CRYOGENIC ENGINEERING

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Lecture No - 12
Earlier Lecture

- We studied the effect of the heat exchanger effectiveness $\varepsilon$ on the performance of a Linde – Hampson system.

- Mathematically,

$$\varepsilon = \frac{Q_{\text{act}}}{Q_{\text{max}}}$$

- In a Linde – Hampson cycle, the heat exchanger effectiveness $\varepsilon$ is also given by

$$\varepsilon = \frac{h_{1'} - h_g}{h_1 - h_g} \quad \text{or} \quad \varepsilon = \frac{h_3' - h_2}{h_3 - h_2}$$
• The liquid yield $y$ for a Linde – Hampson system is given by

$$y = \frac{(h_1 - h_2) - (1 - \varepsilon)(h_1 - h_g)}{(h_1 - h_f) - (1 - \varepsilon)(h_1 - h_g)}$$

• The effectiveness should be more than 85% in order to have a liquid yield in the Linde – Hampson cycle.
Outline of the Lecture

Topic: Gas Liquefaction and Refrigeration Systems (contd)

• Precooled Linde – Hampson system
  • Liquid yield
  • Work requirement
  • Maximum liquid yield

• Comparison between the Simple and Precooled Linde – Hampson systems
We have seen earlier that, as the compression temperature decreases, the yield $y$ increases for a Linde – Hampson system.

The method of cooling the gas after the compression or before the entrance to the heat exchanger is called as precooling.
• The Linde – Hampson cycle with a precooling arrangement is called as Precooled Linde – Hampson cycle.

• Here after, we refer these two cycles as Simple Linde – Hampson system and Precooled Linde – Hampson system respectively.
The Simple Linde – Hampson system is as shown in the figure.

A 3 fluid heat exchanger is used to thermally couple the precooling and the Linde – Hampson systems.

Hence, the temperature is lowered after compression or before the entry to the heat exchanger.
The features of the precooling system are as follows.

- It is a closed cycle refrigerator with the cold heat exchanger thermally coupled to the simple Linde – Hampson system.

- In other words, the cooling object for this refrigerator is the Linde – Hampson cycle.
Precooled L – H Cycle

- The heat exchanger of precooling system is cooled by water and J – T device is used to attain lower temperature.

- The process of compression is assumed to be adiabatic. Hence, $Q_R = 0$.

- R134a, NH$_3$, CO$_2$ are the common refrigerants in the precooling systems.
The salient features of a Precooled Linde – Hampson system are as follows:

- The system consists of a compressor, heat exchangers (2 and 3 – fluid) and a J – T expansion device.

- Compression process is isothermal (adiabatic in precooling system) while the J – T expansion is isenthalpic.
Precooled L – H Cycle

- All the processes are assumed to be ideal in nature and there are no pressure drops in the system.

- The heat exchangers are assumed to be 100% effective and the processes are isobaric in nature.
The gas to be liquefied by the liquefaction system is called as Primary Fluid.

Whereas, the refrigerant in the precooling system is called as Secondary Fluid.
Precooled L – H Cycle

\[ W_{c1} \]

\[ W_{c2} \]

\[ (m - \dot{m}_f) \]

\[ \dot{m}_f \]

\[ \dot{m}_r \]

1. Precooling
2. Temp.
3. \( p = \text{const} \)
4. \( h = \text{const} \)
5. 4
6. \[ f \]

\[ g \]
The precooling limit of the precooling cycle is governed by the boiling point of refrigerant at its suction pressure.

Boiling point of the common refrigerants at 1 bar are

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Boiling Pt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>216.6 K</td>
</tr>
<tr>
<td>NH₃</td>
<td>240 K</td>
</tr>
<tr>
<td>R134a</td>
<td>247 K</td>
</tr>
</tbody>
</table>
Precooled L – H Cycle

- Consider a control volume for this system as shown in the figure.

- It encloses the 3 fluid heat exchanger, J – T device and the liquid container.

- The 1st Law is applied to analyse the system. The changes in the velocities and datum levels are assumed to be negligible.
Precooled L – H Cycle

- The quantities entering and leaving the control volume are as follows.

