results
- Additional verification for MLI, Powder, Mat Type specimen
Results and Discussion

Modified Only Vacuum

- Chamber
  - Vacuum Space
  - Ambient
  - Atmospheric exposure of specimen mounting part

Modified Glass Bubble

- Chamber
  - GB Container
  - Hot Plate
  - PUF

- Chamber
  - GB Container
  - Hot Plate

Heat Flux Sensor

Control Hot plate installation

Keeping separation to block direct heat transfer conduction

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Vacuum Only</th>
<th>Modified Method (Vacuum)</th>
<th>GB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum (mtorr)</td>
<td>0.0034</td>
<td>0.0262</td>
<td>81.35</td>
</tr>
<tr>
<td>Flow rate (mL/min)</td>
<td>597</td>
<td>637</td>
<td>735</td>
</tr>
<tr>
<td>$K_e$ (mW/mK)</td>
<td>11.608</td>
<td>12.386</td>
<td>14.282</td>
</tr>
</tbody>
</table>
Results and Discussion

**Conclusion**

- In this study, a cryogenic effective thermal conductivity evaluation facility was designed for the liquid hydrogen storage.
- To validate the data of the evaluation facility, the effective thermal conductivity was measured and verified for various filling materials in an environment similar to that of liquid nitrogen in a similar existing facility.

**Future work**

- Conduct evaluation of effective thermal conductivity for the complex composite insulation system.
- Acquire effective thermal conductivity data below 77K. (Liquid helium at 4K)
- Validate the existing predictive model for effective thermal conductivity.
Thank you for your attention