Introduction to Cryogenics

Philippe Lebrun
President of the IIR General Conference

International Institute of Refrigeration
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Contents

• Introduction
• Cryogenic fluids
• Heat transfer & thermal insulation
• Thermal screening with cold vapour
• Refrigeration & liquefaction
• Cryogen storage
• Thermometry
• κρύος, ούς (τὸ) | 1 deep cold [Arist. Meteor.]
2 shiver of fear [Aeschyl. Eumenid.]

• **cryogenics**, that branch of physics which deals with the production of very low temperatures and their effects on matter

  *Oxford English Dictionary*

• **cryogenics**, the science and technology of temperatures below 120 K

  *New International Dictionary of Refrigeration*
### Characteristic temperatures of cryogens

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>Triple point [K]</th>
<th>Normal boiling point [K]</th>
<th>Critical point [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>90.7</td>
<td>111.6</td>
<td>190.5</td>
</tr>
<tr>
<td>Oxygen</td>
<td>54.4</td>
<td>90.2</td>
<td>154.6</td>
</tr>
<tr>
<td>Argon</td>
<td>83.8</td>
<td>87.3</td>
<td>150.9</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>63.1</td>
<td>77.3</td>
<td>126.2</td>
</tr>
<tr>
<td>Neon</td>
<td>24.6</td>
<td>27.1</td>
<td>44.4</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>13.8</td>
<td>20.4</td>
<td>33.2</td>
</tr>
<tr>
<td>Helium</td>
<td>2.2 (*)</td>
<td>4.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

(*): λ Point
Cryogenic transport of natural gas: LNG

130 000 m³ LNG carrier with double hull

Invar® tanks hold LNG at ~110 K
Air separation by cryogenic distillation

Capacity up to 4500 t/day LOX
LIN as byproduct

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JUAS 2017 Intro to Cryogenics
Densification, liquefaction & separation of gases
Rocket fuels

Ariane 5
25 t LHY, 130 t LOX

Space Shuttle
100 t LHY, 600 t LOX
What is a low temperature?

- The entropy of a thermodynamical system in a macrostate corresponding to a multiplicity $W$ of microstates is
  $$S = k_B \ln W$$
- Adding reversibly heat $dQ$ to the system results in a change of its entropy $dS$ with a proportionality factor $T$
  $$T = \frac{dQ}{dS}$$

⇒ high temperature: heating produces small entropy change
⇒ low temperature: heating produces large entropy change

L. Boltzmann’s grave in the Zentralfriedhof, Vienna, bearing the entropy formula
Temperature and energy

• The average thermal energy of a particle in a system in thermodynamic equilibrium at temperature $T$ is

$$E \sim k_B T$$

$k_B = 1.3806 \times 10^{-23}$ J.K$^{-1}$

• 1 K is equivalent to $\sim 10^{-4}$ eV or $\sim 10^{-23}$ J thermal energy
  - a temperature is « low » for a given physical process when the corresponding average thermal energy $k_B T$ is small compared with the characteristic energy $E$ of the process considered
  - cryogenic temperatures reveal phenomena with low characteristic energy and enable their study and their application
## Characteristic temperatures of low-energy phenomena

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debye temperature of metals</td>
<td>few 100 K</td>
</tr>
<tr>
<td>High-temperature superconductivity</td>
<td>~ 100 K</td>
</tr>
<tr>
<td>Low-temperature superconductivity</td>
<td>~ 10 K</td>
</tr>
<tr>
<td>Intrinsic transport properties of metals</td>
<td>&lt; 10 K</td>
</tr>
<tr>
<td>Cryopumping</td>
<td>few K</td>
</tr>
<tr>
<td>Cosmic microwave background</td>
<td>2.7 K</td>
</tr>
<tr>
<td>Superfluid helium 4</td>
<td>2.2 K</td>
</tr>
<tr>
<td>Bolometers for cosmic radiation</td>
<td>&lt; 1 K</td>
</tr>
<tr>
<td>Low-density atomic Bose-Einstein condensates</td>
<td>~ μK</td>
</tr>
</tbody>
</table>
Useful range of liquid cryogens & critical temperature of superconductors

- Helium
- Hydrogen
- Neon
- Nitrogen
- Argon
- Oxygen

T [K]

