Measurement of heat flux in multi-layer insulated helium cryostats after loss of insulating vacuum

C1Or2A-07 – Applications: Safety and Instrumentation

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Outline

- Motivation
- Experimental setup
- Heat transfer mechanism
- Results & Discussion
- Summary & Outlook

PICARD

Pressure Increase in Cryostats and Analysis of Relief Devices
Motivation

- Profound understanding of the dimensioning process of Pressure Relief Devices (PRD)
  - Thermodynamic process tailored to the application;
  - Uniform & detailed understanding of heat transfer mechanisms.

- Compare with existing data for continuous improvement of the ‘state-of-the-art’

- Emphasis on heat flux in multi-layer insulated (MLI) helium cryostats after loss of insulating vacuum (LIV)
Experimental setup

**Characteristics**

<table>
<thead>
<tr>
<th>Type</th>
<th>$N_{\text{Layer}}$</th>
<th>$\delta_R$ (µm)</th>
<th>$\delta_S$ (µm)</th>
<th>$\phi$ (mm)</th>
<th>Grid (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>6</td>
<td>55</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>18</td>
<td>-</td>
<td>6</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>12</td>
<td>55</td>
<td>4</td>
<td>150</td>
</tr>
</tbody>
</table>

Layer density: 10 cm$^{-1}$

Thermal bridges warm-cold layers avoided using aluminum adhesive
Heat transfer mechanism

Measurement of heat flux in multi-layer insulated helium cryostats after loss of insulating vacuum
Heat transfer mechanism

1D heat transfer equation for cryogenic wall temperature ($T_{w,i}$ & $T_{w,o}$)

- Deposition heat flux: Enthalpy balance – $f (\dot{M}_{in}, p_v)$
- Thermal radiation: Stefan-Boltzmann equation
- Thermal conduction MLI: Fourier equation (radial)
- Thermal conduction wall: Fourier equation
- Heat transfer in helium: Convective heat transfer

Note:
- Vacuum vessel: Convective heat transfer neglected due to low Grashof numbers
- Deposition: Solid air enthalpies included (ideal mixture of N$_2$, O$_2$, Ar, and water)
Results – Heat Flux

Plot shape (MLI Experiments):

1) Influence on the flow resistance of the MLI blanket
Results – Heat Flux

Plot shape (Vacuum space):
1) Influence on the flow resistance of the MLI blanket

Plot shape (Helium):
1) $\dot{q}_{He}$ small due to film boiling
Results – Heat Flux

Plot shape (Vacuum space):
1) Influence on the flow resistance of the MLI blanket
2) Increase of heat flux to peak due to $p_v \approx \text{atm}$

Plot shape (Helium):
1) $q_{\text{He}}$ small due to film boiling
2) Peak due to property data in vicinity of $p_{\text{Crit}}$
Results – Heat Flux

Plot shape (Vacuum space):
1) Influence on the flow resistance of the MLI blanket
2) Increase of heat flux to peak due to $p_v \approx$ atm
3) First opening of PRD

Plot shape (Helium):
1) $\dot{q}_{\text{He}}$ small due to film boiling
2) Peak due to property data in vicinity of $p_{\text{Crit}}$
3) Free convection
First opening of the PRD – Heat flux relevant for dimensioning
- From $\sim 1.2$ – $0.7$ W/cm$^2$
Results – Heat Flux

Plot shape (Vacuum Space):
1) Influence on the flow resistance of the MLI blanket
2) Increase of heat flux to peak due to $p_v \approx \text{atm}$
3) First opening of PRV
4) Heat flux limited by cryopumping effect

Plot shape (Helium):
1) $\dot{q}_{\text{He}}$ small due to film boiling
2) Peak due to property data in vicinity of $p_{\text{Crit}}$
3) Free convection
   First opening of the PRD – Heat flux relevant for dimensioning
   - From ~ 1.2 – 0.7 W/cm²
4) Heat flux quasi-independent of the MLI type
Results – Exp. 3 vs Exp. 4

Heat transfer limited by Helium ($Bi < 1$)

24 layers Type 1 vs 10 layers Type 3

<table>
<thead>
<tr>
<th>Type</th>
<th>$N_{Layer}$</th>
<th>Thickness (µm)</th>
<th>Perforation holes (mm)</th>
<th>Free Perforation area (mm² / m² MLI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>6</td>
<td>55</td>
<td>2 50 1250</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>12</td>
<td>55</td>
<td>4 150 550</td>
</tr>
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</table>
## Results

### Comparison with literature

<table>
<thead>
<tr>
<th>N_{Layers}</th>
<th>Reference</th>
<th>Heat flux (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Lehmann &amp; Zahn [12]</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>PICARD</td>
<td>1.4</td>
</tr>
<tr>
<td>1</td>
<td>Lehmann &amp; Zahn [12]</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>PICARD</td>
<td>1.2</td>
</tr>
<tr>
<td>10</td>
<td>Lehmann &amp; Zahn [12]</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>PICARD</td>
<td>0.7</td>
</tr>
<tr>
<td>12</td>
<td>Lehmann &amp; Zahn [12]</td>
<td>0.59*</td>
</tr>
<tr>
<td></td>
<td>PICARD</td>
<td>1.0</td>
</tr>
<tr>
<td>24</td>
<td>Lehmann &amp; Zahn [12]</td>
<td>0.38*</td>
</tr>
<tr>
<td></td>
<td>PICARD</td>
<td>0.7</td>
</tr>
</tbody>
</table>

