Introduction to Cryogenic Engineering

5. - 9.12.2005

G. Perinić, G. Vandoni, T. Niinikoski, CERN
Introduction to Cryogenic Engineering

MONDAY  From History to Modern Refrigeration Cycles  (G. Perinić)

TUESDAY  Standard Components, Cryogenic Design  (G. Perinić)

WEDNESDAY  Heat Transfer and Insulation  (G. Vandoni)

THURSDAY  Safety, Information Resources  (G. Perinić)

FRIDAY  Applications of Cryogenic Engineering  (T. Niinikoski)
Day 1
What is cryogenics?
History
Time of I. Newton

• F. Bacon (1561 - 1621)

Novum organum (1620)

The third of the seven modes […] relates to […] heat and cold. And herein man's power is clearly lame on one side. For we have the heat of fire which is infinitely more potent and intense than the heat of the sun as it reaches us, or the warmth of animals.

But we have no cold save such as is to be got in wintertime, or in caverns, or by application of snow and ice, […]

And so too all natural condensations caused by cold should be investigated, in order that, their causes being known, they may be imitated by art.
Time of I. Newton

- Known refrigeration methods
  - refrigeration by a colder object
e.g. ice or snow
  - refrigeration by evaporation
  - refrigeration by dissolving saltpeter in water
    (saltpeter = sodium nitrate NaNO₃ or potassium nitrate KNO₃)
Time of I. Newton

- R. Boyle (1627 - 1691); E. Mariotte (1620 - 1684)

\[ p \, V = \text{constant} \]
Time of I. Newton

- G. Amontons (1663 - 1705)

Diagram showing the relationship between absolute zero, freezing temperature, and boiling temperature.
Further development of thermodynamics

• J. Black (1728 - 1799) latent heat
• A. Lavoisier (1743 - 1794) caloric theory
• S. Carnot (1824) work
• R. Clausius (1865) entropy
• W. Gibbs (1867); R. Mollier (1923) enthalpy
Incentives for refrigeration and cryogenics

• Early 19th century
  – large scale refrigeration only by natural ice
  – increasing demand for artificial refrigeration by
    • the butchers,
    • the brewers and later on
    • the industrialists
Incentives for refrigeration and cryogenics

- Examples of first commercial refrigeration applications

S.S. Strathleven, equipped with Bell&Coleman air-cycle refrigerator. First meat cargo transported from Australia to London 6.12.1879 - 2.2.1880.
By courtesy of "La Trobe Picture Collection", State Library of Victoria

Standard ammonia cycle ice machine from York's 1892 catalogue.
The successful liquefaction of Oxygen was announced at the meeting of the Académie de Sciences in Paris on December 24th, 1877 independently by the physicist Louis Paul Cailletet from Paris and the professor Raoul Pictet from Geneva.

Cailletet’s apparatus

- compression to 200 bar in a glass tube with a hand-operated jack, using water and mercury for pressure transmission
- pre-cooling of the glass tube with liquid ethylene to -103°C
- expansion to atmosphere via a valve
Braking the cryo-barrier II

- Pictet’s apparatus
  - production of oxygen under pressure in a retort
  - two pre-cooling refrigeration cycles:
    first stage \( \text{SO}_2 \) (-10°C)
    second stage \( \text{CO}_2 \) (-78°C)
  - oxygen flow is pre-cooled by the means of heat exchangers and expands to atmosphere via a hand valve

Fig. 1.— Grand appareil de R. Pictet pour la liquéfaction des gaz. (d’après une photographie.)
## Milestones in the history of cryogenic technology

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1892</td>
<td>Dewar - use of silvering and vacuum in double walled glass vessel</td>
</tr>
<tr>
<td>1895</td>
<td>Linde and Hampson build air liquefiers with recuperative heat exchangers</td>
</tr>
<tr>
<td>1898</td>
<td>Dewar - liquefies hydrogen</td>
</tr>
<tr>
<td>1902</td>
<td>Claude - use of piston expander</td>
</tr>
<tr>
<td>1908</td>
<td>Kamerlingh Onnes - liquefies helium</td>
</tr>
<tr>
<td>1908</td>
<td>Becquerel - freezes seeds and single cells</td>
</tr>
<tr>
<td>1910</td>
<td>use of LOx in the production of steel</td>
</tr>
<tr>
<td>1911</td>
<td>discovery of superconductivity</td>
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</tbody>
</table>
Thermodynamics
The magic of throttling - physicist’s explanation
The magic of throttling - physicist’s explanation

- Repulsion dominates (Coulomb)
- Ideal gas
- Attraction dominates (gravity)

Gay-Lussac
Joule-Thompson
Throttling - thermodynamist’s explanation (and first law of thermodynamics)

- Energy conservation
  \[ \text{d}Q + \text{d}W = \text{d}E = 0 \]

- Internal energy closed system
  \[ E = U + E_{\text{kin}} + E_{\text{pot}} \]

- Energy content open system
  \[ E = U + pV + E_{\text{kin}} + E_{\text{pot}} = H \]

\[ \begin{align*}
  m, u_1, p_1, w_1 & \quad \rightarrow \quad A_1 \\
  H_1 & \quad = \\
  A_2 & \quad \rightarrow \\
  m, u_2, p_2, w_2 & \quad = \quad H_2
\end{align*} \]
Household refrigerator cycle
Linde and Hampson

Linde liquefier

Hampson liquefier

C. von Linde
1842-1934
Nitrogen

Linde/Hampson refrigeration cycle

Q_{ref}, Q_{W}
Claude refrigeration cycle

$$Q_{ref} = TdS$$

$$Q_{w} = TdS$$
Carnot cycle

- heat removed / heat introduced
  $$Q_w = (S_A - S_B) \times T_W \quad Q_{\text{ref}} = (S_D - S_C) \times T_C$$

- energy conservation
  $$Q_w = Q_{\text{ref}} + W \quad \text{and} \quad (S_A - S_B) = (S_D - S_C)$$
  $$\Rightarrow W = (S_A - S_B) \times (T_W - T_C)$$

- coefficient of performance or efficiency (index $i$ = ideal)
  $$\text{COP}_i = \eta_i = \frac{Q_{\text{ref}}}{W} = \frac{T_C}{T_W - T_C}$$

- figure of merit or thermodynamic (Carnot) efficiency
  $$\text{FOM} = \frac{\text{COP}_{\text{real}}}{\text{COP}_i} = \eta_{\text{th}} = \frac{\eta_{\text{real}}}{\eta_i}$$