Below Patm
Above Patm

Nb-Ti
Mg B\textsubscript{2}
YBCO Bi-2223

Nb\textsubscript{3}Sn

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Introduction to Cryogenics
Cooling of superconducting devices

LHe 1.9 K

SCHe 4.5 K

LIN ~70 K

LHe 4.2 K
Contents

• Introduction
• Cryogenic fluids
  • Heat transfer & thermal insulation
  • Thermal screening with cold vapour
  • Refrigeration & liquefaction
  • Cryogen storage
  • Thermometry
## Properties of cryogens compared to water

<table>
<thead>
<tr>
<th>Property</th>
<th>He</th>
<th>N₂</th>
<th>H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal boiling point</td>
<td>[K]</td>
<td>4.2</td>
<td>77</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>[K]</td>
<td>5.2</td>
<td>126</td>
</tr>
<tr>
<td>Critical pressure</td>
<td>[bar]</td>
<td>2.3</td>
<td>34</td>
</tr>
<tr>
<td>Liq./Vap. density (*)</td>
<td></td>
<td>7.4</td>
<td>175</td>
</tr>
<tr>
<td>Heat of vaporization (*)</td>
<td>[J.g⁻¹]</td>
<td>20.4</td>
<td>199</td>
</tr>
<tr>
<td>Liquid viscosity (*)</td>
<td>[µPl]</td>
<td>3.3</td>
<td>152</td>
</tr>
</tbody>
</table>

(*) at normal boiling point
Vaporization of normal boiling cryogens under 1 W applied heat load

Let \( h \) be the enthalpy of the fluid

At constant pressure

\[
\dot{Q} = L_v \dot{m} \quad \text{with} \quad L_v = h_{\text{vap}} - h_{\text{liq}}
\]

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>[mg.s(^{-1})]</th>
<th>[l.h(^{-1})] (liquid)</th>
<th>[l.min(^{-1})] (gas NTP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>48</td>
<td>1.38</td>
<td>16.4</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>5</td>
<td>0.02</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Amount of cryogens required to cool down 1 kg iron

Assuming perfect heat exchange between iron and the fluid

\[
\int_{T_{final}}^{T_{initial}} M_{Fe} C_{Fe} dT = m \left[ L_v + (h_{vap}^{final} - h_{vap}^{sat}) \right] \approx m \left[ L_v + C_p (T_{final} - T_{sat}) \right]
\]

<table>
<thead>
<tr>
<th>Using</th>
<th>Latent heat only</th>
<th>Latent heat and enthalpy of gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHe from 290 to 4.2 K</td>
<td>29.5 litre</td>
<td>0.75 litre</td>
</tr>
<tr>
<td>LHe from 77 to 4.2 K</td>
<td>1.46 litre</td>
<td>0.12 litre</td>
</tr>
<tr>
<td>LN2 from 290 to 77 K</td>
<td>0.45 litre</td>
<td>0.29 litre</td>
</tr>
</tbody>
</table>
Phase diagram of helium

Temperature [K]
Pressure [kPa]

SOLID
VAPOUR
He I
He II
CRITICAL POINT
PRESSURIZED He II (Subcooled liquid)
SATURATED He II
SUPER-CRITICAL
SATURATED He I

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Introduction to Cryogenics
### Helium as a cooling fluid

<table>
<thead>
<tr>
<th>Phase domain</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
</table>
| Saturated He I | Fixed temperature  
High heat transfer | Two-phase flow  
Boiling crisis |
| Supercritical | Monophase  
Negative J-T effect | Non-isothermal  
Density wave instability |
| He II | Low temperature  
High conductivity  
Low viscosity | Second-law cost  
Subatmospheric |
Contents

• Introduction
• Cryogenic fluids
• Heat transfer & thermal insulation
• Thermal screening with cold vapour
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• Cryogen storage
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Typical heat transfer coefficients at cryogenic temperatures

- Same basic processes as at temperatures above ambient, but large variations in
  - absolute values
  - dependence on temperature

- These variations can be exploited for
  - cooling equipment
  - thermal insulation of cryostats

- Particular importance of two-phase heat transfer
Non-linear heat transfer to liquid cryogens
Pool boiling nitrogen

\[ \sim 1.5 \times 10^5 \text{ W/m}^2 \]

Heat flux, W/m\(^2\)