*extrapolated

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**Comparison with literature**

- **12 layer blankets** – higher values
- **Bare & 1 Layer** – lower values
Summary and Outlook

**Summary**
- Experiments performed at PICARD with MLI
- Effect of multi-layer insulated helium cryostats was measured and evaluated
- Influence on manufacturing characteristics of the MLI demonstrated (e.g. perforation holes)
- Relevant heat flux for dimensioning of PRD discussed
- Results differ from literature – higher heat flux for Type 1 MLI

**Outlook**
- Further experimental investigations on types of MLI
- Investigate the possibility of an ‘equivalent’ MLI resistance in the dynamic model
- Evaluation of model uncertainty (Bayesian approach)
Thank you for your attention
References

Spare Slides
Heat transfer mechanism - MLI

\[ \dot{q}_{\text{Cond},n} : \text{Residual gas & solid thermal conduction} \ (n \ ; \ n+1) \]
- Total thermal resistance derived from [6], including:
  - Gaseous air, spacer and the reflective screens

\[ \dot{q}_{\text{Rad}} : \text{Radiated heat considering} \ N \text{ reflective MLI layers as grey emitters. Emissivity values:} \]
  - \( \epsilon_v = 0.8 \) – vacuum vessel (oxidized SS)
  - \( \epsilon_{Cr} = 0.07 \) – helium vessel (electro-polished SS)
  - \( \epsilon_{MLI} = 0.04 \) – reflector (electro-polished Al)

\[ \dot{q}_{\text{Dep}} : \text{Measured based on mass flow of venting air and rise in vacuum pressure [7]} \]
Heat transfer mechanism - Helium

\( \dot{q}_{\text{He}} \): Heat transfer coefficient \( \alpha_{\text{He}} \) depends on thermodynamic state and fluid phase

- **Correlations subcritical state:**
  - \( A_{\text{Cr}} \) in contact with liquid \( \alpha_{\text{He}} \) - pool boiling [8,9]
  - \( A_{\text{Cr}} \) in contact with gas \( \alpha_{\text{He}} \) - free convection [10]

- **Correlations supercritical state:**
  - \( \alpha_{\text{He}} \) - free convection [11]
Formulas

Cryo wall temperatures:
\[
\frac{dT_{W,o}}{dt} = \frac{A_C}{c_{Cr} \cdot M_{Cr}} \cdot (\dot{q}_{\text{Dep}} + \dot{q}_{\text{Rad}} + \dot{q}_{\text{Con}} - \dot{q}_{\lambda,W}) ; \quad \frac{dT_{W,i}}{dt} = \frac{A_C}{c_{Cr} \cdot M_{Cr}} \cdot (\dot{q}_{\lambda,W} - \dot{q}_{\text{He}})
\]

Stefan-Boltzmann:
\[
\dot{q}_{\text{Rad}} = \sigma \cdot (T_{V}^4 - T_{W}^4) \cdot \left( \left( \frac{1}{\epsilon_{Cr}} + \frac{1}{\epsilon_{\text{MLI}}} - 1 \right) + (N - 1) \cdot \left( \frac{2}{\epsilon_{\text{MLI}}} - 1 \right) + \left( \frac{1}{\epsilon_{V}} + \frac{1}{\epsilon_{\text{MLI}}} - 1 \right) \right)^{-1}
\]

Fourier (cryo wall):
\[
\dot{q}_{\lambda,W} = \frac{\lambda_{Cr}}{s_{Cr}} \cdot (T_{W,o} - T_{W,i})
\]

Fourier (MLI):
\[
\dot{q}_{\text{Cond,n}} = \frac{(r_{n+1} - r_n) \cdot (T_{n+1} - T_n)}{r_n \cdot \left( R_g + \frac{R_e + R_s'}{R_e + R_s} + R_v \right) \cdot \ln \left( \frac{r_{n+1}}{r_n} \right)}
\]

Convective heat flux to He:
\[
\dot{q}_{\text{He}} = \alpha_{\text{He}} \cdot (T_{W,i} - T_{\text{He}})
\]

Deposition heat flux:
\[
\dot{q}_{\text{Dep}} = \frac{M_{\text{Dep}}}{A_{Cr}} \cdot (h_{\text{air}} (p_{\text{amb}}, T_{\text{amb}}, \varphi_{\text{amb}}) - h_{\text{air}} (p_V, T_{W_o}, \varphi_{\text{amb}}))
\]
Heat flux plot

Image of a graph showing heat flux measurements in multi-layer insulated helium cryostats after loss of insulating vacuum.