<table>
<thead>
<tr>
<th>$T_C$</th>
<th>80 K</th>
<th>20 K</th>
<th>4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP$_i$, $\eta_i$</td>
<td>0.364</td>
<td>0.071</td>
<td>0.014</td>
</tr>
</tbody>
</table>
no gain with expansion machine in household refrigerator
Summary - refrigeration

refrigeration can be achieved by

– contact with a colder surface
– throttling
– work extraction

refrigeration can reach lower temperatures by

– heat recovery
Cycles
Bricks to build a refrigerator

A - expansion device

J-T valve

expansion machine

B - heat regeneration/recuperation

heat exchanger

regenerator
### Refrigeration cycles/principles

<table>
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<tr>
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<th>without heat recovery</th>
<th>with recuperator</th>
<th>with regenerator</th>
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<td><strong>cascade sorption</strong></td>
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<td>thermoelectric (cascade)</td>
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Mixed refrigerant cascade (MRC) refrigerator (Klimenko)

Pictet’s cascade

Cascade refrigerator

LNG storage

isothermal compression

natural gas feed

LNG

CO₂

SO₂

 compression

 compression

 compression

 compression A

 compression B

 compression C

 natural gas feed

 liquid propane

 liquid ethylene

 liquid methane

 LNG
## Refrigeration cycles/principles

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J-T cooler

By courtesy of Air Liquide
Dilution refrigerator

- **principle**
  - temperature reduction by dilution of He3 in a He4 bath
  - combined with a heat exchanger

- **range**
  - e.g. 15mK - 2K

By courtesy of Lot Oriel Group Europe
### Refrigeration cycles/principles

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Modified Claude cycle refrigerator

Linde refrigerator as used for the LHC

Aluminium fin plate heat exchanger

18kW at 4.4K
Expansion machines
Expansion machines
Refrigeration cycles/principles

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Principle of regenerator cycles

Various types of regenerators

Claude cycle
Stirling cycle refrigerator

Cycle
1 - Compression in warm end
2 - Displacement warm \(\rightarrow\) cold
3 - Expansion in cold end
4 - Displacement cold \(\rightarrow\) warm
Principle of regenerator cycles

Compression → Cooler → Recuperator → Refrigeration → Expansion →
Claude cycle

Gifford - McMahon cycle
Solvay cycle
Stirling cycle

1.5 W at 4.2K

By courtesy of Sumitomo Heavy Industries
Gifford - McMahon cycle refrigerator

1.5 W at 4.2K

By courtesy of Sumitomo Heavy Industries
Principle of regenerator cycles
Ranque Hilsch

- Vortex tube
  - a vortex is created by tangential injection
  - acceleration of molecules from external to internal vortex
  - friction between vortices ➔ faster molecules of internal vortex work on slower molecules of external vortex
Commercial refrigerators and cryocoolers
Other refrigeration principles

- radiation cooling
- space simulation chamber

- magnetic refrigeration

- thermoelectric cooling - Peltier cooler
Bath cryostat
# Introduction to Cryogenic Engineering

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## Course Outline

- **Refrigerants**
- **Standard Cryostats**
- **Material properties**
- **Specifying a refrigeration task**
- **Manufacturing techniques and selected hardware components**
Refrigerants
Refrigerants - ranges

- He3
- He
- H2
- D2
- Ne
- N2
- CO
- F2
- Ar
- O2
- CH4
- Kr
- Xe
- C2H4
- C2H6
- CO2

- liquid/gas. (<10bar)
- liquid/gas. (<Tb)
- solid/gas. (>10mbar)
# Refrigerants - data

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>He³ Helium</th>
<th>He⁴ Helium</th>
<th>H₂ Hydrogen</th>
<th>D₂ Deuterium</th>
<th>Ne Neon</th>
<th>N₂ Nitrogen</th>
<th>CO Carbon Monoxide</th>
<th>F₂ Fluorine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperatures [K]</td>
<td>liq</td>
<td>liq</td>
<td>liq</td>
<td>liq</td>
<td>liq</td>
<td>liq</td>
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<tr>
<td>2-phase equilibrium at 10 mbar</td>
<td>0.97</td>
<td>1.67</td>
<td>11.4</td>
<td>15</td>
<td>18.1</td>
<td>53</td>
<td>57</td>
<td>58</td>
</tr>
<tr>
<td>triple point</td>
<td>13.9</td>
<td>18.7</td>
<td>24.559</td>
<td>63.148</td>
<td>68.09</td>
<td>53.6</td>
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<tr>
<td>boiling point at 1.01325bar</td>
<td>3.19</td>
<td>4.22</td>
<td>20.3</td>
<td>23.6</td>
<td>27.097</td>
<td>77.313</td>
<td>81.624</td>
<td>85.24</td>
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<tr>
<td>2-phase equilibrium at 10 bar</td>
<td>31.36</td>
<td>34.7</td>
<td>37.531</td>
<td>103.641</td>
<td>108.959</td>
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<tr>
<td>critical point</td>
<td>3.33</td>
<td>5.2</td>
<td>33.19</td>
<td>38.3</td>
<td>44.49</td>
<td>126.19</td>
<td>132.8</td>
<td>144.41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Ar Argon</th>
<th>O₂ Oxygen</th>
<th>CH₄ Methane</th>
<th>Kr Krypton</th>
<th>Xe Xenon</th>
<th>C₂H₄ Ethylene</th>
<th>C₂H₆ Ethane</th>
<th>CO₂ Carbon</th>
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<tr>
<td>2-phase equilibrium at 10 mbar</td>
<td>60.7</td>
<td>61.3</td>
<td>76.1</td>
<td>84.3</td>
<td>117.3</td>
<td>117.6</td>
<td>127.8</td>
<td>151.2</td>
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<td>triple point</td>
<td>83.82</td>
<td>54.361</td>
<td>90.67</td>
<td>115.94</td>
<td>161.36</td>
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<td>87.281</td>
<td>90.191</td>
<td>111.685</td>
<td>119.765</td>
<td>165.038</td>
<td>169.242</td>
<td>184.548</td>
<td>194.65</td>
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<tr>
<td>2-phase equilibrium at 10 bar</td>
<td>116.55</td>
<td>119.623</td>
<td>149.198</td>
<td>149.198</td>
<td>218.612</td>
<td>221.25</td>
<td>241.9</td>
<td>233.038</td>
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<tr>
<td>critical point</td>
<td>150.66</td>
<td>154.58</td>
<td>190.56</td>
<td>109.43</td>
<td>289.73</td>
<td>282.35</td>
<td>305.33</td>
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</table>
Specific heat

Helium 4 - specific heat

![Graph showing specific heat of Helium 4 as a function of temperature and pressure.](image)
Particularities of Hydrogen

- exists in two molecular spin states: orthohydrogen and parahydrogen
- equilibrium depends on temperature
  300K  75% ortho  25% para
  20.4K  0.2% ortho  99.8% para
- conversion is slow (days) and exotherm
  \( Q_{\text{conv}} = -703 \text{ kJ/kg}_{\text{ortho}} \)
  or 527 kJ/kg_{n-H2} > evaporation enthalpy of 447kJ/kg
- specific heat and thermal conductivity of ortho- and parahydrogen are significantly different
- forms slush
Particularities of Helium