Wall superheat, K

Nucleate boiling
Transition boiling
Minimum heat flux
Film boiling

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Non-linear heat transfer to liquid cryogens
Pool boiling helium

- Experimental critical heat flux
- Predicted critical heat flux

10^4 W/m^2

(The points of minimum film boiling are given by either the correlation of Lienhard & Wong or of Zuber, et al.)
Heat conduction in solids

- Fourier’s law
  \[ \dot{Q}_{\text{cond}} = k(T)A \frac{dT}{dx} \]

- Thermal conductivity
  \[ k(T) \ [W/m.K] \]

- Integral form
  \[ \dot{Q}_{\text{cond}} = \frac{A}{L} \int_{T_1}^{T_2} k(T) dT \]

- Thermal conductivity integral
  \[ \int_{T_1}^{T_2} k(T) dT \ [W/m] \]

- Thermal conductivity integrals for standard construction materials are tabulated
Thermal conductivity integrals of selected materials [W/m]

<table>
<thead>
<tr>
<th>From vanishingly low temperature up to</th>
<th>20 K</th>
<th>80 K</th>
<th>290 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFHC copper</td>
<td>11000</td>
<td>60600</td>
<td>152000</td>
</tr>
<tr>
<td>DHP copper</td>
<td>395</td>
<td>5890</td>
<td>46100</td>
</tr>
<tr>
<td>1100 aluminium</td>
<td>2740</td>
<td>23300</td>
<td>72100</td>
</tr>
<tr>
<td>2024 aluminium alloy</td>
<td>160</td>
<td>2420</td>
<td>22900</td>
</tr>
<tr>
<td>AISI 304 stainless steel</td>
<td>16.3</td>
<td>349</td>
<td>3060</td>
</tr>
<tr>
<td>G-10 glass-epoxy composite</td>
<td>2</td>
<td>18</td>
<td>153</td>
</tr>
</tbody>
</table>
Non-metallic composite support post with heat intercepts

5 K cooling line (SC He)

Aluminium intercept plates glued to G-10 column

Aluminium strips to thermal shield at 50-75 K
Thermal radiation

- **Wien’s law**
  - Maximum of black-body power spectrum
  \[ \lambda_{\text{max}} T = 2898 \, [\mu\text{m.K}] \]

- **Stefan-Boltzmann’s law**
  - Black body
    \[ \dot{Q}_{\text{rad}} = \sigma A T^4 \]
    with \( \sigma = 5.67 \times 10^{-12} \, \text{W/m}^2\text{K}^4 \)
  - «Gray» body
    \[ \dot{Q}_{\text{rad}} = \varepsilon \sigma A T^4 \]
    with \( \varepsilon \) surface emissivity
  - Between «gray» surfaces at temperatures \( T_1 \) and \( T_2 \)
    \[ \dot{Q}_{\text{rad}} = E \sigma A (T_2^4 - T_1^4) \]
    with \( E \) function of \( \varepsilon_1, \varepsilon_2 \) and geometry of facing surfaces
# Emissivity of technical materials at low temperatures

<table>
<thead>
<tr>
<th>Material</th>
<th>Radiation from 290 K Surface at 77 K</th>
<th>Radiation from 77 K Surface at 4.2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel, as found</td>
<td>0.34</td>
<td>0.12</td>
</tr>
<tr>
<td>Stainless steel, mech. polished</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>Stainless steel, electropolished</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>Stainless steel + Al foil</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Aluminium, as found</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>Aluminium, mech. polished</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>Aluminium, electropolished</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Copper, as found</td>
<td>0.12</td>
<td>0.06</td>
</tr>
<tr>
<td>Copper, mech. Polished</td>
<td>0.06</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Residual gas conduction

- Two different regimes, depending upon the relative values of heat transfer distance $d$ and mean free path of gas molecules $\lambda_{molecule}$

- Viscous regime
  - At higher pressure $\lambda_{molecule} \ll d$
  - Classical conduction $\dot{Q}_{residual} = A k(T) \frac{dT}{dx}$
  - Thermal conductivity $k(T)$ independant of pressure

