Coldplate design

Design guidelines:
- **Least amount of custom parts** - use off-the-shelf components when possible
- **Ease of use** - exchanging modules should be simple
- **Modularity** - Same design should be used for all module types with only change of a few parts

This is only to illustrate the idea, not a final design!
No measurements are final.
Metal base
- No requirements
Liquid cooled coldplate
- E.g. Ohmite CP4A-114C-108E
- Roughly 10x10 cm cooled area
Peltier elements
- E.g. TE-71-1.4-2.5
- 4 elements in parallel
- Elements are glued to cold plate with thermal conductive epoxy
  - E.g. Masterbond EP3HTS-LO
Copper vacuum chuck
- Copper: low thermal resistance to peltier elements
- Vacuum suction ensures homogenous and excellent thermal contact between module and chuck.
- Have not found any suppliers yet, still inquiring!
Module frame holders
- Module-specific holders
- Consists of arms with dowels
- Module handling frame slides onto dowels for repeatable alignment of module
Insulation suggestion: Vacuum plates

Positives:
- 10x better (!) insulating properties than Thermaflex
- Impervious to humidity
- Comes in many sizes and thicknesses
- Rated for our thermal range
- Mass produced for building construction -> cheap
- Rigid, not flexible

Negatives:
- Insulation properties are lost if outer metal foil is broken

Heat loss through box can be made negligible with the use of vacuum plates. See calculations on following slides.

Fragility of vacuum plates can be mitigated by covering vacuum plates in thin layer of solid insulator.
New heat loss calculation
Keep the modules at -50 degrees

- Old heat loss calculation:
  - Estimated total heat loss of 170W
  - Only looking at conductive heat transfer
  - Power consumption of modules

- New heat loss calculation:
  - Overall heat transfer (convection and conduction)
  - (Power consumption of modules and Peltier elements)
  - Included heat loss from tubes
  - Included heat loss from wires
  - Calculations on nitrogen (negligible)
  - Compared two systems

1) Original setup: Armaflex

2) Vacuum setup: Vacuum plates and thin layer of armaflex
Overall heat transfer

Separates into two steady state calculations

1. Calculate the heat loss from the floor
   Chiller plate will cool the floor insulation material
   Approximation → That whole upper surface of the floor = -25°C (Reality: Temperature gradient)

2. Calculate the cooling to air and the heat loss of air
   Air will get cooled by the cold floor surface, the chiller plate and the vacuum copper plate
   The air will get heated by the side surfaces and top surface of the box
Floor conductive calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>0.4896 m²</td>
</tr>
<tr>
<td>$T_h$</td>
<td>20°C</td>
</tr>
<tr>
<td>$T_c$</td>
<td>-25°C</td>
</tr>
<tr>
<td>$L_1$</td>
<td>0.010 m</td>
</tr>
<tr>
<td>$k_1$</td>
<td>0.034 W/mk</td>
</tr>
<tr>
<td>$L_2$</td>
<td>0.040 m</td>
</tr>
<tr>
<td>$k_2$</td>
<td>0.0035 W/mk</td>
</tr>
</tbody>
</table>

**Vacuum setup**

\[
P_{floor} = \frac{A(T_h - T_c)}{\frac{L_1}{k_1} + \frac{L_2}{k_2}}
\]

- $P_{floor}$ (vacuum): 1.88 W
- $P_{floor}$ (original): 23.409 W
Air system

Vacuum setup

<table>
<thead>
<tr>
<th>Area</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area floor</td>
<td>0.4896 m²</td>
</tr>
<tr>
<td>Area top</td>
<td>0.4896 m²</td>
</tr>
<tr>
<td>Area sides</td>
<td>0.48 m²</td>
</tr>
<tr>
<td>Area of 9 chiller plates</td>
<td>0.0576 m²</td>
</tr>
<tr>
<td>Area of 9 copper plate</td>
<td>0.1152 m²</td>
</tr>
<tr>
<td>α_air (Heat transfer coeff)</td>
<td>5 W/m²K (10)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_air</td>
<td>?</td>
</tr>
<tr>
<td>Th</td>
<td>20°C</td>
</tr>
<tr>
<td>Tc</td>
<td>-25°C</td>
</tr>
<tr>
<td>L1</td>
<td>0.010 m</td>
</tr>
<tr>
<td>k1</td>
<td>0.034 W/mK</td>
</tr>
<tr>
<td>L2</td>
<td>0.040 m</td>
</tr>
<tr>
<td>K2</td>
<td>0.0035 W/mK</td>
</tr>
<tr>
<td>Pair (vacuum)</td>
<td>21.42 W</td>
</tr>
<tr>
<td>Pair (original)</td>
<td>29.28 W</td>
</tr>
</tbody>
</table>

