Cooling technology for HTS power applications

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Outline

- Taking into account different backgrounds of the course participants, the aim of this course is
  - to provide an overview of existing HTS cooling technologies
  - to explain their technological differences
  - to discuss future development potentials

- Therefore, the course is structured in the following sections
  - Technology overview
  - Cryocoolers
  - Cryoplants (refrigerators)
  - Development potentials
  - Summary
Cooling technology for HTS power applications

TECHNOLOGY OVERVIEW
### Three-phase HTS power cables

**Example**

- **AmpaCity project**
- **Partners** RWE, Nexans, KIT
- **Cable length** $L = 1000 \text{ m}$
- **Voltage** $U = 10000 \text{ V}$
- **Nominal current** $I_N = 2300 \text{ A}$
- **Nominal capacity** $P_N = \sqrt{3} \cdot U \cdot I_N = 40 \text{ MW}$

![Diagram of HTS power cable components](image.png)

#### Technical specification
- 1 km distance between substations
- 10 kV system voltage
- 2.3 kA operating current (40 MVA)

![Cable installation route in downtown Essen, Germany](image.png)

Official start of field test on April 30, 2014
Cooling unit in the AmpaCity project

Specification 1)

- Sub-cooled LN$_2$ cooling of the HTS cable
- Open LN$_2$ cooling cycle
- Each one redundant LN$_2$ and vacuum pump
- Nominal cooling capacity $\dot{Q}_{0,N} = 4$ kW @ 67 K
- Nominal LN$_2$ consumption $\dot{M}_{LN_2,N} = 110$ kg/h

1) Herzog, F.; Kutz, T.; Stemmle, M.; Kugel, T.: Cooling unit for the AmpaCity Project – one year successful operation. IWC 2015, Matsue - Japan
## Cooling methods

### General overview

<table>
<thead>
<tr>
<th>Priniciple</th>
<th>Open cycle</th>
<th>Closed cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principle</strong></td>
<td>Evaporation of LN$_2$ obtained from air separation units (ASU)</td>
<td>Cryocooler</td>
</tr>
<tr>
<td>Air composition:</td>
<td></td>
<td>Oscillating regenerative process</td>
</tr>
<tr>
<td></td>
<td>78.09 Vol% N$_2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20.95 Vol% O$_2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.934 Vol% Ar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ CO$_2$, Ne, He, Kr, H$_2$, Xe, O$_3$, Rn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>+ Water, HCs, CFCs, dust, …</td>
<td></td>
</tr>
<tr>
<td><strong>Capacities</strong></td>
<td>Any range</td>
<td>Small</td>
</tr>
<tr>
<td><strong>Temperatures</strong></td>
<td>$T_{\text{min}} &gt; T_{\text{tr,N2}} = 63$ K</td>
<td>Any down to ~2 K</td>
</tr>
<tr>
<td><strong>Operation supplies</strong></td>
<td>Electricity LN$_2$</td>
<td>Electricity (Cooling water)</td>
</tr>
<tr>
<td><strong>Other criteria</strong></td>
<td>Investment cost, operating cost, reliability, space requirements, noise, maintenance etc.</td>
<td>are <em>project-dependent</em></td>
</tr>
</tbody>
</table>

*Note: This information is subject to project-specific considerations.*
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CRYOCOOLERS
**Principle of Stirling cryocoolers**

**Steps in a Stirling cycle**

1. **I → II:** The gas is in the compression space. During *isothermal* compression, heat is removed at $T_h$.

2. **II → III:** Isochoric displaced ($V = \text{const.}$) of the gas through the regenerator, cooling the gas down to $T_c$.

3. **III → IV:** The gas is *isothermally* expanded in the expansion space, absorbing the heat $Q_c$ at $T_c$.

4. **IV → I:** Isochoric displacement back in the compression space, warming the gas up to $T_h$ while cooling the regenerator.
## Cryocooler types