- Molecular regime
  - At lower pressure $\lambda_{molecule} \gg d$
  - Kennard’s law $\dot{Q}_{residual} = A \alpha(T) \Omega P (T_2 - T_1)$
  - Heat transfer proportional to pressure, independant of spacing between surfaces
  - $\Omega$ depends on gas species
  - Accommodation coefficient $\alpha(T)$ depends on gas species, $T_1, T_2$ and geometry of facing surfaces
Multi-layer insulation (MLI)

- Complex system involving three heat transfer processes
  - \( \dot{Q}_{\text{MLI}} = \dot{Q}_{\text{rad}} + \dot{Q}_{\text{contact}} + \dot{Q}_{\text{residual}} \)
  - With \( n \) reflective layers of equal emissivity, \( \dot{Q}_{\text{rad}} \sim 1/(n + 1) \)
  - Due to parasitic contacts between layers, \( \dot{Q}_{\text{contact}} \) increases with layer density
  - \( \dot{Q}_{\text{residual}} \) due to residual gas trapped between layers, scales as \( 1/n \) in molecular regime
  - Non-linear behaviour requires layer-to-layer modeling

- In practice
  - Typical data available from (abundant) literature
  - Measure performance on test samples
## Typical heat fluxes at vanishingly low temperature between flat plates [W/m²]

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black-body radiation from 290 K</td>
<td>401</td>
</tr>
<tr>
<td>Black-body radiation from 80 K</td>
<td>2.3</td>
</tr>
<tr>
<td>Gas conduction (100 mPa He) from 290 K</td>
<td>19</td>
</tr>
<tr>
<td>Gas conduction (1 mPa He) from 290 K</td>
<td>0.19</td>
</tr>
<tr>
<td>Gas conduction (100 mPa He) from 80 K</td>
<td>6.8</td>
</tr>
<tr>
<td>Gas conduction (1 mPa He) from 80 K</td>
<td>0.07</td>
</tr>
<tr>
<td>MLI (30 layers) from 290 K, pressure below 1 mPa</td>
<td>1-1.5</td>
</tr>
<tr>
<td>MLI (10 layers) from 80 K, pressure below 1 mPa</td>
<td>0.05</td>
</tr>
<tr>
<td>MLI (10 layers) from 80 K, pressure 100 mPa</td>
<td>1-2</td>
</tr>
</tbody>
</table>
Cross-section of LHC dipole cryostat
LHC cryostat heat inleaks at 1.9 K

\[ \dot{Q} = \dot{m} \Delta h(P, T) \]

Measured

He property tables

\begin{align*}
\text{On full LHC cold sector (2.8 km)}
- & \text{Measured 560 W, i.e. 0.2 W/m} \\
- & \text{Calculated 590 W, i.e 0.21 W/m}
\end{align*}
Contents

• Introduction
• Cryogenic fluids
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• Cryogen storage
• Thermometry
Vapour cooling of cryostat necks and supports with perfect heat transfer

• Assuming perfect heat transfer between solid and vapour, i.e. \( T_{\text{solid}}(x) = T_{\text{vapor}}(x) = T(x) \)

\[
\dot{Q}_{\text{cond}} = \dot{Q}_{\text{bath}} + \dot{m} C_p(T)(T - T_{\text{bath}})
\]

\[
A k(T) \frac{dT}{dx} = \dot{Q}_{\text{bath}} + \dot{m} C_p(T)(T - T_{\text{bath}})
\]

• \( C_p(T) \) specific heat of vapour

• \( k(T) \) thermal conductivity of support

• \( \dot{Q}_{\text{bath}} \) can be calculated by numerical integration for
  - different cryogens
  - different values of aspect ratio \( L/A \)
  - different values of vapour flow

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Introduction to Cryogenics
He vapour screening of stainless steel neck between 300 K and 4 K
Vapour cooling of cryostat necks and supports in self-sustained mode

- A particular case of gas cooling is the self-sustained mode, i.e. the vapour flow is generated only by the residual heat $\dot{Q}_{bath}$ reaching the bath
- Then
  $$\dot{Q}_{bath} = L_v \dot{m}$$
  with $L_v$ latent heat of vaporization

- Given the general equation
  $$A k(T) \frac{dT}{dx} = \dot{Q}_{bath} + \dot{m} C_p(T)(T - T_{bath})$$
- The variables can be separated and integration yields
  $$\dot{Q}_{bath} = \frac{A}{L} \int_{T_{bath}}^{T} \frac{k(T)}{1 + \frac{C_p(T)}{L_v}(T - T_{bath})} dT$$