- transition to a superfluid phase below the $\lambda$-point (2.17K)

  effects:
  
  - viscosity decreases by several orders of magnitude
  - creeps up the wall
  - thermomechanic (fountain) effect
  - heat conductivity increases by several orders of magnitude
  - second sound

  due to the two-fluid character
heat transfer

- heat transfer principle
- solid conduction
- convection
- heat radiation
Standard Cryostats
Cryostats - bath cryostats

• **principle**
  - direct cooling of probe in cryogenic liquid bath
  - operation range: 1 - 4.2 K (63 - 78 K with LN2)

• **advantages**
  - no vibrations
  - stable temperatures
  - up-time (LHe-bath) several days (consumption 0.5-1% per hour)

• **disadvantages**
  - long cool-down time (in the order of 1 hour)
Cryostats - bath cryostats 2

- tails
  - cryostat add-on for different applications: e.g. NMR-magnets or optical systems

Courtesy of Janis Research Company, Inc.
Cryostats - bath cryostats 3

- anticryostat
  a) evacuate interspace
      probes can be exchanged while cryostat remains cold
  b) interspace flooded with contact gas
      operation - the temperature control is achieved with a heater in the probe support
Cryostats - evaporation cryostats

- principle
  - A small flow of cryogen is evaporated and cools the probe
  - operation range 1.5-300K
  - indirect cooling of probe
    i.e.
    probe in contact gas shown)
    or
    probe in vacuum
    or
    ...

Courtesy of AS Scientific Products Ltd.
Cryostats - evaporation cryostats 2

- principle …
  - direct cooling
    i.e.
    probe submerged in the evaporated helium/nitrogen
Cryostats - evaporation cryostats

- principle ...
  - without liquid cryogen baths

- advantages
  - compact
  - low cost
  - flexible orientation
  - fast cool-down
    (in the order of 10 minutes)

- disadvantages
  - high consumption (e.g. 0.5l LHe/h)
  - temperature control close to boiling point difficult
Cryostats - overall system
Cryostats - refrigerator cryostats

• principles
  – operation range 4.5 -300K

• advantages
  – compact
  – no cryogenic liquids
  – low operation costs
  – high autonomy
  – flexible orientation

• disadvantages
  – high investment cost
  – some can create vibrations
Specification
What to specify?

- Refrigeration task and operation conditions
  - refrigeration object dimensions, operation temperature and cooling principle, cool-down and warm-up conditions

- Minimum requirements
  - capacities, functions, materials, redundancies, measurement points and precision, automation degree

- Installation and environmental conditions
  - infrastructure (power supply, cooling, comp. air), accessibility, crane, environment (vibrations, magnetic field, radiation)
  - emissions (noise, vibrations, gas emission)

- Interfaces
  - infrastructure (gas recovery, cooling water, instrument air, energy), controls

- Quality requirements

- Documentation
  - drawings, design calculations, diagrammes, manuals, certificates, maintenance schedule, safety analysis
  - paper form or computer readable
Specification - typical quality requirements

- **Materials**
  - e.g. special material specifications
  - material certificates

- **Joining techniques**
  - requirements for weldments
  - requirements for joints

- **Surface properties**
  - free of ferritic impurities
  - dirt, grease, weld XXX

- **Leak rates**
  - e.g.
    - $< 10^{-8}$ mbar s$^{-1}$ individual welds
    - $< 10^{-7}$ - $10^{-6}$ mbar s$^{-1}$ overall leakrate He$\rightarrow$Vac
    - $< 10^{-6}$ - $10^{-5}$ mbar s$^{-1}$ overall leakrate air$\rightarrow$Vac
    - $< 10^{-4}$ mbar s$^{-1}$ valve seats
    - $< 10^{-4}$ mbar s$^{-1}$ flanges with non-metallic seals

- **Thermal losses**
  - z.B.
    - 0,3-2,3% /24h liq. helium transp. vessel
    - 0,1-0,5% /24h liquid nitrogen tank
    - 0,5-2 W/m liquid nitrogen transfer line
    - 5-500 mW/m shielded helium transfer line
Materials
Materials - selection criteria

- mechanical strength
  - $\sigma_{0.2}$, $\sigma_B$, $E$, $\delta$, $\alpha$
- working properties
  - forming, extrusion, welding
- further properties
  - magnetic properties, electric properties
- thermal properties
  - heat conductivity, heat capacity, thermal contraction
- surface properties
  - corr. resist., emissivity, spec. surf. area, outgassing
- economic properties
  - price, availability
## Materials - selection criteria

<table>
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<tr>
<th></th>
<th>1.5662 9% Nickel</th>
<th>1.4306/07 304L</th>
<th>1.4404/35 316L</th>
<th>Al 5083</th>
<th>Cu-OF</th>
<th>3.7165 Ti Al6 V4</th>
<th>GF reinforced epoxy</th>
<th>PTFE</th>
</tr>
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<tr>
<td>price/kg</td>
<td>3.5</td>
<td>4.5</td>
<td>4.7</td>
<td>7.3</td>
<td>9</td>
<td>70</td>
<td>35</td>
<td>26.5</td>
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</tbody>
</table>
Materials - thermal properties

- heat capacity
  - Debye temperature of metals:
    Fe 453K, Al 398, Cu 343, Pb 88K

- thermal conductivity
  - energy transport by electrons
# Materials - steels

## Austenitic Stainless Steel
- **Examples:**
  - 1.4301 (304),
  - 1.4306/07 (304L),
  - 1.4311 (304LN),
  - 1.4401 (316),
  - 1.4404/35 (316L),
  - 1.4541 (321),
  - 1.4550 (347)

- **Properties**
  - Universally applicable
  - Good weldability

- **Reference**
  - AD W10

## Low Temperature Steel
- **Examples:**
  - 1.3912 (FeNi36, Invar)
  - 1.5662 (X8Ni9, 9% nickel steel)

- **Properties**
  - High strength (1.5662)
  - Low thermal contract. (1.3912)
  - Cheaper than stainless steel

- **Remark**
  - 1.5662 is not suitable for application below -196°C
Materials - non ferrous materials

Al and Aluminium alloys

e.g. AW3003 (Al-Mn1Cu),
    AW1100 (Al99,0Cu),
    AW6061 (Al-Mg1SiCu),
    AW6063 (Al-Mg),
    AW5083 (Al-Mg4,5Mn)

- properties
  - high thermal cond. (1100, 6063)
  - moderate strength (6061, 5083)
  - good vacuum properties, low emissivity
  - extrudable
  - weldable

- reference
  - AD W 6/1

Cu and Copper alloys

e.g.
    SF-Cu (99.9)
    CuZn28Sn1 (2.0470, brass)
    CuNi30Mn1Fe (2.0882, Ni-bronze)
    CuBe1,9 (Berylliumbronze)

- high strength and good thermal conductivity

- reference
  - AD W 6/2
## Materials - polymers

### non filled polymers

- **thermoplastic polymers**
  - PET (Mylar)
    - superinsulation, windows
  - PI (Kapton, Vespel)
    - insulation, seals
  - PTFE (Teflon)
    - seals

- **duroplastic polymers**
  - epoxy resins
    - electrical insulation

### filled + fibre reinforced poly.

- **fibre reinforced polymers**
  - with glass fibres
    - thermal expansivity like metals
  - with carbon fibres
    - thermal conductivity like steel
    - thermal expansion ~0
  - Kevlar fibres
    - low weight

- **powder filled polymers**
  - with powders to adjust the thermal expansivity
  - with powders to increase the thermal conductivity

### reference

Materials - others

glass

e.g.
- borosilicate glass
  - cryostats
- quartz glass
  - windows

ceramics

e.g.
- Aluminiumoxide, Zirconiumsilicate
  - filler powders
- Siliziumdioxide
  - Perlite
Materials - mech., opt. and electrical propert.