<table>
<thead>
<tr>
<th>Stirling</th>
<th>Gifford-McMahon</th>
<th>Pulse tube</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Integral Stirling" /> <img src="image2" alt="Split Stirling" /></td>
<td><img src="image3" alt="Gifford-McMahon" /></td>
<td><img src="image4" alt="Pulse tube" /></td>
</tr>
<tr>
<td>Integral design</td>
<td>Split design</td>
<td>Continuously working compressor unit (air/water cooled)</td>
</tr>
<tr>
<td>Moving regenerator</td>
<td>Displacer piston</td>
<td>Compression and expansion by switching to high-pressure and low-pressure lines (amount of fluid contained changes)</td>
</tr>
<tr>
<td>Fixed regenerator</td>
<td></td>
<td>Replacement of the displacer piston by a gas piston (wear, reliability)</td>
</tr>
<tr>
<td>Integral Stirling</td>
<td></td>
<td>Control of the phase shift between mass flow and pressure waves by orifice or capillary combined with a buffer vessel</td>
</tr>
<tr>
<td>Build-in 90° phase shift</td>
<td></td>
<td>Thermodynamically equivalent to Stirling cycle</td>
</tr>
<tr>
<td>+ High efficiency, low weight</td>
<td>+ Continuous working</td>
<td>- Vibration, noise, lifetime</td>
</tr>
<tr>
<td>- Vibration, noise, lifetime</td>
<td>+ Low vibration and noise</td>
<td>- Less efficient</td>
</tr>
<tr>
<td>Split Stirling</td>
<td>Low pressure line</td>
<td></td>
</tr>
</tbody>
</table>
## Cryocooler types (examples)

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<thead>
<tr>
<th>Stirling</th>
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<th>Pulse tube</th>
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<tr>
<td><img src="source1" alt="Stirling" /></td>
<td><img src="source2" alt="Gifford-McMahon" /></td>
<td><img src="source3" alt="Pulse tube" /></td>
</tr>
<tr>
<td>0.5-4 W @ 77 K</td>
<td>200 W @ 77 K</td>
<td>90 W @ 77 K</td>
</tr>
<tr>
<td><img src="source4" alt="Stirling" /></td>
<td><img src="source5" alt="Gifford-McMahon" /></td>
<td><img src="source6" alt="Pulse tube" /></td>
</tr>
<tr>
<td>1000 W @ 77 K</td>
<td>140 W @ 77 K</td>
<td>6-8 W @ 77 K</td>
</tr>
<tr>
<td><img src="source7" alt="Stirling" /></td>
<td><img src="source8" alt="Gifford-McMahon" /></td>
<td><img src="source9" alt="Pulse tube" /></td>
</tr>
<tr>
<td>150 W @ 77 K</td>
<td>120 W @ 77 K</td>
<td></td>
</tr>
</tbody>
</table>
Thermodynamic modelling

- **Time domain**
  - Sinusoids
  - Math: Differential equations

- **Frequency domain**
  - Phasors ($\tau = 0$, complex space)
  - Math: Algebra, real and imaginary parts

**Acoustic power** of the pressure oscillator for the real gas EOS $p v = ZRT$

$$P = \frac{1}{2} Z R T m \dot{M}_a \frac{P_a}{P_m} \cos(\varphi M_p)$$
Illustration of cryocooler operation

- \( T, s \) – diagram (simplified)

- Consider \( P \) as the average *acoustic power* provided by the pressure oscillator, causing pressure oscillations \( p_m \pm p_a \)
  - Minimum temperature \( T_{\text{min,ideal}} \) of the ideal cryocooler cycle at zero load \( q_0 = 0 \)

- Additional entropy production due to gradients in \( \{T, p\} \) in a *real* cryocooler
  - Minimum temperature \( T_{\text{min}} \) of the real cryocooler at zero load \( q_0 = 0 \)

- Cooling power \( q_0 \) available at \( T_0 > T_{\text{min}} \)
  - Work available to compensate the entropy difference between absorbing / dissipating the heat \( q_0 \) between \( T_0 / T_h \)
  - The higher the temperature \( T_0 \), the larger the cooling capacity \( q_0 \)
  - *Strong dependence* \( q_0 = f(T_0) \)
Exemplary performance plots

- Single-stage cryocoolers
  
  ![Single-stage cryocoolers graph](image)

- Two-stage cryocoolers
  
  ![Two-stage cryocoolers graph](image)
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CRYOPLANTS (REFRIGERATORS)
Linde-Hampson cycle

**Layout**

- **Simplest configuration**
- Positive Joule-Thomson coefficient $\mu_T = (\partial T / \partial p)_h$
- required

**Process in $T, h$-diagram**

- Very low cooling capacity $q_0 = h_7 - h_5$
- Very low efficiency $\eta = q_0 / l_t$
- Warm process part at $T > T_a$ not shown
Linde-Hampson cycle

- **Layout**
  - Multi-stage compression to e.g. $p_H = 200$ bar
  - Different number of stages depending on compressor technology (flow rates)

