The Design of a Hydrogen Pulsating Heat Pipe

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1. Motivation

- Regenerative cryocoolers provide localized cooling

- Cryogenic applications require distributed cooling
  - Superconducting magnet example: accelerators, MRI
  - Length scale are typically ~ 1 meter
1. Motivation

Options for distributing the cooling power

- Metallic materials or component materials:
  - Copper, Aluminum.
  - \( \text{Cu}_{100}(4\text{K}): Q=1\text{W}, \nabla T=1.5\text{K/m} \rightarrow A \approx 10\text{cm}^2 \)

- Thermo-siphon and re-condenser

- Heat Pipe
  - Conventional Heat Pipe
  - Capillary Loop Pipe
  - Pulsating Heat Pipe (PHP)
2. Introduction of PHP

➢ First developed in 1990 by Akachi
➢ Multiple loops of capillary tubing (no wicking structure)
➢ Partially filled with heat transfer fluid—alternating liquid slugs and vapor plugs
➢ Oscillatory and circulatory motions effectively transfer heat from evaporator to condenser
➢ Influencing factors: fluid properties, geometry, filling ratio, inclination and heat input.
➢ World wide interest for room temperature applications
2. Introduction of PHP-Review

- Natsume, et al. (Toki, Japan)
  - Cooling and thermal equalizer for HTS coils
  - Nitrogen, Neon, and Hydrogen

- Ma et al. (University of Missouri)
  - Cell cryopreservation
  - Nitrogen

- Bonnet et al. (CEA, France)
  - Distribute cryogenic cooling from cryocoolers
  - Helium

- UW-Madison
  - Fundamental mechanisms
  - Distribute cryogenic cooling from cryocoolers
  - Helium
# 2. Introduction of PHP-Review

<table>
<thead>
<tr>
<th>Institute</th>
<th>working fluid</th>
<th>Capillary pipe</th>
<th>N</th>
<th>Filling ratio (%)</th>
<th>Heat (W)</th>
<th>Inclination (°)</th>
<th>Thermal conductivity (W/m · K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UM</td>
<td>N₂</td>
<td>Cu</td>
<td>8</td>
<td>48</td>
<td>20.5~380.1</td>
<td>0</td>
<td>11600~26100</td>
</tr>
<tr>
<td>CEA-France</td>
<td>He</td>
<td>Cu-Ni</td>
<td>5</td>
<td>-</td>
<td>0.015~0.145</td>
<td>0~40</td>
<td>2.5 K/W (Resistance)</td>
</tr>
<tr>
<td>the National Institute for Fusion Science</td>
<td>H₂</td>
<td>SSL</td>
<td>5</td>
<td>31~80</td>
<td>0~1.2</td>
<td>90</td>
<td>500~3000</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
<td>SSL</td>
<td>5</td>
<td>17~70</td>
<td>0~7</td>
<td>90</td>
<td>5000~18000</td>
</tr>
<tr>
<td></td>
<td>Ne</td>
<td>SSL</td>
<td>5</td>
<td>16~95</td>
<td>0~1.5</td>
<td>90</td>
<td>1000~8000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>50.6~86.1</td>
<td>0.588~16</td>
<td>-90~90</td>
<td>5100~19440 (0-90°)</td>
</tr>
<tr>
<td>UW-Madison</td>
<td>He</td>
<td>SSL</td>
<td>32</td>
<td>4~26.5</td>
<td>0.003~0.86</td>
<td>0</td>
<td>1800~2457</td>
</tr>
</tbody>
</table>

## Future:

1. Heat input with respect to the start of PHP
2. Thermal conductivity with respect to adiabatic section
3. Critical turns
3. Experimental Setup Design

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryocooler</td>
<td>KDE410: <a href="mailto:1W@4.2K">1W@4.2K</a></td>
</tr>
<tr>
<td>Shield</td>
<td>Copper, D_in=316mm, TH=2mm, H=980mm</td>
</tr>
<tr>
<td>Condenser/Evaporator</td>
<td>Copper, U, L=200mm, H=70mm, TH=10mm</td>
</tr>
<tr>
<td>Capillary Pipe</td>
<td>U-copper, StraightPipe-SSL; D_in=2.3mm, D_outer=3.2mm</td>
</tr>
<tr>
<td>Filling Pipe</td>
<td>SSL, D_in=2.3mm, D_outer=3.2mm</td>
</tr>
</tbody>
</table>