- The denominator of the integrand $1 + \frac{C_p(T)}{L_v}(T - T_{bath})$ acts as an attenuation factor of the thermal conductivity $k(T)$
Reduction of heat conduction by self-sustained helium vapour cooling

<table>
<thead>
<tr>
<th>Material</th>
<th>Effective thermal conductivity integral from 4 to 300 K</th>
<th>Purely conductive regime [W.cm(^{-1})]</th>
<th>Self-sustained vapour-cooling [W.cm(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETP copper</td>
<td></td>
<td>1620</td>
<td>128</td>
</tr>
<tr>
<td>OFHC copper</td>
<td></td>
<td>1520</td>
<td>110</td>
</tr>
<tr>
<td>Aluminium 1100</td>
<td></td>
<td>728</td>
<td>39.9</td>
</tr>
<tr>
<td>Nickel 99% pure</td>
<td></td>
<td>213</td>
<td>8.65</td>
</tr>
<tr>
<td>Constantan</td>
<td></td>
<td>51.6</td>
<td>1.94</td>
</tr>
<tr>
<td>AISI 300 stainless steel</td>
<td></td>
<td>30.6</td>
<td>0.92</td>
</tr>
</tbody>
</table>
Vapour cooling of cryostat necks and supports with imperfect heat transfer

- Introducing efficiency of heat transfer $f$ between solid and vapour ($0 \leq f \leq 1$)

\[ dQ = f \dot{m} C_p(T) \, dT \]

- The steady-state heat balance equation becomes

\[ \frac{d}{dx} \left[ A k(T) \frac{dT}{dx} \right] = f \dot{m} C_p(T) \frac{dT}{dx} \]

- This non-linear equation needs to be solved by numerical integration
Vapor-cooled current leads

- The (imperfect) heat transfer between solid and vapor can be written
  \[ dQ = f \dot{m} C_p(T) \, dT \]

- Introducing electrical resistivity \( \rho(T) \), the steady-state heat balance equation reads
  \[
  \frac{d}{dx} \left[ A \frac{k(T)}{dA} \frac{dT}{dx} \right] - f \dot{m} C_p(T) \frac{dT}{dx} + \frac{\rho(T) I^2}{A} = 0
  \]

- Assuming the material follows the Wiedemann-Franz-Lorenz (WFL) law
  \[ k(T) \rho(T) = \mathcal{L}_0 T \]
  with \( \mathcal{L}_0 = 2.45 \times 10^{-8} \text{ W} \cdot \Omega \cdot \text{K}^{-2} \)

The aspect ratio \( L/A \) can be chosen for minimum heat inleak \( \dot{Q}_{\text{bath}} \), and the minimum heat inleak does not depend on the material.
Uncooled 47 W/kA

Material obeying the WFL law

Minimum residual heat load 1.04 W/kA
Beating the WFL law: HTS current leads

- The WFL law essentially states that good electrical conductors are also good thermal conductors
- Efficient current leads need good electrical conductors with low thermal conductivity
- Superconductors are bad thermal conductors with zero resistivity

⇒ Build current lead with superconductor up to temperature as high as possible, i.e. use HTS
## HTS vs. normal conducting current leads

<table>
<thead>
<tr>
<th>Type</th>
<th>Resistive [W/kA]</th>
<th>HTS (4 to 50 K) Resistive (above) [W/kA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat into LHe</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total exergy consumption</td>
<td>430</td>
<td>150</td>
</tr>
<tr>
<td>Electrical power from grid</td>
<td>1430</td>
<td>500</td>
</tr>
</tbody>
</table>
Contents

- Introduction
- Cryogenic fluids
- Heat transfer & thermal insulation
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- Cryogen storage
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**Basic thermodynamics of refrigeration**

- First principle (Joule)
  \[ Q_0 = Q_i + W \]
- Second principle (Clausius)
  \[ \frac{Q_0}{T_0} \geq \frac{Q_i}{T_i} \]
  (= for reversible process)
- Hence
  \[ W \geq T_0 \frac{Q_i}{T_i} - Q_i \]