- **Process in $T, h$-diagram**
  - Higher specific cooling capacity $q_0 = h_7 - h_5$
  - Still low efficiency $\eta = q_0 / l_t$
  - Warm process part at $T > T_a$ not shown

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Institute of Technical Thermodynamics and Refrigeration
Institute of Technical Physics
Brayton cycle

Layout

Expansion of *single-phase* working fluid in super-heated region (e.g. Ne)

Recovery of expansion work

Process in \( T, h \)-diagram

Expansion of *single-phase* working fluid in super-heated region (e.g. Ne)

Recovery of expansion work
Brayton cycle

■ Layout

■ Process in $T, s$-diagram

- Expansion of *single-phase* working fluid in super-heated region (e.g. Ne)
- Recovery of expansion work

Efficient due to turbo-expander, but cost factor of cold turbo-machinery
- Costly and rare working fluid (0.0018 Vol% in air)
Turbo-Brayton refrigerator

- Commercial system available (Air Liquide)

- Applications
  - Gas (re)liquefaction (HCs, air gases)
  - Cryogenic gas purification/separation
  - Smallest unit suitable for HTS power applications

Source: [http://www.airliquideadvancedtechnologies.com/](http://www.airliquideadvancedtechnologies.com/)
Claude cycle

**Layout**

- Single-phase expansion of *partial flow* in super-heated region
- Pre-cooling of remaining flow

**Temperature profiles in CFHX I–III**

- Efficient due to turbo-expander, but cost factor of cold turbo-machinery
- Pinch-points to be considered
Claude cycle

Layout

- Single-phase expansion of partial flow in superheated region
- Pre-cooling of remaining flow

Sources of energy demand

- Example process with $N_2$, $T_a = 300$ K, $p_1 = 1$ bar, $p_7 = 40$ bar, $\Delta p_{ij} = 0.5$ bar, $\eta_{Comp} = 0.7$, $\eta_{Exp} = 0.8$, $\Delta T_{min} = 3$ K in all heat exchangers
- Most efficient operating point at a cold flow $M = 0.3$ und $T_{16} = 170$ K (expander flow 1–$M$)
Variants of the Claude cycle

- **Claude cycle**

- **Kapitza cycle**

- **Collins cycle**
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DEVELOPMENT POTENTIALS
We can conclude that either technology has limitations in the HTS power application range.
Makeshift solution at 4 K

Excessive cryocooler use on a superconducting magnet and RF cryostat

- 25 GM cryocooler on one cryostat
  - Cooling power: \( \dot{Q}_0 = 37.5 \text{ W @ } 4.2 \text{ K} \rightarrow (25 \times 1.5 \text{ W @ } 4.2 \text{ K}) \)
  - Power consumption: \( P = 180 \text{ kW} \times (25 \times 7.2 \text{ kW}) \)
  - Specific power consumption: \( P^* = 4800 \text{ W/W}_{\text{Cooling power}} \)
  - Other issues: Space, vibrations, noise, reliability, maintenance, …

- Comparison to recuperative cycle (Collins process)
  - Specific power consumption: \( P^* = 250 \ldots 400 \text{ W/W}_{\text{Cooling power}} \)
Back to the Linde-Hampson cycle

**Reason** for poor efficiency

- Different capacity flows \( \dot{C} = \dot{M} \cdot c_p(T, p) \) yield increasing \( \Delta T \)
- Large entropy production \( \Delta s_{irr} = \int \frac{T_h - T_c}{T_h \cdot T_c} \, dq \)

**Technical options**

- **Aim:** \( \dot{M}_{HP} \cdot c_{p,HP} = \dot{M}_{LP} \cdot c_{p,LP} \) in order to keep \( \Delta T_{min} \) along the CFHX

  I) **Adaptation of flow rates** \( \dot{M} \)
  - The Claude cycle includes this solution in CFHX II

  II) **Manipulation of spec. heat capacities** by using *wide-boiling refrigerant mixtures*
  - Mixed refrigerant cycle (MRC)
Phase behavior of zoetrope mixtures

Phase diagram (example)

- Different concentrations of saturated liquid and vapor phases

Closed condensation 1 → 4

1. Single-phase super-heated vapor
2. Saturated vapor 2″; first liquid drop 2′
   - High-boiler CH₄ has lower vapor pressure and condenses first
3. Saturated liquid 3′; last vapor bubble 3″
4. Single-phase sub-cooled liquid

Basics (ideal mixtures)

- Dalton’s law \( p_i = y_i \cdot p \)
- Raul’s law \( p_i'' = x_i \cdot p_{\text{sat},i} \)
- Equilibrium \( p_i = p_i'' \)