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_r \ @ \ d$</td>
<td>$m_r \ @ \ a$</td>
</tr>
<tr>
<td>$m \ @ \ 2$</td>
<td>$m - m_f \ @ \ 1$</td>
</tr>
<tr>
<td>$m_f \ @ \ f$</td>
<td></td>
</tr>
</tbody>
</table>

- Applying the 1st law, we have

$$\dot{m}_r h_{d,r} + \dot{m} h_2 = \dot{m}_r h_{a,r} + (m - m_f) h_1 + m_f h_f$$
Precooled L – H Cycle

\[ \dot{m}_r h_{d,r} + \dot{m} h_2 = \dot{m}_r h_{a,r} + (\dot{m} - \dot{m}_f) h_1 + \dot{m}_f h_f \]

• Rearranging the terms, we have

\[ \frac{\dot{m}_f}{\dot{m}} = \left( \frac{h_1 - h_2}{h_1 - h_f} \right) + \frac{\dot{m}_r}{\dot{m}} \left( \frac{h_{a,r} - h_{d,r}}{h_1 - h_f} \right) \]

• Denoting the ratio

\[ \frac{\dot{m}_r}{\dot{m}} = r \]
We have,

\[
y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f} + r \left( \frac{h_{a,r} - h_{d,r}}{h_1 - h_f} \right)
\]

The first term in the above expression is the yield for a simple Linde – Hampson system.

The second term is the additional yield occurring due to the precooling of the Simple system.
Precooled L – H Cycle

\[ y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f} + r \left( \frac{h_{a,r} - h_{a,r}}{h_1 - h_f} \right) \]

- This increment in the yield is dependent on the
- The change in enthalpy values from \((h_d \rightarrow h_a)\) of the refrigerant.
- Refrigerant flow rate \((m_r)\).
Precooled L – H Cycle

• Since, the 3 – fluid heat exchanger is assumed to be 100% effective, the following conditions hold true.

• The minimum value of $T_3$ would be equal to $T_{d_r}$, which is the boiling point of the refrigerant.

• The maximum value of $T_6$ would be equal to $T_{d_r}$, which is the boiling point of the refrigerant.
Precooled L – H Cycle

- At this condition, the system produces the maximum yield for a given refrigerant.

- Mathematically,
  \[
  y = y_{\text{max}} \quad \text{for} \quad T_3 = T_6 = T_d
  \]

- Consider a control volume enclosing the heat exchanger, J – T device and the liquid container as shown in the figure.
Precooled L – H Cycle

• The quantities entering and leaving the control volume are as follows.

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m ) @ 3</td>
<td>( m_f ) @ ( f )</td>
</tr>
<tr>
<td>( m - m_f ) @ 6</td>
<td></td>
</tr>
</tbody>
</table>

• Applying the 1\text{st} law, we have

\[ \dot{m}h_3 = \dot{m}_f h_f + (\dot{m} - \dot{m}_f) h_6 \]
Precooled L – H Cycle

• Rearranging the terms, we have

\[ \dot{m}_f \left( h_6 - h_f \right) = \dot{m} \left( h_6 - h_3 \right) \]

• The quantities \( h_3 \) and \( h_6 \) are evaluated at the boiling point of the refrigerant \( (T_d) \).
Consider a control volume for the compressor in the liquefaction cycle as shown in the figure.

The quantities entering and leaving this control volume are as given below.

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>m @ 1</td>
<td>m @ 2</td>
</tr>
<tr>
<td>-W_{c1}</td>
<td>-Q_{R}</td>
</tr>
</tbody>
</table>
Using 1st Law for the following table, we get

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</thead>
<tbody>
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<td>m @ 1</td>
<td>m @ 2</td>
</tr>
<tr>
<td>-W_{c1}</td>
<td>-Q_{R}</td>
</tr>
</tbody>
</table>

\[ E_{in} = E_{out} \]

\[ m h_1 - W_{c1} = m h_2 - Q_{R} \]

Rearranging the terms, we have

\[ Q_{R} - W_{c1} = m (h_2 - h_1) \]
The heat of compression $Q_R$ can be obtained by using the 2nd Law for an isothermal compression. It is given by,

$$Q_R - W_{c1} = \dot{m}(h_2 - h_1)$$

- Combining the above equations, we have

$$-W_{c1} = \dot{m}T_1(s_1 - s_2) - \dot{m}(h_1 - h_2)$$
Similarly, a control volume is taken enclosing the refrigerating compressor.