- This equation can be written in three different ways
  
  \[ \begin{align*}
  W &\geq T_0 \Delta S_i - Q_i \text{ introducing entropy } S \text{ defined by } \Delta S_i = \frac{Q_i}{T_i} \\
  W &\geq Q_i \left( \frac{T_0}{T_i} - 1 \right) \text{ where } \left( \frac{T_0}{T_i} - 1 \right) \text{ is called the Carnot factor} \\
  W &\geq \Delta E_i \text{ introducing exergy } E \text{ defined by } \Delta E_i = Q_i \left( \frac{T_0}{T_i} - 1 \right)
  \end{align*} \]
Minimum refrigeration work

- Consider the extraction of 1 W at liquid helium temperature 4.5 K, rejected at room temperature 300 K

- The minimum refrigeration work is

\[ W_{\text{min}} = Q_i \left( \frac{T_0}{T_i} - 1 \right) = 1 \left( \frac{300}{4.5} - 1 \right) \approx 65.7 \text{ W/W} \]

- In practice, the most efficient helium refrigerators have an efficiency \( \eta \) of about 30% with respect to the Carnot limit

\[ W_{\text{real}} = \frac{W_{\text{min}}}{\eta} = \frac{65.7}{0.3} \approx 220 \text{ W/W} \]
Refrigeration cycles

- Introducing the temperature-entropy diagram
  - Consider the thermodynamic transform from A to B, involving heat transfer $\Delta Q$
  - If it is reversible $\Delta Q = \int_A^B T \, dS$
  - $\Delta Q$ is proportional to the area under the curve in the temperature-entropy diagram

- To make a refrigeration cycle, one needs a substance, the entropy of which depends on some other physical variable than temperature, e.g.
  - Pressure of gas or vapor (compression/expansion)
  - Magnetization of solid (magnetic refrigeration)

- Refrigeration cycle ABCD
  - $\Delta Q_1$ heat absorbed at $T_1$
  - $\Delta Q_2$ heat rejected at $T_2$
T-S diagram for helium

Red: liquid-vapour dome
Blue: isobars
Black: isochores
Green: isenthalps

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Introduction to Cryogenics
A Carnot cycle is not feasible for helium liquefaction

- It would need a HP of 613 kbar!
- There exists no true isothermal compressor
- There exists no true isentropic compressor or expander

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Enthalpy (J/g.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>3.89</td>
</tr>
<tr>
<td>300</td>
<td>8.07</td>
</tr>
</tbody>
</table>

Ph. Lebrun

Introduction to Cryogenics
A real cycle needs internal heat exchange and para-isothermal compression. Practical compressors are adiabatic, need aftercooling and if multistage, intercooling.

Heat exchanger between HP and LP streams.
Refrigerator

Compressor

HP

LP

Cold Box

LOAD

T₁ = 4.5 K

T₀ = 300 K

4.5 K

S

Q₁

18.8 J.g⁻¹

4.2 J.g⁻¹.K⁻¹

Liquefier

Compressor

HP

LP

Cold Box

LOAD

T₁ = 4.5 K

T₀ = 300 K

LHe

R

isobar (1.3 bar)

18.8 J.g⁻¹

1543 J.g⁻¹

4.5 K

23.1 J.g⁻¹.K⁻¹

4.2 J.g⁻¹.K⁻¹

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Introduction to Cryogenics
Thermodynamic equivalence between refrigeration and liquefaction

- What is the equivalent to 1 g helium liquefaction in terms of isothermal refrigeration at liquid helium temperature $T_1 = 4.5 \, \text{K}$?

$$W_{liq} = m_{liq} (T_0 \Delta S - Q_1 - R)$$

with $T_0 = 300 \, \text{K}$

$\Delta S = 27.3 \, \text{J/g.K}$

$Q_1 = 18.8 \, \text{J/g}$

$R = 1543 \, \text{J/g}$

hence $W_{liq} = 6628 \, \text{J}$

- Write that the same work is used to produce isothermal refrigeration at 4.5 K

$$W_{ref} = Q_1 \left(\frac{T_0}{T_1} - 1\right) = 6628 \, \text{J}$$

hence $Q_1 \cong 100 \, \text{J}$

- For refrigerators and liquefiers of the same efficiency

$1 \, \text{g/s liquefaction} \approx 100 \, \text{W refrigeration at 4.5 K}$
Measured refrigeration/liquefaction equivalence
12 kW @ 4.5 K helium refrigerators for LEP 2

