Cryogenic refrigeration with neon-helium mixtures for FCC beam screens: Specification of Components

Steffen Klöppel, Hans Quack, Fridolin Holdener, Christoph Haberstroh

FCC WEEK Rome 4/13/2016
Agenda

• Collaboration between CERN and TUD
• Refrigeration below 80 K / The Nelium concept
  • Compressors
  • Heat Exchangers
• Summary and next steps
Anticipated heat loads for FCC-hh per sector

- 1.8K
- 40K
- 60K
- 300K

12 kW
500 kW

Beam screen + 70 kW Thermal shields

- equivalent cooling power for beam screens is two times that for magnet cooling
- efficient refrigeration is mandatory!
Conventional He cycle
Screw compressor

≈30 % of Carnot efficiency
⇒ 13 MW input power

Alternative Ne He cycle
Turbo compressor

≈45 % of Carnot efficiency
⇒ 8.7 MW input power

Photo courtesy: MAN Diesel and Compressor
Required pressure ratios in the cycles: $\approx 7$

Achievable pressure ratios per stage:
- Pure helium: 1.05 $\Rightarrow$ 39 stages
- Pure neon: 1.27 $\Rightarrow$ 8 stages, but large HXs

Compromise:
- 20 mol-% Ne + 80 mol-% He,
- Pressure ratio per stage: 1.1 $\Rightarrow$ 20 stages

$\Delta h = 45 \text{kJ/kg}$

\[ K = 1.4 \quad \text{and} \quad K = 1.6 \]
Requirements main compressor

Machine parameters
- Mass flow: 11 kg/s
- Pressure ratio: 7
- Inlet pressure: 5.1 bar
- Volume flow at inlet cond.: 6.7 m³/s
- Th. isothermal power: 6.1 MW

Working fluid
- 20-% Ne + 80-% He
- Light weight
- Cost-intensive (neon)
- Small molecules

Compressor:
- Centrifugal
- High speed
- Hermetic
Available compressors

Commercially available:
Compressors for natural gas storage and transport with active magnetic bearings (oilfree)

Siemens
STC-ECO

Dresser-Rand
Datum I

MAN
Hofim

GE
Blue-C

Image courtesy: resp. companies
Technical restrictions:

- **speed**
  - max 12,500 rpm with MAN motor
  - strength of motor windings (copper)
  - shaft-impeller joint (shrinking)
- **Wheel diameter**
  - max 630 mm outer diameter
  - Installation by human workers (arm length)
- **Stiffness of the rotor**
  - High flow coefficients require thin shafts

General: energy increase limited to ≈45 kJ/kg per stage for economical reasons
Multi shaft design (by MAN):
19 stages
4 inter/after-coolers
Stages 1..9: \( n = 9000 \text{ RPM} \)
Stages 10..19: \( n = 11300 \text{ RPM} \)
Reverse calculation of MAN compressor:
- Pressure drop in inter and after coolers: 200 mbar
- Isentropic efficiencies: $\eta_{is} \approx 92\%$
- Outlet flow angle: $\beta_2 = 40..50^\circ \Rightarrow \psi \approx 1$
- Flow coefficient: $\varphi^* = 0.6$ (1st stage)

⇒ starting point for different designs/optimizations
Further development of compressors

- The market for compressors for very light gases is quite small
- Compressors from natural gas business can be adopted

Such compressors are available for the FCC Ne-He cycle, but not optimal

Lesser stages = lower CAPEX
Optimal would be a configuration with a single machine

\((1 \text{ motor, 1 AMB, 1 VFD})\)

Possible improvements to increase the head per stage:
- Larger impellers \(\Rightarrow\) change in assembly routine
- Aluminium instead of steel \(\Rightarrow\) impeller shaft connection
- Increased flow angle \(\beta_2\) \(\Rightarrow\) decreased stall margins
- Redesign of motor \(\Rightarrow\) …

Low incentive of industry for these changes
Why not use pure neon?

Neon has inferior heat exchange properties compared to helium:

<table>
<thead>
<tr>
<th>Property</th>
<th>Neon</th>
<th>Helium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ [W/mK]</td>
<td>48</td>
<td>156</td>
</tr>
<tr>
<td>$c_p$ [kJ/kg]</td>
<td>1.0</td>
<td>5.2</td>
</tr>
<tr>
<td>$\rho$ [kg/m³]</td>
<td>0.81</td>
<td>0.16</td>
</tr>
<tr>
<td>$\eta$ [$\mu$Pa s]</td>
<td>31</td>
<td>20</td>
</tr>
</tbody>
</table>

Heat exchangers (HX) with neon will be bigger, less efficient and/or have higher pressure drop.
Heat exchanger selection

High effectiveness:

- Counter-flow
- Plate
- Serrated-Fin

Source: http://www.chartindustries.com
Heat exchanger sizing

Volume:

\[ V = \frac{\dot{m} Pr}{\beta} \left( \frac{f^{1/2}}{\lambda^{3/2}} \right) \left[ \left( \frac{NTU_i}{\eta_0} \right)^3 \frac{1}{2\Delta p \rho} \right]^{1/2} \]

Fluid-dependent properties:

\[ V \propto \frac{Pr}{\rho^{1/2} c_p} \]
\[ V \propto \frac{\mu}{\lambda \rho^{1/2}} \]

Heat exchanger volume scales less than linearly with neon content

⇒ Low neon content (up to 50%) favorable
Frontal area:

\[ A_c = \dot{m} \left[ \frac{f}{j} \left( \frac{Pr^{2/3} NTU_i}{2\rho \eta_0 \Delta p} \right) \right]^{1/2} \]

Fluid-dependent properties:

\[ A_c \propto \frac{Pr^{1/3}}{c_p \rho^{1/2}} \]

Heat exchanger frontal area increases more than linearly with neon content
Heat exchanger sizing

Length:

\[ L = \frac{V}{A_c} \propto Pr^{2/3} \]

- Overall heat exchanger size: shorter, but wider compared to pure helium
Design for 20% neon

Maximum size:
- Width: 1500 mm
- Height: 3000 mm
- Length: 8200 mm

Sizes are well below limits!
Influence of neon content

Design for 20% neon

Optimal system is defined by lowest cost

CAPEX:
- compressor
- HX
- coldbox
- Initial neon filling

... OPEX:
- input power
- neon losses

Design for 40% neon

Compressor: 19 stages

Compressor: 12 stages
Summary and outlook

• Using Ne/He mixtures makes centrifugal compression feasible
• Such compressors are available, but not optimal
• Heat exchangers are readily available

Next steps
• Develop model for expansion turbine/booster compressor
• Optimize total cost based on neon content
  • Define cost functions for compressors, heat exchangers, coldbox and refrigerant
  • Estimate refrigerant leakage rates
• Investigate transient operation