The quantities entering and leaving this control volume are as given below.

<table>
<thead>
<tr>
<th>IN</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_r ) @ a</td>
<td>(m_r ) @ b</td>
</tr>
<tr>
<td>(-W_{c2})</td>
<td>0</td>
</tr>
</tbody>
</table>

The heat of compression is zero because the process is adiabatic.
Using 1st Law for the following table, we get

<table>
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<tbody>
<tr>
<td>m_r @ a</td>
<td>m_r @ b</td>
</tr>
<tr>
<td>-W_{c2}</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ E_{in} = E_{out} \]

\[ \dot{m}_r h_{a,r} - W_{c2} = \dot{m}_r h_{b,r} \]

Rearranging the terms, we have

\[ -W_{c2} = \dot{m}_r (h_{b,r} - h_{a,r}) \]
Precooled L – H Cycle

• The total work requirement for this system is

\[ W_c = W_{c1} + W_{c2} \]

• Substituting the following values, we have

\[ -W_{c1} = \dot{m}T_1(s_1 - s_2) - \dot{m}(h_1 - h_2) \]

\[ -W_{c2} = \dot{m}_r(h_{b,r} - h_{a,r}) \]

\[ -W_c = \dot{m}T_1(s_1 - s_2) - \dot{m}(h_1 - h_2) + \dot{m}_r(h_{b,r} - h_{a,r}) \]
Precooled L – H Cycle

The work required for a unit mass of primary gas compressed is given as

\[-W_c = \dot{m}T_1(s_1 - s_2) - \dot{m}(h_1 - h_2) + \dot{m}_r(h_{b,r} - h_{a,r})\]

\[-\frac{W_c}{\dot{m}} = T_1(s_1 - s_2) - (h_1 - h_2) + \frac{\dot{m}_r}{\dot{m}}(h_{b,r} - h_{a,r})\]
Precooled L – H Cycle

• Denoting the ratio

\[ \frac{\dot{m}_r}{\dot{m}} = r \]

\[ -\frac{W_c}{\dot{m}} = T_1 (s_1 - s_2) - (h_1 - h_2) \]

\[ + \frac{\dot{m}_r}{\dot{m}} (h_{b,r} - h_{a,r}) \]

\[ -\frac{W_c}{\dot{m}} = T_1 (s_1 - s_2) - (h_1 - h_2) \]

\[ + r (h_{b,r} - h_{a,r}) \]
The first and second terms are the work requirement in a Simple Linde – Hampson system.

The third term is the additional work required to precool the system.
Tutorial – 1

• Determine the $y$, $y_{\text{max}}$, the work/unit mass compressed, work/unit mass liquefied and FOM for the Simple and Precooled Linde – Hampson systems with Nitrogen as working fluid. The R134A is the refrigerant for the precooling system with ratio $r$ as 0.08. The liquefaction system is operated between 1.013 bar (1 atm) and 101.3 bar (100 atm) at 300 K. The following is the data for R134a. Comment on the results.

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$ (bar)</td>
<td>1.013</td>
<td>10.13</td>
<td>10.13</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>300</td>
<td>373</td>
<td>300</td>
</tr>
<tr>
<td>$h$ (J/g)</td>
<td>390</td>
<td>482</td>
<td>260</td>
</tr>
</tbody>
</table>
## Tutorial – 1

### Given

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Simple and Precooled L – H System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Fluid</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>Pressure</td>
<td>1 atm → 100 atm</td>
</tr>
<tr>
<td>Temperature</td>
<td>300 K</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>R134a, 1 atm → 10 atm</td>
</tr>
<tr>
<td>Mass ratio(r)</td>
<td>0.08</td>
</tr>
</tbody>
</table>