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Introduction to Cryogenics
Elementary cooling processes on T-S diagram

- **P1**
- **P2 (< P1)**
- **T**
- **S**

**A**

- **B1**
- **B2**
- **B3**
- **B'2**

**isobar** (heat exchanger)

**adiabatic** (expansion engine)

**isentropic**

**isenthalpic** (Joule-Thomson valve)
Brazed aluminium plate heat exchanger
Elementary cooling processes on T-S diagram

- **isobar** (heat exchanger)
- **adiabatic** (expansion engine)
- **isentropic**
- **isenthalpic** (Joule-Thomson valve)
Cryogenic turbo-expander

Cryogenic turboexpander
Self-acting gas bearing system
Elementary cooling processes on T-S diagram

- **isobar** (heat exchanger)
- **adiabatic** (expansion engine)
- **isentropic**
- **isenthalpic** (Joule-Thomson valve)

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Introduction to Cryogenics
Joule-Thomson inversion temperatures

Isenthalps in T-S diagram can have positive or negative slope, i.e. isenthalpic expansion can produce warming or cooling
⇒ **inversion temperature**

<table>
<thead>
<tr>
<th>Cryogen</th>
<th>Maximum inversion temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium</td>
<td>43</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>202</td>
</tr>
<tr>
<td>Neon</td>
<td>260</td>
</tr>
<tr>
<td>Air</td>
<td>603</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>623</td>
</tr>
<tr>
<td>Oxygen</td>
<td>761</td>
</tr>
</tbody>
</table>

While air can be cooled down and liquefied by JT expansion from room temperature, helium and hydrogen need precooling down to below inversion temperature by heat exchange or work-extracting expansion (e.g. in turbines)
Two-stage Claude cycle

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Introduction to Cryogenics
Claude-cycle helium refrigerators/liquefiers

*Air Liquide & Linde*

<table>
<thead>
<tr>
<th></th>
<th>HELIAL SL</th>
<th>HELIAL ML</th>
<th>HELIAL LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Liquefaction capacity without LN2</td>
<td>25 L/h</td>
<td>70 L/h</td>
<td>145 L/h</td>
</tr>
<tr>
<td>Max. Liquefaction capacity with LN2</td>
<td>50 L/h</td>
<td>150 L/h</td>
<td>330 L/h</td>
</tr>
<tr>
<td>Compressor electrical motor</td>
<td>55 kW</td>
<td>132 kW</td>
<td>250 kW</td>
</tr>
<tr>
<td>Specific consumption for liquefaction w/o LN2</td>
<td>645 W/W</td>
<td>552 W/W</td>
<td>505 W/W</td>
</tr>
</tbody>
</table>

% Carnot

<table>
<thead>
<tr>
<th></th>
<th>10%</th>
<th>12%</th>
<th>13%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without LN, precooling</td>
<td>20 – 35 l/h</td>
<td>40 – 70 l/h</td>
<td></td>
</tr>
<tr>
<td>L70</td>
<td>45 – 70 l/h</td>
<td>90 – 140 l/h</td>
<td></td>
</tr>
<tr>
<td>L140</td>
<td>100 – 145 l/h</td>
<td>200 – 290 l/h</td>
<td></td>
</tr>
<tr>
<td>LR70</td>
<td>100 – 145 Watt</td>
<td>130 – 190 Watt</td>
<td></td>
</tr>
<tr>
<td>LR140</td>
<td>210 – 290 Watt</td>
<td>255 – 400 Watt</td>
<td></td>
</tr>
<tr>
<td>LR280</td>
<td>445 – 640 Watt</td>
<td>560 – 900 Watt</td>
<td></td>
</tr>
</tbody>
</table>
Process cycle & T-S diagram of LHC 18 kW @ 4.5 K cryoplant

20 K - 280 K loads (LHC current leads)
50 K - 75 K loads (LHC shields)
4.5 K - 20 K loads (magnets + leads + cavities)

Adsorber
Precooler
LN2

201 K
75 K
49 K
32 K
20 K
13 K
10 K
9 K
4.4 K

0.3 MPa
0.4 MPa
1.9 MPa
0.1 MPa

From LHC loads
To LHC loads

Introduction to Cryogenics
LHC 18 kW @ 4.5 K helium cryoplants

- 33 kW @ 50 K to 75 K
- 23 kW @ 4.6 K to 20 K
- 41 g/s liquefaction
- 4 MW compressor power
- C.O.P. 220-230 W/W @ 4.5 K