Equivalent for heating/boiling from 4 → 1
- Low-boiler N₂ has higher vapor pressure and evaporates first
Effects of using refrigerant mixtures

- Partial condensation and evaporation (HP and LP sides), respectively, of mixture components along the CFHX
  - High-boiling components condense/evaporate at the warm end
  - Low-boiling components condense/evaporate at the cold end

- Reduced entropy production $\Delta s_{\text{irr}}$ during heat transfer
  - Manipulation of capacity flows $\dot{C} = \dot{M} \cdot c_p(T, p)$ through the specific heat capacities of the condensing/evaporating components $i$ (phase change implies $c_{p,i} \to \infty$)
  - Minimization of temperature gradients in the CFHX

- Reduced entropy production $\Delta s_{\text{irr}}$ during throttling
  - Higher Joule-Thomson coefficients $\mu_{JT} = \left( \frac{\partial T}{\partial p} \right)_h$ at lower temperature
  - Lower $\Delta p$ required for the same $\Delta T$
Throttling in the Linde-Hampson cycle

Example process
- Higher specific cooling capacity at higher pressure
- Necessity of c. 200 bar in case of $\text{N}_2$

Joule-Thomson coefficient of $\text{N}_2$
- $\mu_{JT} \uparrow$ bei $T \downarrow$
  - Better pre-cooling ($T_{12}$) with mixtures
- $\mu_{JT} \uparrow$ bei $p \downarrow$
  - Lower pressure needed as well

![Diagram showing enthalpy versus temperature for nitrogen and Joule-Thomson coefficient](image_url)
Low-temperature limits of MRCs

- **State-of-the-art**
  - MRCs are *widely used* in natural gas liquefaction since the 1970s
    - C3MR process (C3 pre-cooling)
    - DMR process (double MR process)
    - MFC process (mixed fluid cascade)
  - Typical use of hydrocarbon mixtures ($C_1$...$C_5$) at $T > 100$ K
    - $T_{nb,CH4} = 112$ K
  - Low-temperature limits
    - Achievable temperature influenced by lowest boiling component
    - Some reduction of boiling temperatures $T_b(p)$ by addition of intent gases (N$_2$, ...)
      - $\sum_{i} y_i \cdot p = x_i \cdot p_{sat,i}$, i.e. $T_b = f\left(p_i\right)$
    - Low-temperature limit determined by *freezing* of high-boilers and oil

- **Theoretical limit for HTS application**
  - Classical limit of vapor compression cycles given by the *triple point* of N$_2$
    - $T_{tr,N2} = 63$ K
  - N$_2$/O$_2$ binary mixtures, however, have freezing points as low as $\sim 50$ K
    - Eutectic point at 50.1 K and 77 mole-% O$_2$

![Temperature vs. Mole fraction N$_2$](image)


- Data for ternary Ne/N$_2$/O$_2$ mixtures not yet available ( várias studies at KIT)
Prevention of freeze-out

**Kleemenko cycle**

- Similarity with the Claude cycle, but *phase separator* and *expansion valve* instead of the expander
- Separation of high-boilers (e.g. C$_5$, C$_4$) as well as oil at ~250…270 K
  - Concentration-dependent freezing point
  - No complete separation

**Principle**

- Various process configurations
  - Several phase separators, especially for low-temperature operation
  - Complexity, …
Cryogenic mixed refrigerant cascade (CMRC)

- **Layout**
  - Separate pre-cooling and second stage
  - No high-boilers and no risk of freeze-out in the second stage

- **Example temperature profiles**
Approaches for cooling system improvements

- Linde-Hampson process

- Claude process

Options for efficiency increase

Higher efficiency by using refrigerant mixtures (MRC)
- "Molecular Engineering"
- Negligible cost

Higher efficiency by increased system complexity
- Cold expander
- Number of HX ↑
- Control ↑
- Investment cost ↑

Use of standard refrigeration technology
Potential HTS mixture applications

- Use of wide-boiling refrigerant mixtures in closed cycle cooling units
  - Longer power cable lengths by re-cooling units at the far cable end

Potential use of O\textsubscript{2}/N\textsubscript{2} mixtures as cooling liquid in HTS power cables

Open issues: Material compatibility, safety, …
Cooling technology for HTS power applications

CONCLUSIONS
Conclusions

I\textsuperscript{st} + II\textsuperscript{nd} Law of Thermodynamics

HTS application requirements