### For above cycles, Calculate and comment

<table>
<thead>
<tr>
<th></th>
<th>1 Liquid Yield $y$, $y_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Work/unit mass of gas compressed</td>
</tr>
<tr>
<td>3</td>
<td>Work/unit mass of gas liquefied</td>
</tr>
<tr>
<td>4</td>
<td>FOM</td>
</tr>
</tbody>
</table>
### Tutorial – 1

<table>
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<th></th>
<th>a</th>
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<tbody>
<tr>
<td>(p \text{ (bar)})</td>
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<td>101.3</td>
<td>1.013</td>
</tr>
<tr>
<td>(T \text{ (K)})</td>
<td>300</td>
<td>300</td>
<td>77</td>
</tr>
<tr>
<td>(h \text{ (J/g)})</td>
<td>462</td>
<td>445</td>
<td>29</td>
</tr>
<tr>
<td>(s \text{ (J/gK)})</td>
<td>4.42</td>
<td>3.1</td>
<td>0.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th>e</th>
<th>f</th>
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<td>(s \text{ (J/gK)})</td>
<td></td>
<td></td>
<td><strong>R134a</strong></td>
</tr>
</tbody>
</table>

- \(h_d = h_c\), since the expansion is isenthalpic.
Tutorial – 1

• Ideal Work Requirement

\[
-W_i = T_1 (s_1 - s_f) - (h_1 - h_f)
\]

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<td>3.1</td>
<td>0.42</td>
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</table>

\[
-W_c = \frac{100}{m} \left( 4.42 - 0.42 \right) - \left( 462 - 29 \right) = 767 \text{ J/g}
\]
- Liquid yield

\[ y = \left( \frac{h_1 - h_2}{h_1 - h_f} \right) \]

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</table>

\[ y = \left( \frac{462 - 445}{462 - 29} \right) = \left( \frac{17}{433} \right) = 0.04 \]
Tutorial – 1

• Work/unit mass of gas compressed

\[
-\frac{W_c}{\dot{m}} = T_1 (s_1 - s_2) - (h_1 - h_2)
\]

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</table>

\[
-\frac{W_c}{\dot{m}} = 300(4.42 - 3.1) - (462 - 445) = 379 \ J / g
\]
Tutorial – 1

- Work/unit mass of gas liquefied

\[- \frac{W_c}{m} = 379\]

\[y = 0.04\]

\[- \frac{W_c}{m_f} = - \frac{W_c}{ym} = \frac{379}{0.04} = 9475 \text{ J/g}\]
Figure of Merit (FOM)

\[ \frac{W_c}{m_f} = 9475 \]

\[ \frac{W_i}{m_f} = 767 \]

\[ FOM = \frac{W_i}{m_f} / \frac{W_c}{m_f} = \frac{767}{9475} = 0.081 \]
Tutorial – 1

• The T – s diagram for a Precooled Linde – Hampson system is as shown.

• The state properties are as tabulated below.

<table>
<thead>
<tr>
<th></th>
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</tr>
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<tbody>
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Tutorial – 1

• Liquid yield

\[ y = \frac{\dot{m}_f}{\dot{m}} = \frac{h_1 - h_2}{h_1 - h_f} + r \left( \frac{h_{a,r} - h_{d,r}}{h_1 - h_f} \right) \]

\[ r = 0.08 \]

<table>
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<td>s (J/gK)</td>
<td>4.42</td>
<td>3.1</td>
<td>0.42</td>
<td>R134a</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ y = \frac{(462 - 445)}{(462 - 29)} + 0.08 \frac{(390 - 260)}{(462 - 29)} = \frac{(17)}{(433)} + 0.08 \frac{(130)}{(433)} = 0.063 \]
Tutorial – 1

- Work/unit mass of \( \text{N}_2 \) compressed

\[
\frac{W_c}{m} = \frac{1}{m} \left( T_1 (s_1 - s_2) - (h_1 - h_2) + r(h_{b,r} - h_{a,r}) \right)
\]

\[ r = 0.08 \]

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\[
\frac{W_c}{m} = 300(4.42 - 3.1) - (462 - 445) + 0.08(482 - 390) = 386.3 \text{ J/g}
\]