\[
\frac{1}{kA} = \frac{1}{\alpha_1 A_1} + \sum_i \frac{\delta_i}{\lambda_{mi} A_{mi}} + \frac{1}{\alpha_2 A_2}
\]
Calculations

**Cooling to air**

Chiller: \( q_A = A_1 (T_{th} - T_{a}) = 0.288 \text{ W/K} \times (T_{air} + 25 \text{K}) \)

Floor: \( q_A = A_1 (T_{th} - T_{a}) = 2.448 \text{ W/K} \times (T_{air} + 25 \text{K}) \)

Ceiling: \( q_A = A_1 (T_{th} - T_{a}) = 0.576 \text{ W/K} \times (T_{air} + 50 \text{K}) \)

**Heat Loss from Air**

\[
\frac{1}{h_A} = \frac{1}{h_{A1}} + \frac{L_1}{K_{A2}} + \frac{L_2}{K_{A3}} + \frac{A_1}{h_{A4}} = 24.84
\]

\( h_{A1} = 0.04 \text{ W/K (Sides)} \)

\( h_{A2} = 0.42 \text{ W/K (Top)} \)

\( P_{sides} = 0.04 \text{ W/K} \times (20K - T_{air}) \)

\( P_{top} = 0.42 \text{ W/K} \times (20K - T_{air}) \)

**With Nitrogen**

\[ Q = m \cdot C \cdot \Delta T \]

\[ Q = 1.25 \times 10^{-5} \times 1040 \times 9.75 \times 10^{-3} = 0.585 \text{ W/min} = 9.75 \times 10^{-3} \text{ W} \]

**Temperature of Air**

\[
P_{in} = P_{out}
\]

\[
P_{chiller} + P_{flow} + P_{sides} = P_{in} + P_{out}
\]

\[
T_{air} = 0.288 + 7.2 + T_{air} - 2.448 + 61.2 + T_{air} - 0.576
\]

\[
25.8 = -T_{air} + 0.04 + 0.8 - T_{air} \cdot 0.12 + 8.4
\]

\[
T_{air} = 0.788 + 7.448 + 0.576
\]

\[
T_{air} = -7.2 - 61.2 - 25.8 + 0.1 + 8.4
\]

\[
T_{air} = -26.59^\circ\text{C}
\]

\[
P_{out} = P_{flow} + P_{sides} + P_{chiller}
\]

\[
= 1.88 \text{ W} + 1.86 \text{ W} + 19.56
\]

\[
= 23.3 \text{ W}
\]

**For original setup**

\[
P_{flow} = 23.40 \text{ W}
\]

\[
P_{chiller} = 0.723 \times (20 - T_{air})
\]

\[
T_{air} = 4.035 = -52.74^\circ
\]

\[
T_{air} = -20.5^\circ\text{C}
\]

\[
P_{out} = 23.40 \text{ W} + 29.78 \text{ W} = 53.18 \text{ W}
\]
## Total passive heat loss

### Currently upper limits

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{Vacuum box}}$</td>
<td>23.3 W</td>
</tr>
<tr>
<td>$P_{\text{Original box}}$</td>
<td>52.7 W</td>
</tr>
<tr>
<td>$P_{\text{tubes}}$</td>
<td>60 W</td>
</tr>
<tr>
<td>$P_{\text{wires}}$</td>
<td>10 W</td>
</tr>
<tr>
<td>$P_{\text{TOT (Vacuum)}}$</td>
<td>93.3 W</td>
</tr>
<tr>
<td>$P_{\text{TOT (Original)}}$</td>
<td>122.7 W</td>
</tr>
</tbody>
</table>

- The box floor temperature must be multiplied by a factor $0.3 < k < 1$.
- Other simplifications (Air flow from nitrogen).