- **mechanical properties**
  - Bei tiefen Temperaturen erhöhen sich bei vielen Werkstoffen die Dehngrenze und die Zugfestigkeit, die Bruchdehnung verringert sich jedoch in vielen Fällen. (Tieftemperaturversprödung)

- **emissivity**
  - see lecture by G. Vandoni

- **electrical properties**
  - energy transport by electrons
    ⇒ analogous to thermal conductivity, in alloys the effect of Störstellenstreuung becomes predominant.
Techniques and Selected Hardware
Methoden und Bauelemente

- Joining technique and seals
- Valves
- Pipework and transfer lines
- Radiation shields
- Adsorbers
- Heaters
- Instrumentation
- Vacuum technique
Joining techniques - overview

- **welding (TIG)**
  - advantage - excellent leak tightness
  - for precision manufacturing - electron beam welding
  - material transitions with friction welded joints
  - attention - copper forms bubbles
  - provide for eventual cuts

- **soldering**
  - hard soldering
    - thermal expansivity to be considered
    - good for copper - stainless steel joints
    - disadvantage - ageing possible
  - soft soldering
    - e.g. In97-Ag3, In52-Sn48
    - attention - standard Sn60-Pb40 soft solder becomes brittle at low temp.
    - not applicable for stainless steel
    - special soft solder exists:
      - non superconducting
      - with low thermo-electric potent.

- **glueing**
  - electrical feed throughs
  - electrical insulation
  - thermal contacts
    e.g. sensor attachement
  - e.g.
    - Araldite CW1304GB/HY1300GB,
    - Eccobond 285 + Härter 24LV,
    - Epo-Tek T7110,
    - Poxycemet F,
    - Scotch-Weld DP190,
    - Stycast 2850FT + hardener 9,
    - not applicable for stainless steel
Joining techniques - examples

welded joints

soldered joints

copper

stainless steel

socket style
Joining techniques - errors

• thermal contraction
  – identical materials - different temperatures
    • shear load of the joint due to the contraction of the internal part
  – different materials - parallel cooling
    • different thermal expansivity can cause plastic deformation of one component
    • e.g. Aluminium - stainless steel
      Al outside - plastic deformation of Al
      Al inside - extreme load on the joint
Joining techniques - flanges 1

- double seal for leak testing
  (main seal Kapton)

- separation of sealing function
  and force is possible

- material combinations

In order to obtain a constant force, the thermal expansivity of flange and bolt must be taken into account.

  e.g.: Flanges of stainless steel and aluminium with stainless steel bolts can be joined with an Invar spacer.
Joining techniques - flanges 2

- Flange
  - risk of leaks by manufacturing

  Inclosures from the material manufacturing are lengthened by the forming process. The prevailing inclosure direction must be taken into account as they can otherwise lead to leaks.

  Alternatives:
  - forged material,
  - vacuum molten material
Joining techniques - seals 1

- seals
  - copper, aluminium
    → sufficient compression force along the sealing line is required to ensure yield
  - indium
    → e.g. V-groove mit seal cord
    cross section seal cord = 1.5 x cross section of the groove
  - polyimide (Kapton)
    → compression force of 50N/mm²
Joining techniques - seals 2

- seals
  - O-rings
    e.g.
    out of metal - some are coated,
    out of polymers with internal spring

NOTE: Seals containing polymers cannot be used in a vacuum environment due to their high diffusion rate.
Joining techniques - heat transfer aspect

Aim - increase the heat transfer

• surface contact
  • $Q \neq f(\text{surface})$;
  • $Q = f(\text{contact pressure})$ !
  e.g. Cu-Cu at 300K, 500N - $10^{-2}$-$10^{-1}$ W/K
  Cu-Cu at 4K, 500N - $3 \times 10^{-3}$-$10^{-2}$ W/K
  Au-Au at 4,2K, 100N - $10^{-1}$ W/K
  Au-Au at 4,2K, 500N - $4 \times 10^{-1}$W/K
  • Improvement by increased contact pressure, vacuum grease (Apiezon grease) or gold-plated contact surfaces
  • where possible solder or weld (silver solder joint 2 W/Kcm$^2$)
  • glue with filled epoxy resins

• connectors
  • flexible bands and braids
  • heat pipes

Aim - decrease the heat transfer

• principles
  • reduction of ratio cross section/length
    – tie rods, cables (steel, Kevlar)
  • increase of the number of heat transfer barriers
    – chains, bundle of sheet

• supports
Verbindungen - Wärmeleitung

<table>
<thead>
<tr>
<th></th>
<th>Cu 99.99%</th>
<th>Cu 99.9%</th>
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<th>Al 99.9%</th>
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\[
\begin{align*}
\text{kleines } \Delta T : \quad & \dot{Q} = \frac{A}{l} \lambda \Delta T \\
\text{großes } \Delta T : \quad & \dot{Q} = \frac{A}{l} \int_{t_1}^{t_2} \lambda(T) \, dT \\
\end{align*}
\]

mit \( A \) = Querschnitt, \( l \) = Länge, \( \lambda \) = Wärmeleitung und \( \int_{t_1}^{t_2} \lambda(T) \, dT = \text{Wärmeleitungsintegral} \)
Specification of Valves operating at Cryogenic Temperature

Cryogenic valves must be able to cover both the control and the shut-off function. Only valves of the extended-spindle type with body and stem in co-axial design are accepted. These valves must be welded to the pipework and to the top plates of the cold boxes. Rotating type valves or valves with actuators inside the cold boxes will generally not be accepted. Proposals of exceptions for specific reasons have to be submitted to CERN with full justification, for approval.

The choice of any non-metallic material must be in accordance with the CERN Safety Instruction 41.