Cryogenics
3. Experimental Setup Design—Shield

\[ Bo = d \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} < 2 \]

Material: Copper
Size: \(D_{\text{in}}=316\text{mm}, TH=2\text{mm}, H=960\text{mm}, m=32\text{Kg}\)

![Graph showing the relationship between maximum diameter and average temperature](image1)

![Cylindrical shield model with ANSYS simulation](image2)
3. Experimental Setup Design—PHP、dewar

Features:

1. U-shaped copper block is a whole;
2. Turn numbers can change;
3. The length of adiabatic section can change;
4. There is no shrinking on the capillary pipe.
3. Experimental Setup Design—Structure calculation

- Screw rod bearing:
  
  \[ M_{PHP}=20\text{Kg}, M_{\text{shield}}=32\text{Kg} \]

- The four SSL rod between shield and PHP:
  
  \[ \text{ID}=4\text{mm}, \text{OD}=10\text{mm}, \text{L}=280\text{mm} \]
  
  Tensile strength=0.64MPa,
  
  Bending normal strength=142.6MPa,
  
  Bending shear strength=0.85MPa

- The 7 SSL rod between the shield with the dewar:
  
  \[ \text{ID}=0\text{mm}, \text{OD}=12\text{mm}, \text{L}=200\text{mm} \]
  
  Tensile strength=0.66MPa
  
  Bending normal strength=87.6MPa,
  
  Bending shear strength=0.88MPa

Limiting values of SSL:

\[
[\sigma] = 630 \text{MPa}, n_b=3, \sigma_{\text{max}}=210 \text{ MPa} \\
[\sigma]_{0.2}=215\text{MPa}, n_s=1.5, \sigma_{\text{max}}=143 \text{ MPa} \\
[\tau] = 77.5\text{MPa}
\]
3. Experimental Setup Design—Heat leak calculation

<table>
<thead>
<tr>
<th>Heat load and cooling capacity of first stage cold head</th>
<th>Radiation between shield and dewar</th>
<th>1.7 W</th>
<th>15 W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conduction of support rod</td>
<td>12 W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat load of filling pipe</td>
<td>0.5 W</td>
<td></td>
</tr>
<tr>
<td>Heat load and cooling capacity of second stage cold head</td>
<td>Radiation between shield and PHP</td>
<td>20 mW</td>
<td>77.5 mW</td>
</tr>
<tr>
<td></td>
<td>Conduction of support rod</td>
<td>54.7 mW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat load of filling pipe</td>
<td>2.8</td>
<td></td>
</tr>
</tbody>
</table>
3. Experimental Setup Design

The diagram shows the relationship between the temperature of the first stage and the cooling capacities of both stages. The graph contains data points for different cooling capacities of the first stage, with corresponding temperatures for the second stage. The graph includes data from KD, the first experiment, and the second experiment.

- The red triangles represent the data of KD.
- The blue stars represent the first experiment data.
- The purple circles represent the second experiment data.

The axes are labeled as follows:
- X-axis: Temperature of first stage (K)
- Y-axis: Temperature of second stage (K)
- The graph shows the cooling capacity of the first stage in watts (W).

The diagram visually illustrates the experimental setup design for the Institute of Refrigeration and Cryogenics.
4. Conclusion

(1) Introducing a highly efficient heat transfer method (Pulsating Heat Pipe) and summarizing the recent research.

(2) Utilizing software ANSYS and Solidworks to realize the experimental setup design.

<table>
<thead>
<tr>
<th>Component</th>
<th>Design objection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryocooler</td>
<td>First stage: 15W@36K, Second stage: 14W@20K</td>
</tr>
<tr>
<td>Filling Ratio</td>
<td>10%-90%</td>
</tr>
<tr>
<td>Heat</td>
<td>0-13W</td>
</tr>
<tr>
<td>Working Fluid</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>Turn numbers</td>
<td>1-28</td>
</tr>
<tr>
<td>Length of adiabatic</td>
<td>100mm, 500mm</td>
</tr>
<tr>
<td>section</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>-90~90</td>
</tr>
</tbody>
</table>
References:

Thanks for your attention!