→ Could get more accurate and flexible calculations with simulations (ANASYS / calculation-script)
We wish to take the modules to -50C. We need an idea of the required cooling capacity by the external chiller at this temperature.

**External chiller must compete against two sources of heat:**
- Power dissipation in modules and peltier elements.
- Absorption of heat through insulation, e.g. box walls, tubing insulation, electrical cables.

**Cold loss via heat absorption through insulation depends primarily on temperature of cooling liquid**
- We can reduce cold loss by increasing the liquid temperature
- The ITK modules are cooled further down with Peltier elements

**Factors to consider:**
- Peltier element heat dissipation increases as hot-cold delta T increases
- Chiller cooling capacity increases as liquid temperature increases
- Heat absorption decreases as liquid temperature increases

=> There should be a liquid T “sweet spot” where the greatest possible cooling capacity is reached!
Heat loss and required cooling capacity

Peltier elements

Generates a $T$ difference:

$$\Delta T_{\text{Peltier}} = -55 \degree C - T_{\text{plate}}$$

ITK module

$$T_{\text{module}} \approx T_{\text{chuck}} + 5 \degree C$$

Vacuum chuck

$$T_{\text{chuck}} \approx T_{\text{plate}} + \Delta T_{\text{Peltier}}$$

Cooling plate

$$T_{\text{plate}} \approx T_{\text{liquid}}$$
Heat loss and required cooling capacity

Heat absorption ("Cold loss") through:
- Coldbox insulation
- Tubes between chiller/box
- Electrical cables exiting box

Assuming:
- 3m Julabo triple insulated tubing
- Vacuum plate box insulation
- Electrical cables loss is upper limit (10W @ \( T_{\text{plate}} = -25^\circ\text{C} \))
- Box size = 110cm x 56cm x 20cm
Heat loss and required cooling capacity

ITK modules power dissipation is constant regardless of cooling plate temperature.

10W per module x 9 modules = 90W
Heat loss and required cooling capacity

For each cooling plate temperature, an optimal Peltier element exists.
- Minimum power draw
- Meets heat load requirements

Used TE’s Peltier calculator.

Assuming:
- Four peltier elements in parallel per module

Observation:
Peltier module heat dissipation surpasses cooling requirements of rest of system at $T_{\text{plate}} = -30^\circ\text{C}$. 
We (Bergen) already have a Julabo DD-1000F recirculating chiller.

Cooling capacity is lower than requirement for all cooling plate temperatures.

\( T_{\text{module}} = -50 \, ^\circ \text{C} \) can not be reached.
Adding a second smaller chiller brings the total cooling capacity above the requirements.

Other institutions can use this approach or purchase a single chiller with sufficient cooling capacity.
Heat loss and required cooling capacity

Cooling budget is greatest at $T_{\text{plate}} = -15\,\text{C}$. Cooling capability is 213W greater than requirement.

We will be able to reach $T_{\text{module}} = -50\,\text{C}$.

The time this will take from room $T$ depends on the slope $K/\text{min}$ and has to be calculated.
We have calculated upper limits on passive cold loss.

Cold loss from the box can be made negligible by using vacuum insulation plates.

The optimal cold-plate temperature is -15C when using the Dyneo DD-1000F and Curio CD-600F chillers and 4 TE-71-1.4-2.5 Peltier elements per module.

213 W of additional cooling capacity will allow us to take ITK modules to -50C even if there are unforeseen heat sources or inefficiencies.

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Heating power @ $T_{\text{plate}} = -15C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller liquid tubes</td>
<td>45W</td>
</tr>
<tr>
<td>Box insulation</td>
<td>18W</td>
</tr>
<tr>
<td>Electrical cables</td>
<td>8W</td>
</tr>
<tr>
<td>ITK modules</td>
<td>90W</td>
</tr>
<tr>
<td>Peltier modules</td>
<td>525W</td>
</tr>
<tr>
<td>SUM</td>
<td>687W</td>
</tr>
</tbody>
</table>

Chiller capacity 900W
Budget 213 W