Materials and Design

The valve body must be in austenitic stainless steel AISI 316L or the equivalent DIN type. The spindle may be of the same material as the body or may consist partly of composite material. In case of composite material, the steel-to-composite connection must have a mechanical link in addition to any glued link. This mechanical link must be realised in order not to weaken the structure of the composite part. For valve stems in composite material, the difference in thermal contraction between ambient and liquid helium temperature must be compensated by the design in order stay below two percent of the valve travel.

The spindle-and-bells assembly must be dismountable from the top and must allow changing either the seat seal or the valve trim without the necessity to break the isolation vacuum.

In order to allow for misalignment introduced by the piping following thermal expansion and contraction, valve plugs for a maximum seat diameter of 15 mm or above, must have a flexible connection to the valve stem. For plugs with a smaller seat diameter this misalignment may be compensated be the elasticity of the valve stem. The stem itself must by its design allow for such misalignments, any guiding of it in the valve body must be protected against friction. Any flexible connection of the valve plug to the valve stem must be designed such that vibration of the plug due to the fluid flow is prevented and no damage of the plug, the seat or the seal occurs.

A flexible and clearance-free clutch device must protect the valve stem from any misalignments introduced from the actuator.

The valve bore and plug must be fabricated with a tolerance allowing for a rangeability of at least 1:100.

Sealing system

The static and the dynamic seal must be placed at the top warm end of the valve, easily available for maintenance or replacement.

The dynamic spindle seal must be welded metallic bellows. The bellows must be protected against twist load. Its lifetime design shall be made for a minimum of 10'000 full travel cycles at full design pressure. The bellows seal must be backed by an additional safety stuffing box with check-connection to the space enclosed in between.

The static seal to the ambient between body and spindle inset must be an O-ring seal. The O-ring seal groove must be designed for pressure and vacuum conditions. For sub-atmospheric operation conditions a double O-ring seal joint, covering static and dynamic sealing, with guard gas connection into the space in-between must be included.

The valve seat must be tightened with a soft seal for the shut-off function that must be placed on an area different from the regulation cone of the plug. For this soft seal only plastic materials proven for operation at liquid helium temperature are accepted.

Tests and material certificates

The chemical and physical qualities of the raw materials for pressure stress parts must be verified and documented by material test certificates.

The following tests, all recorded with a written protocol must be carried out on each ready assembled valve.

A pressure test, following the CERN Pressure Vessel Code D2, which refers to the European Directive CE93/C246.

A functional test to verify that the valve stem moves without friction

Leak tests to verify the leak rates listed below.

The cryogenic valves must satisfy the following leak rate criteria at maximum working pressure and room temperature.

Individual leak rate to atmosphere: $10^{-6}$ Pa m$^3$/s ($10^{-5}$ mbar l/s), Individual leakage across valves seat: $10^{-5}$ Pa m$^3$/s ($10^{-4}$ mbar l/s), Individual leak rate to the vacuum insulation: $10^{-9}$ Pa m$^3$/s ($10^{-8}$ mbar l/s).
Valves - design 2

valve with integrated actuator

By courtesy of Flowserve Kämmer
Valves - design (DIN534)

numerical value equation!

Liquid (incompressible fluid):

\[ k_v = \frac{\dot{m}}{\sqrt{1000 \, \rho \, \Delta p}} \]

with \( \rho \) = density in kg/m\(^3\), \( \Delta p \) = pressure drop in bar, 
\( \dot{m} \) = mass flow in kg/h

Gas:

subcritical flow (\( p_2 > p_1/2 \))

\[ k_v = \frac{\dot{m}}{519 \, \sqrt{T_i \, \rho_G \, p_2 \, \Delta p}} \]

with \( T_i \) = temperature in K, \( \rho_G \) = density at normal conditions, 
\( p_2 \) = pressure in bar

supercritical flow (\( p_2 \leq p_1/2 \))

\[ k_v = \frac{\dot{m}}{259.5 \, p_1 \, \sqrt{T_i \, \rho_G}} \]
Pipework - pressure drop

\[ \Delta p = \frac{\rho}{2} \frac{v^2 l}{d} \frac{1}{\lambda} \]

mit \( \rho \) = Dichte, \( v \) = Geschwindigkeit, \( l \) = Länge, \( d \) = Durchmesser

Reynolds Zahl: \( \text{Re} = \frac{v d}{\nu} \)

mit \( \nu \) = kinematische Viskosität: \( \nu = \frac{\eta}{\rho} \), \( \eta \) = dynamische Viskosität

laminare Strömung (\( \text{Re} < 2300 \)):
\[ \lambda_{\text{lamb}} = \frac{64}{\text{Re}} \]

turbulente Strömung (\( \text{Re} \geq 2300 \)):
\( \lambda_{\text{turb}} \) aus Nikuradse - Diagramm entnehmen oder für glatte Rohre

Formel von Blasius für \( 2300 < \text{Re} < 10^5 \):
\[ \lambda_{\text{turb}} = \frac{0.3164}{\text{Re}^{0.25}} \]

Formel von Nikuradse für \( 10^5 < \text{Re} < 10^8 \)
\[ \lambda_{\text{turb}} = 0.0032 + \frac{0.221}{\text{Re}^{0.837}} \]
pipe systems - direction of installation

- ascent towards warm end in order to allow thermal stratification
  
  - otherways - descend after a short ascent

- avoid low points (Siphons) in liquid carrying lines

- take into account thermal contraction
Transfer lines - design 1
Transfer lines

Courtesy of AS Scientific Products Ltd.
Transfer lines - design 2

SECTION 'A-A'
SEE SH. 1

VIEW ON ARROW 'F'

SECTION 'D-D'
Transfer lines - couplings 1

Courtesy of NEXANS Deutschland Industries GmbH & Co. KG
Transfer lines - couplings 2

Courtesy of NEXANS Deutschland Industries GmbH & Co. KG
Transfer lines - phase separator

- phase separator

The installation of a phase separator at the delivery end of a siphons can improve the transfer of liquid.

NOTE: As these filters can clog, they should only be installed in accessible places.
Shield - design

a) shield out of two concentric cylinders

b) shield with brazed cooling pipes

c) shield assembled from extruded elements (e.g. finned pipes)

d) quilted panel type shield
   (made by 1. spot welding two plates and 2. hydraulically forming them)
Distance of the cooling pipes:

\[ l = \sqrt{\frac{8 \lambda s (T_{\text{max}} - T_{\text{refrigerant}})}{\dot{q}}} \]

with

\( \lambda \) = thermal conductivity,
\( s \) = thickness of the shield,
\( T_{\text{max}} \) = maximum temperature of the shield in between two cooling pipes,
\( \dot{q} \) = specific heat flux
Adsorber - design

• Capacity

\[ V_{\text{Adsorber}} = \frac{x \dot{m} T}{\rho \beta} \]

with
- \( x \) - concentration of impurities
- \( \dot{m} \) - mass flow
- \( T \) - up time
- \( \rho \) - density of the impurities at RT
- \( \beta \) - adsorption capacity

