Cryogenic Heat Sink for Helium Gas Cooled Superconducting Power Devices

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Superconducting Power Cables

- Superconducting cables for shipboard power system
  - Temperatures below LN2 → higher current density
  - Liquid cryogens not permitted (asphyxiation & explosion hazard)
  - Solution: Helium gas at 50...60 K and 1.8 MPa; flow rate up to 20 g/s

- $^g$He has lower heat capacity than LN2
  - Cooling more challenging, especially at terminations

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**Helium circulation system**

- 1200 W @ 77 K
- 500 W @ 40 K
- Cylindrical tank
- AL 330
- Cryo Fan
- Top View
- Side View
Model Heat Sink

- **Problem:**
  - Heat influx from ambient
  - Joule heating in bushing

- **Solution:**
  - Heat intercept attached to copper conductor
  - Cold He gas flow through heat sink

- **Design:**
  - Finned heat sink inside tube
  - Entirely made from copper
  - Design and dimensions need to be optimized by FEA
  - Small-scale model built for model validation
Finite Element Model: 2D Heat Transfer

**Goal:** Determine optimal number of fins  
**Symmetry:** All BC for ½ heat sink

- **Physics**
  - *Heat Transfer in Solids*
  - No CFD, but

- **Boundary conditions**
  - Heat influx 50 W
  - Symmetry
  - Insulation (vacuum)
  - In channels: Convective cooling boundary condition (h = 90 W/m²K for the 9-fin model, obtained by Dittus-Boelter correlation)

- **Initial temperature:** 50 K
- **Material properties**
  - Copper: $k$, $c_p$, $\rho$ as a function of temperature
- **Mesh size:** normal (2986 elements for 9-fin model)
- **Pressure drop calculated separately using Moody Diagram**
Maximum heat sink temperature and pressure drop as a function of number of fins for three different mass flow rates

- 9 Fins seem to be optimal
- Flow rates of below 1 g/s are sufficient (50 W input power)
Finite Element Model: 3D Fluid Flow

- **Physics**
  - *Conjugate Heat Transfer*
  - Laminar flow

- **Boundary conditions**
  - Inlet: Helium, 50 K, volume flow rate
  - Outlet: Pressure
  - Heat influx: same as 2D model

- **Helium properties**
  - Density considered constant (at 58 K)

- **Mesh**
  - Fluid domain: normal
  - Solid domain: finer
  - Total 1.54 million elements

- **Convergence**
  - GMRES: 240 iterations
  - Non-lin: 45 iterations

Interesting detail: Temperature BC should not touch solid edge

Temperature field for 100 W heat influx

Simulation time: 156 min (on 2x Intel Xeon X5570)
Experiment for Model Validation

- Made from copper
  - Most parts mechanically machined
  - Fins were machined by EDM
  - Joined by silver braze (optimal heat transfer; leak free)
- Heater based on resistance wire
- Wrapped in aluminized Mylar
- Installed in vacuum chamber

![Image of the experiment setup]
## Results of Validation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>50 W for full HS</th>
<th>100 W for full HS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model</td>
<td>Experiment</td>
</tr>
<tr>
<td>Temperature inlet [K]</td>
<td>58.6</td>
<td>58.6</td>
</tr>
<tr>
<td>Temperature increase [K]</td>
<td>4.15</td>
<td>4.7</td>
</tr>
<tr>
<td>Temp. heat sink [K]</td>
<td>63.0</td>
<td>77.3</td>
</tr>
<tr>
<td>Pressure drop [Pa]</td>
<td>284</td>
<td>294</td>
</tr>
</tbody>
</table>

- Generally good agreement between simulation results and measurements
  - Except for heat sink temperature
  - Investigations under way to determine the reason for discrepancy (Model or measurement?)
Conclusion

- The chosen geometry is suitable
  - Low pressure drop
  - Excellent heat transfer
  - Higher flow rates for turbulent flow are under investigation

- The developed models are very useful tools for heat sink design and optimization
  - It will be used for a real application in near future

- Model will be extended to incorporate turbulent flow

- Optimization studies for geometrical parameters (non-uniform spacing of fins; thickness of fins)