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Tutorial – 1

- Work/unit mass of \( \text{N}_2 \) liquefied

\[
\frac{-W_c}{\dot{m}} = 386.3
\]

\[
y = 0.063
\]

\[
\frac{-W_c}{\dot{m}_f} = \frac{-W_c}{y \dot{m}} = \frac{386.3}{0.063} = 6131.7 \text{ J/g}
\]
• Figure of Merit (FOM)

\[
\frac{-W_c}{\dot{m}_f} = 6131.7 \quad \text{and} \quad \frac{-W_i}{\dot{m}_f} = 767
\]

\[
FOM = \frac{\frac{W_i}{\dot{m}_f}}{\frac{W_c}{\dot{m}_f}} = \frac{767}{6131.7} = 0.1251
\]
Tutorial – 1

• Maximum Liquid yield

\[ y = y_{\text{max}} \quad T_3 = T_6 = T_d = 247 \, K \]

\[ y_{\text{max}} = \frac{h_6 - h_3}{h_6 - h_f} \]

\[ r = 0.08 \]

<table>
<thead>
<tr>
<th></th>
<th>3</th>
<th>6</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>p (bar)</td>
<td>101.3</td>
<td>1.013</td>
<td>1.013</td>
</tr>
<tr>
<td>T (K)</td>
<td>247</td>
<td>247</td>
<td>77</td>
</tr>
<tr>
<td>h (J/g)</td>
<td>380</td>
<td>408</td>
<td>29</td>
</tr>
</tbody>
</table>

\[ y_{\text{max}} = \frac{(408 - 380)}{(408 - 29)} = \frac{(28)}{(379)} = 0.074 \]
### Tutorial – 1

<table>
<thead>
<tr>
<th></th>
<th>Simple</th>
<th>Precooled</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y$</td>
<td>0.04</td>
<td>0.063</td>
<td>0.074</td>
</tr>
<tr>
<td>$-\frac{W_c}{\dot{m}}$</td>
<td>379</td>
<td>386.3</td>
<td>386.3</td>
</tr>
<tr>
<td>$-\frac{W_c}{\dot{m}_f}$</td>
<td>9475</td>
<td>6131.7</td>
<td>5220.2</td>
</tr>
<tr>
<td>$FOM$</td>
<td>0.081</td>
<td>0.1251</td>
<td>0.147</td>
</tr>
</tbody>
</table>

- Tabulating the results, we have the above comparison for Simple and Precooled Linde–Hampson System.
Assignment

1. Compare and comment on the following for both Simple and Precooled Linde – Hampson systems with Air as working fluid when the system is operated between 1.013 bar (1 atm) and 202.6 bar (200 atm) at 300 K. The effectiveness of HX is 100% and \( r = 0.1 \).

- Ideal Work requirement
- Liquid yield
- Work/unit mass compressed
- Work/unit mass liquefied
- FOM
Summary

• The method of cooling the gas after the compression or before the entrance to the heat exchanger is called as precooling.

• The Linde – Hampson cycle with a precooling arrangement is called as Precooled Linde – Hampson cycle.

• In a Precooled Linde – Hampson system, a closed cycle refrigerator is thermally coupled to a simple Linde – Hampson system through a 3 – fluid heat exchanger.
Summary

• Compression process is isothermal in Liquefaction cycle but it is adiabatic in precooling system of a Precooled Linde – Hampson system.

• The precooling limit of the precooling cycle is governed by the boiling point of refrigerant at its suction pressure.

• The yield for a Precooled Linde – Hampson system is

\[
\frac{m_f}{m} = \frac{h_1 - h_2}{h_1 - h_f} + r \left( \frac{h_{a,r} - h_{d,r}}{h_1 - h_f} \right)
\]

\[
\frac{m_r}{m} = r
\]
The maximum liquid yield is given by the above expression. The enthalpy values are evaluated at the boiling point of the refrigerant.

The work requirement for the unit mass of primary fluid compressed is

\[-\frac{W_c}{\dot{m}} = T_1 (s_1 - s_2) - (h_1 - h_2) + r (h_{b,r} - h_{a,r})\]

From the tutorial, the yield of the precooled system is more than that of a simple system.
Thank You!