• Pressure drop - Ergun equation

\[ \Delta p = \frac{150(1-\varepsilon)^2 \mu u_0 L}{\varepsilon^3 D_p^2} + \frac{1.75 \rho L u_0^2}{D_p^2} \frac{1-\varepsilon}{\varepsilon^3} \]

with
- \( D_p \) - particle diameter
- \( L \) - length of the adsorber
- \( u_0 \) - gas velocity = \( \frac{\dot{V}}{A} \)
- \( \varepsilon \) - void fraction
- \( \mu \) - viscosity
- \( \rho \) - gas density

Attention – Avoid the formation of a turbulence layer!
### Adsorber - data

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Activated charcoal</th>
<th>Silica gel</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density</td>
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<td>[kg/m³] 720</td>
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<tr>
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<td>[2]</td>
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<tr>
<td>Particle density</td>
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<td>[kg/m³] 1200</td>
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</tr>
<tr>
<td>Void fraction ϵ</td>
<td>[-] 0.64</td>
<td>[-] 0.6</td>
<td>[2]</td>
</tr>
<tr>
<td>Specific heat capacity at RT</td>
<td>[kJ/kgK] 0.84</td>
<td>[kJ/m³K] 403.2</td>
<td>[kJ/kgK] 0.92</td>
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<tr>
<td>Specific surface area</td>
<td>[10⁶ m²/kg] 1.2</td>
<td>[10⁶ m³/m³] 576</td>
<td>[10⁶ m²/kg] 0.78</td>
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</table>

#### Adsorption properties

<table>
<thead>
<tr>
<th></th>
<th>per unit of mass</th>
<th>per unit of bulk volume</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Monolayer capacity for N₂ at 90.1K following BET</td>
<td>[m³/kg] 0.173</td>
<td>[m³/m³] 83</td>
<td>[m³/kg] 0.127</td>
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<tr>
<td>Monolayer capacity for O₂ at 90.1K following BET</td>
<td>[m³/kg] 0.235</td>
<td>[m³/m³] 113</td>
<td>[m³/kg] 0.132</td>
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<tr>
<td>Monolayer capacity for Ar at 90.1K following BET</td>
<td>[m³/kg] 0.216</td>
<td>[m³/m³] 104</td>
<td>[m³/kg] 0.122</td>
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<tr>
<td>Monolayer capacity for N₂ at 77.3K following BET</td>
<td>[m³/kg] 0.182</td>
<td>[m³/m³] 87</td>
<td>[m³/kg] 0.135</td>
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<tr>
<td>Adsorption capacity for N₂ at 76K</td>
<td>[m³/kg] 0.240</td>
<td>[m³/m³] 115</td>
<td>[m³/kg] 0.250</td>
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<tr>
<td>Adsorption capacity for N₂ at 77.4K</td>
<td>[m³/kg] 0.246</td>
<td>[m³/m³] 118</td>
<td>[m³/kg] 0.196</td>
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</table>

Sources:

[5] Unpublished measurements by Air Liquide: Adsorption from a 99.5% He + 0.5% N₂ mixture at 70-150bar (activated charcoal) and 30bar (silica gel), respectively.
Heater elements

- **Heater wire**
  - e.g. constantan wire (CuNi), manganin wire (CuMnNi)
  - tension up to 50V
  - advantage – no inertia

- **Foil heaters**
  - e.g. on polyimide foil (=Kapton foil)
  - typical power 2W/cm²
  - on cryogen side or on vacuum side
  - advantage – equally distrib. power

- **encapsulated heater elements**
  - Tension up to 400V
  - advantages
    - high heating powers are possible
    - no electrical feedthroughs

- **Attention!**
  - For heaters in the liquid – safety interlocks are required for low level and for vacuum pressure!
Instrumentation - temperature measurement

- Primary thermometers
  - gas thermometer
  - vapour thermometer

- Secondary thermometers
  - metallic resistances
  - non-metallic resistances
  - thermocouples

  - others: capacitance t., resonance t., inductance t.

- Precision factors
  - sensitivity (e.g. $\Omega/K$)
  - reproducability (factors - installation, self heating, ageing)
  - magnet field dependence

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PT 100  Silicon diode
**Instrumentation - level and flow**

- **Level measurement**
  - Differential pressure
  - Superconducting wire
  - Capacitance based
    - not for LHe

- **Flow measurement**
  - Differential pressure method
    - orifice
    - Venturi tube
    - V-cone
  - Other physical principles
    - Coriolis
    - Turbine

![Diagram of V-cone](image-url)
Insulation vacuum - permanent vacuum

- Operation range
  $10^{-3}$ mbar (RT) - $10^{-5}$ mbar (cold)
  (i.e. $10^{-1}$ Pa - $10^{-3}$ Pa)

- Privilege weld connections
- Avoid elastomer joints (diffusion)

- Extension of the up-time by installation of adsorber packages on the cold surfaces
  → activation (regeneration) is important
Insulation vacuum - pumped vacuum

- Operation range
  $10^{-5}\text{mbar} (=10^{-3}\text{Pa})$ and better

- Primary pump
  rule of thumb for pumping speed
  $$S_{\text{Primary Pump}} > 0.005 \times S_{\text{High Vacuum Pump}}$$

- Secondary pump (high vac. pump) types
  Diffusion pump
  advantage - cheap

  Turbomolecular pump
  the pumping speed depends on the molecular weight ⇒
  advantage - hydrocarbon free vacuum
  disadvantage - low pumping speed for He and $H_2$
Insulation vacuum - vacuum technique

- avoid trapped volumes
  - trapped volumes can create virtual leaks
Day 3
Introduction to Cryogenic Engineering

MONDAY  From History to Modern Refrigeration Cycles  (G. Perinić)

TUESDAY  Standard Components, Cryogenic Design  (G. Perinić)

WEDNESDAY  Heat Transfer and Insulation  (G. Vandoni)

THURSDAY  Safety, Information Resources  (G. Perinić)

FRIDAY  Applications of Cryogenic Engineering  (T. Niinikoski)

- Physiological hazards
- Sources of accidents and failures
- Information resources
Safety
Physiological Hazards

Cold Burns - Asphyxiation - Toxicity

• Cold Burns
  – Contact with cryogenic liquids or cold surfaces

• Asphyxiation
  – Reduction of oxygen content

(• Toxicity
  – CO, F₂, O₃)
Physiological Hazards

Cold Burns - Asphyxiation - Toxicity

• **Effects:**

  Similar to burns

• **First Aid:**

  = identical procedure as in the case of burns
  
  – rinse injured part with lukewarm water
  – cover injured skin with sterile gaze
  – do not apply powder or creams

• **Protection:**

  – eye protection
  – gloves of insulating and non combustible material which can be easily removed
  – high, tight-fitting shoes
  – trousers (without turn-ups) which overlap the shoes
Physiological Hazards

Cold Burns - Asphyxiation - Toxicity

• **Effect:**
  - 19% - 15% pronounced reduction of reaction speed
  - 15% - 12% deep breaths, fast pulse, co-ordination difficulties
  - 12% - 10% vertigo, false judgement, lips slightly blue
  - 10% - 8% nausea, vomiting, unconsciousness
  - 8% - 6% death within 8 minutes, from 4-8 minutes brain damages
  - 4% coma within 40 seconds, no breathing, death

• **First Aid:**
  In case of indisposition - remove person from the danger area.
  In case of unconsciousness - call doctor immediately.

