Lecture 6
Refrigeration & Liquefaction (Part 2)

J. G. Weisend II
Joule-Thomson Expansion

- Isenthalpic \((h=\text{constant})\) expansion
- Fluid cools as it is expanded at constant enthalpy through a valve
- However, depending on both the fluid and the temperature, such an expansion can also cause heating.
- Define the Joule-Thomson expansion coefficient \(\mu_j \equiv \left( \frac{\partial T}{\partial P} \right)_h\)
- \(\mu_j\) must be positive for cooling to occur
- Cooling by JT expansion has some advantages
  - No moving parts
  - Can easily handle two-phase mixtures
**JT Inversion Curve & Maximum Inversion Temperatures**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Max Inversion Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>623</td>
</tr>
<tr>
<td>Argon</td>
<td>723</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>202</td>
</tr>
<tr>
<td>He</td>
<td>43</td>
</tr>
</tbody>
</table>

- Maximum inversion temperature for helium is 43 K
- Note that below ~ 2 K He again warms on JT expansion
- Many fluids, such as N\textsubscript{2} can be liquefied using JT expansion – JT cycle

Inversion curve for Helium

Lecture 6 | Refrigeration & Liquefaction (Part 2) - J. G. Weisend II
January 2016  Slide 3
Joule-Thomson Refrigerator

- Simple
- Mainly used for cryocoolers (more later) and not for large plants
- Also known as a Linde-Hampson Refrigerator

From Cryogenic Systems
R. Barron
Modern large scale Helium refrigerators/liquefiers use a variation of the Claude cycle known as the Collins cycle.

The key difference between these cycles and the JT cycle is the addition of expansion engines (pistons or turbines) that the fluid does work against and thus cools.

The process through these expansion engines may be idealized as Isentropic (s = constant) expansion:
- Cooling occurs at any temperature
- $\Delta T$ for a given $\Delta P$ is much larger than for isenthalpic expansion

Claude cycle = 1 expansion engine, Collins cycle = multiple expansion engines
- The post WW II development of the Collins liquefier revolutionized laboratory research in cryogenics
Claude Cycle

From Cryogenic Systems
R. Barron
Collins Cycle

- Cycle consists of:

  1) Compression to ~ 16 Bar with cooling back to 300 K + oil removal
  2) Cooling of high pressure gas with LN₂
  3) Isentropic expansion via 2 or more expansion engines
  4) Cooling of high pressure gas by the cold returning low pressure stream
  5) Isenthalpic expansion through JT valve
  6) Return of gas to compressors at just above 1 Bar
CTI 4000 Refrigerator
(early 80’s vintage ~ 1.2 kW @ 4.5 K)

CTI 4000 Upgrade 12/2/99
* Indicates new or changed component
LHC 4.5 K Refrigeration Plant
18 kW @ 4.5 K – produced in ~ 2004
1of 8 required (4 from Linde, 4 from Air Liquide)

- Note:
  - Large number of expansion turbines – some in series with HP stream
  - Medium pressure return
  - Heat loads at intermediate temperatures
  - Designed to have high % Carnot (roughly 30%)
Note:
1) No LN$_2$ Precooling
2) Last stage of subatmospheric pumping is warm
3) Provides up to 3 kW @ 2K
Note:
1) No LN$_2$ Precooling
2) Last stage of subatmospheric pumping is warm
Major Components of a Helium Refrigeration Plant

- Helium Screw Compressors
  - Operate at room temperature
  - Are oil flooded – compress a mixture of He gas and special oil
  - Require water cooling to remove heat due to compression
  - Vast majority of power goes here
  - We expect the largest compressors at FRIB to use 2000 HP motors

From Dunham Bush Co.

SNS/ORNL Compressors
Schematic of Helium Compressor

Compressor (screws)

Combined control venting valve

Inlet valve

Non-return valve

Bulk oil separator

Oil cooler

Oil filter

Gas cooler

Gas outlet

Courtesy Linde/Kaeser
Major Components of a Helium Refrigeration Plant

- **Oil Removal Systems**
  - Removes oil down to the ppb level – critical for proper operation of the plant
  - Bulk Oil Separators: should reduce level down to < than 250 ppm
  - Coalescers: two or more in series reduce oil level down to < 10 ppm
  - Absorbers:
    - contain activated charcoal
    - Are redundant
    - Reduces level down to < 1 ppb
    - Can be regenerated via warm $N_2$ gas

- **Cold Box**
  - Contains cryogenic components
    - Heat exchangers
    - Valves
    - Expansion Turbines
    - Piping
    - Vacuum insulated
Brazed Plate Fin Heat Exchangers

- All aluminum
- Vacuum brazed
- Very compact
- High efficiency
- Can handle multiple streams
- Standard for cryogenic plants

From The Handbook of Cryogenic Engineering

Courtesy Linde
Expansion Turbines

- One of the key technologies for cryogenic plants
- Proprietary designs resulting from a significant amount of R&D
- Modern ones are quite reliable
- Water cooling is generally required to absorb work at room temperature
- May operate at speeds up to 120,000 rpm
- Two primary suppliers: Air Liquide and Linde
Examples of Expansion Turbines

Compressor Cooler
Brake Compressor
Turbine Cartridge
Turbine Wheel
Low Temperature Housing

Upper Radial Bearing
Speed Sensor
Axial Bearing
Lower Radial Bearing
Inlet filter

Inlet
Outlet

Courtesy Linde

Courtesy Air Liquide
Expansion Turbine Bearing Options
(Gas bearings are the most common now)

Oil Bearing

Static Gas Bearing

Dynamic Gas Bearing

Oil

Sealing Gas

To Compressor

To Compressor

Bearing Gas

Turbine

Turbine

Turbine

Courtesy Linde
Cold Boxes

Liquefier (cold box)
1. Vacuum-insulated cold box
2. Heat-exchanger bricks
3. 20 K adsorber
4. Turbo expanders
5. Genesis He inlet
6. Liquid He discharge
7. Liquid N$_2$ inlet (pre-cooling)

Typical Vertical Cold box
Courtesy Linde

CTI 4000 cold box
with vacuum vessel removed
Cold Boxes

4.5 K cold box at SNS
Major Components of a Helium Refrigeration Plant

- Main Distribution Box
  - Connects refrigeration plant with the distribution lines

- Storage vessels (LN2, LHe, GHe)

- Purifier: separate system that removes impurities from the helium space of the cryogenic system, including piping and items being cooled
  - Contamination control is very important to reliable operation

- Control System
  - Generally PLC based with a higher level HMI
  - Once fully commissioned, modern Helium refrigeration plants can operate autonomously 24/7