Air Liquide

Linde

Ph. Lebrun

Introduction to Cryogenics
ITER 25 kW @ 4.5 K helium refrigerator
Oil-injected screw compressor
Compressor station of LHC 18 kW@ 4.5 K helium refrigerator
Carnot, Stirling and Ericsson cycles

All «sloping» cycles need internal heat exchange

For small machines, this is done by regenerative, rather than recuperative heat exchangers

⇒ alternating rather than continuous operation

Carnot cycle (1,2,3,4), Stirling cycle (1,2,3',4') and Ericsson cycle (1,2,3'',4'')
Operation of a Gifford-McMahon cryocooler (Ericsson cycle)
Two-stage Gifford-McMahon cryocooler

CRYOMECH PT407 & CP970 compressor
~ 0.7 W @ 4.2 K & 25 W @ 55 K
Stirling and pulse-tube cryocoolers

Stirling refrigerator

Pulse tube refrigerator
Mini pulse-tube cryocoolers

ESA MPTC development model – 1W @ 77K

CEA/SBT coaxial PTC– 6W @ 80K
Contents

• Introduction
• Cryogenic fluids
• Heat transfer & thermal insulation
• Thermal screening with cold vapour
• Refrigeration & liquefaction
• Cryogen storage
• Thermometry
Bulk helium storage solutions

11000 gallon liquid container

2 MPa gas tanks

20 MPa gas cylinders
**Specific cost of bulk He storage**

<table>
<thead>
<tr>
<th>Type</th>
<th>Pressure [MPa]</th>
<th>Density [kg/m³]</th>
<th>Dead volume [%]</th>
<th>Cost [CHF/kg He]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Bag</td>
<td>0.1</td>
<td>0.16</td>
<td>0</td>
<td>300(1)</td>
</tr>
<tr>
<td>MP Vessel</td>
<td>2</td>
<td>3.18</td>
<td>5-25</td>
<td>220-450</td>
</tr>
<tr>
<td>HP Vessel</td>
<td>20</td>
<td>29.4</td>
<td>0.5</td>
<td>500(2)</td>
</tr>
<tr>
<td>Liquid</td>
<td>0.1</td>
<td>125</td>
<td>13</td>
<td>100-200(3)</td>
</tr>
</tbody>
</table>

(1): Purity non preserved  
(2): Not including HP compressors  
(3): Not including reliquefier
Contents

- Introduction
- Cryogenic fluids
- Heat transfer & thermal insulation
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- Cryogen storage

- Thermometry
Definition of ITS90 in cryogenic range

Primary thermometers

- Pt resistance thermometer
- He 4 gas thermometer
- He 3 gas thermometer
- He vapour pressure

Temperature [K]

Triple points

H₂ Ne O₂ Ar Hg H₂O
### Primary fixed points of ITS90 in cryogenic range

<table>
<thead>
<tr>
<th>Fixed point</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$ triple point</td>
<td>13.8033</td>
</tr>
<tr>
<td>Ne triple point</td>
<td>24.5561</td>
</tr>
<tr>
<td>O$_2$ triple point</td>
<td>54.3584</td>
</tr>
<tr>
<td>Ar triple point</td>
<td>83.8058</td>
</tr>
<tr>
<td>Hg triple point</td>
<td>234.3156</td>
</tr>
<tr>
<td>H$_2$O triple point</td>
<td>273.16 (*)</td>
</tr>
</tbody>
</table>

(*): exact by definition
From temperature sensor to practical thermometer

Ge
RhFe wire
RhFe thin film
Cernox
Carbon A-B
Carbon TVO
CBT

1cm

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Introduction to Cryogenics
Practical temperature range covered by cryogenic thermometers

- Chromel-constantan thermocouple
- Au-Fe thermocouple
- Pt resistance
- Rh-Fe resistance
- CLTS
- Allen-Bradley carbon resistance
- Cernox
- Ge resistance

Temperature [K]

Ph. Lebrun

Introduction to Cryogenics
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