• **Protection / Prevention:**
  - ensure sufficient ventilation + oxygen monitors
  - Dewar content [l] < laboratory content [m³] / 4
  - Feed exhaust into stack or into recovery pipeline
  - Decanting stations only in large halls or outside
  - Observe rules for confined spaces
  - Observe the rules for transport of dangerous goods
Physiological Hazards

Cold Burns - *Asphyxiation* - Toxicity
Physiological Hazards

Cold Burns - Asphyxiation - Toxicity

• **Effect:**
  – *Carbon monoxide* – Poisoning by replacement of oxygen in the blood
  – *Ozone* - Irritation of eyes and skin already by concentrations as low as 1ppm.
  – *Fluorine* - Irritation of eyes and skin.

• **First Aid:**
  – *Carbon monoxide* – same as asphyxiation
  – *Ozone and Fluorine* - Rinse thoroughly the affected areas of skin with tap water.

• **Protection / Prevention:**
  – *Carbon monoxide and Ozone* – same as asphyxiation.
  – *Fluorine* - The pungent smell is already detected by the human nose at concentrations of 0.2ppm.
Physiological Hazards
Marking/identification

⇒ Warning of „cold“:

⇒ Storage and transport vessels (EN DIN 1251):

  for example –

  LIQUID NITROGEN

⇒ Pipes, pipelines and exhausts - recommendation (DIN 2403):

  for example –

  HELIUM →
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

- Embrittlement
- Thermal stress

- Pressure build-up by evaporation
- Condensation
- Combustion and explosion hazard
- Electric breakdown

- Accidents and failures due to operation
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

- **Low temperature embrittlement**
  - Affects most materials more or less pronounced
  - Is measured by → charpy impact tests
  - Suitable for low temperatures are materials with fcc structure → e.g. Cu, Ni, Cu Ni, Al, Al-alloys, Zr, Ti, stainless steels see AD W10
Sources of accidents and failures

**Properties of materials** – Properties of refrigerants - Operation

- Low temperature embrittlement
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

- Hydrogen embrittlement
  - Several mechanisms exist, can originate from material production or from operation
  - At risk are:
    - Metals with bcc-structure (e.g. ferritic steels),
    - High tensile steels used in the range 200-300K,
    - Materials under loads close to their limit of elasticity
  - Means of protection:
    - linings or coatings with other metals,
    - over dimensioning
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

• Thermal Stress
  - Contraction due to cool-down

  ⇒ permanent loads in operation, e.g. in pipes

  ⇒ temporary loads, e.g. during cool-down of thick walled components
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

• **Pressure build-up by evaporation**

  - due to excessive heat load
    - Cool-down of a component, of an installation
    - Heating components – heaters, quenching magnet
    - Loss of insulation vacuum
    - thermo-acoustic oscillations (Taconis)
  
  - due to other physical effects
    - Boiling retardation
    - stratification
    - roll-over (LNG only)
    - desorption of cryopumped gas

1 l liquid refrigerant ($T_S$)  
$\Leftrightarrow$  
500-1500 l gas (300K)
Pressure build-up

Evaporation by excessive heat load

- fast cool-down of
  → a component or
  → a part of the installation

- excessive heating by
  → a component e.g. quench
  → by installations e.g. heaters

- loss of the insulation vacuum

- thermoacoustic oscillations
Pressure build-up

other physical effects

- boiling retardation
- stratification
- rollover in LNG tanks
- release of cryopumped gas
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

- Pressure build-up

Means of protection:
- safety devices

Principles:
- redundancy and
- diversity

Calculation of safety valves:
- AD-Merkblatt A1/A2
- DIN EN 13648 (=ISO 21013)
Calculation of safety valves for LHe-containers

1. Determination of the maximum heat flux

Possible heat sources:

- loss of vacuum,
- fire,
- electrical heaters,
- quench in superconducting coils, etc.

Typical heat flux in case of insulation vacuum loss:

0.6W/cm²  LHe-cryostat with 10 layers superinsul.
3.8W/cm²  LHe-cryostat without superinsulation

2. Determination of the gas flux

a) Blow-off pressure below critical pressure

\[ \dot{m}_{\text{blow-off}} = \frac{\dot{Q}_{\text{surface}}}{q} \left( 1 - \frac{\rho_{\text{gas}}}{\rho_{\text{liquid}}} \right) \]

with \( q = \Delta h_{\text{evaporation}} \)

(in general \( \Delta h_{\text{He}} \approx \Delta h_{\text{He}}(1,01325\text{bar}, 4,222\text{K}) = 20.91\text{J/s})\)

b) Blow-off pressure above critical pressure

\[ \dot{m}_{\text{blow-off}} = \frac{\dot{Q}_{\text{surface}}}{q} \]

with \( q = v \left( \frac{dh}{dv} \right)_{p=\text{const.}} \)

(up to 5bar \( V(dh/dV) \approx \Delta h_{\text{He}}(1,01325\text{bar}, 4,222\text{K}) = 20.91\text{J/s})\)

\[ \dot{m}_{\text{blow-off}} = \max \text{ for } v \left( \frac{dh}{dv} \right) = \min \]
Minima of the pseudo-evaporation enthalpy of helium as a function of the pressure

<table>
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<td>40</td>
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a) outflow function $\psi$

If

$$\frac{p_{gegen}}{p_{Kryostat}} > \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa - 1}}$$

then (subcritical)

$$\psi = \sqrt[\kappa - 1]{\kappa} * \sqrt{\left(\frac{p_{gegen}}{p_{Kryostat}}\right)^{\frac{2}{\kappa}} - \left(\frac{p_{gegen}}{p_{Kryostat}}\right)^{\frac{\kappa + 1}{\kappa}}}$$

else (supercritical)

$$\psi = \sqrt[\kappa + 1]{\kappa} * \left(\frac{2}{\kappa + 1}\right)^{\frac{1}{\kappa - 1}}$$

b) minimum blow-off surface

$$A_{\text{min.}} = \frac{\dot{m}}{\psi \alpha \sqrt{2 p_{\text{cryostat}} \rho}} \text{ with } \alpha = \text{outflow coefficient} \in \{0..1\}$$
Condensation

**Causes**
- impurities in refrigerant (air, neon, oil)
- leaks, especially in sub-atmospheric conditions
- open exhaust pipes
- not insulated or badly insul. surfaces leaks into the insulation vacuum

**Prevention**
- extensive purging and repeated evacuation before cool-down
- operation with slight overpressure
- use of vacuum insulation where possible – otherways use only non-combustible insulation material equipped with a vapour barrier in order to stop air and oxygen from reaching the cold surface
Condensation

Plugging of exhaust pipes

- open or leaky exhaust pipes
  Attention: acceleration by two exhausts!

- thermally connected LN2-screens

- leaks when pumping on cryogen baths

Prevention:

⇒ do not leave open dewars
⇒ non-return valves in exhaust lines
⇒ use only containers with separated exhaust and safety lines
Sources of accidents and failures

Properties of materials – **Properties of refrigerants** - Operation

- **Fire and explosion risk:**
  - Methane, LNG, Hydrogen

**Other combustion dangers:**

- Superinsulation foils on Polyester base (Mylar®) can be ignited easily!
  - Protect when welding!
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

- Electric breakdown

Fig. 8 Generalized Paschen curves
Sources of accidents and failures

Properties of materials – Properties of refrigerants - Operation

• Plant operation
  – operator errors
  – usage of unsuitable equipment
  – operating system errors
  – malfunctioning or failures of components
  – failure of safety equipment
  – Transport accidents
  – etc.

Preventive measures:
  – Safety analysis and safety management
Information Sources
<table>
<thead>
<tr>
<th>Titel</th>
<th>Autor</th>
<th>Verlag</th>
<th>Jahr</th>
<th>lieferbar</th>
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<td>Cryogenic Engineering</td>
<td>T.M. Flynn</td>
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## Information sources - literature 2

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<td>E.I. Asinovsky</td>
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<td>Kryotechnik</td>
<td>W.G. Fastowski, J.W. Petrowski,</td>
<td>Akademie Verlag</td>
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<td>H. Hausen, H. Linde</td>
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<td>History and origins of cryogenics</td>
<td>R.G. Scurlock</td>
<td>Clarendon</td>
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Information sources - journals/conferences

- Journals
  - Cryogenics  [http://www.elsevier.nl/locate/cryogenics](http://www.elsevier.nl/locate/cryogenics)

- Conferences
Information sources - data bases/formulas

• free information sources
  – UIDAHO Center for Applied Thermodynamic Studies - cryogen property program http://www.webpages.uidaho.edu/~cats/software.htm
  – NIST Cryogenic Technologies Group - material property equations http://cryogenics.nist.gov/NewFiles/material_properties.html

• commercial information sources
  – CRYODATA - cryogen and material database http://www.htess.com/software.htm/
  – Cryogenic Information Center - cryogen and material database and bibliography http://www.cryoinfo.org/
End
Extras
The cryogenists toolbox

- Internal Energy and Enthalpy
- Energy conservation
- Entropy Exergy
- Diagrams TS,
- Cycles
- Efficiency
Energy conservation

- Bernoulli
- static system
Principles of refrigeration

2nd law of thermodynamics
Entropy

- $dQ/T = S = \text{const}$

- state variables $p, T, V, U, H, S$
Principles of refrigeration

2nd law of thermodynamics
Exergy

\[-W_{ex} = h_1 - h_{RT} - T_u (S_1 - S_u)\]
isentropic adiabatic

Ideal

Real

Work

Cooling power

ΔS1

ΔS2
Summary

• throttling

• work
Cryogenics past to present

- time of I. Newton (1642 - 1727)
- R. Boyle (1627 - 1691); E. Mariotte (1620 - 1684) \( pV=\text{constant} \)
- J J Becher (1635 - 1682), G.E Stahl (1660 - 1734) phlogiston
- G. Amontons (1663 - 1705) absolute zero
Other talks

• VDI
  – Thermodynamics
  – Refrigerants
  – Material properties
  – Heat transfer
  – Thermal insulation
  – Measurement and controls
  – Safety
  – Microcoolers -- Large refrigerators
  – Cryopumps
Other talks

• Weisend
  – basics
  – cryogens
  – materials
  – refrigeration
  – He II
  – cryostat design
  – instrumentation
  – safety

• Quack
  – temperature reduction by throttling or mixing
  – temperature reduction by work extraction
  – refrigeration cycles
  – cryogens
  – cooling principles
  – applications
Throttling - as seen by a thermodynamist

- **first law**
  \[ dU = dQ + dW = 0 \]

- **energy content**
  \[ E = U + pV + E_{\text{kin}} + E_{\text{pot}} = H \]
  \[ m u_1 + p_1 A_1 w_1 = m (u_1 + p_1 v_1) = m h_1 \]
  \[ m u_2 + p_2 A_2 w_2 = m (u_2 + p_2 v_2) = m h_2 \]
Sailing ship Dunedin, equipped with a Bell-Coleman air cycle refrigerator. The ship left Port Chalmers on 15 February and arrived in England on 14 May 1882.
Abb. 44. SO₂-Eismaschine von Raoul Pictet.

What is cryogenics?
Time of I. Newton

- J J Becher (1635 - 1682), G.E Stahl (1660 - 1734)
Heat transfer and insulation
Cool and keep cold

heat input

cooling
cooling or heat removal

- heat transfer
  - solid conduction
  - convection
  - heat radiation

choice of the refrigerant
Bath cooling
Sources of heat input

- Radiation
  \[ \dot{q} \sim \varepsilon (T_w^4 - T_k^4) \]

- Convection
  \[ \dot{q} = \lambda \frac{\Delta T}{s} \]

- Solid conduction
  \[ \dot{q} = \lambda \frac{\Delta T}{s} \]

- Gas conduction

Further sources:
- Nuclear radiation
- Induction

\[ \Lambda \ll s \]
\[ \Lambda \gg s \]

\( \lambda \) - heat conductivity
\( \Lambda \) - free path length
- solid conduction

\[ \dot{q} = \lambda \frac{\Delta T}{s} \]

- convection

\[ \dot{q} = \lambda \frac{\Delta T}{s} \]

\[ \dot{q} \sim p \Delta T \]

\[ \dot{q} \sim \varepsilon (T_w^4 - T_k^4) \]
Introduction to Refrigerators and Cryogens
Wärmequellen im Vakuum

• Festkörperleitung durch
  – Kryostatenhals,
  – Rohrleitungen,
  – Ventile,
  – Aufhängungen,
  – Abstützungen,
  – elektrische Leitungen

• Wärmeübertragung durch
  – Restgas im Isolationsvakuum
    \[ p > 10^{-4} \text{ mbar } \dot{Q} \sim 1/L \]
    \[ p < 10^{-4} \text{ mbar } \dot{Q} \sim p \]  
    (bei konstanter Temperaturdifferenz)

• Strahlung
  \[ \dot{Q} = \varepsilon \sigma A T^4 \]

• Sonstige
  – Heizungen
  – Quench
  – induzierte Ströme