Hybrid Heat Pump Solutions for Industrial Energy Savings

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Thermal Energy Section
Agenda

• Introduction to the hybrid absorption compression heat pump
• Advantages of zeotropic mixtures specifically NH₃/H₂O
• Evaluation of important design parameters.
• Prospect for high temperature development \( T_{supply} < 110^\circ C \).
• Conclusion & future work
The Hybrid Heat Pump

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

\[ \dot{Q}_{abs} \]

\[ m_{vapour} \]

\[ m_{vapour} \]

\[ m_{rich} \]

\[ Q_{IHEX} \]

\[ m_{lean} \]

\[ W_{pump} \]

\[ W_{comp} \]

\[ Q_{des} \]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the vapor pressure of zeotropic mixtures over temperature for different compositions (x=0.0 to x=1.0). The graph highlights the temperature range from 63°C to 230°C for R717 and 155°C to 330°C for R718. The critical point is indicated at 130 bar and 28 bar for R717 and R718 respectively.]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Temperature [°C]

Sink

Source

Heat Load [kW]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

<table>
<thead>
<tr>
<th>Source Temperature [°C]</th>
<th>Heat Load [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Refrigerant</td>
<td></td>
</tr>
<tr>
<td>Pure Refrigerant</td>
<td></td>
</tr>
</tbody>
</table>

Sink
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

<table>
<thead>
<tr>
<th>Pure Refrigerant</th>
<th>Zeotropic Mixture</th>
<th>Zeotropic Mixture</th>
<th>Pure Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sink Temperature [°C]</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source Temperature [°C]</td>
<td></td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Heat Load [kW]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\(x=0.9\)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.8 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.7 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x = 0.6 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x = 0.3 \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)

\( Q \ [\text{[kW]}] \)

\( T \ [\text{[\degree C]}] \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( T \ [^\circ \text{C}] \)

\( x=0.3 \)

\( Q \ [\text{kW}] \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ T \text{ [°C]} \]
\[ \dot{Q} \text{ [kW]} \]

\( x=0.2 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.1 \]

\[ T \text{ [°C]} \]

\[ Q \text{ [kW]} \]
The Hybrid Heat Pump: Design parameters $x_r$ & $f$

Diagram of the Hybrid Heat Pump system:

- **Absorber** with mass flow $\dot{m}_\text{rich}$
- **Desorber**
- **IHEX**
- **Liquid/vapour separator**
- **Mixer**
- **Pump** with power input $\dot{W}_\text{pump}$
- **Compressor** with power input $\dot{W}_\text{comp}$

Key equations:

- $\dot{Q}_\text{abs}$
- $\dot{Q}_\text{IHEX}$
- $\dot{Q}_\text{des}$
- $m_\text{lean}$
- $\dot{m}_\text{vapour}$
Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$

Inputs and Assumptions

<table>
<thead>
<tr>
<th>External Inputs</th>
<th>Internal Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{sink, in} = 80^\circ C$</td>
<td>$\Delta T_{pinch, abs} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{sink, out} = 110^\circ C$</td>
<td>$\Delta T_{pinch, des} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{source, in} = 80^\circ C$</td>
<td>$\eta_{is, comp} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{sink} = 1$kg/s</td>
<td>$\eta_{is, pump} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{source} = 10$kg/s</td>
<td>$\epsilon_{IHEX} = 0.8$</td>
</tr>
</tbody>
</table>

Pressure drops are neglected.
Influence of $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink, out} = 110^{\circ}C$, $\Delta T_{lift} = 40^{\circ}C$
Influence of $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 50^\circ C$
Working domain hybrid heat pumps

Constraints corresponding to standard refrigeration components

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th>COP $&gt; 4[−]$</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_H$ $&lt; 25[bar]$</td>
<td>Standard refrigeration equipment</td>
<td></td>
</tr>
<tr>
<td>$P_L$ $&gt; 1[bar]$</td>
<td>No entrainment of air from ambient</td>
<td></td>
</tr>
<tr>
<td>$VHC$ $&gt; 2[MJ/m^3]$</td>
<td>Economic $(\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp})$</td>
<td></td>
</tr>
<tr>
<td>$T_H$ $&lt; 160[^{°}C]$</td>
<td>Thermal stability of oil</td>
<td></td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

\[ T_{\text{out}} = 110[^{\circ}\text{C}] \quad T_{\text{lift}} = 30[^{\circ}\text{C}] \]

Possible design options

COP < 4[−]
Working domain hybrid heat pumps

\[ T_{\text{out}} = 110[^\circ \text{C}] \quad T_{\text{lift}} = 30[^\circ \text{C}] \]
Working domain hybrid heat pumps

$T_{\text{out}} = 110[^\circ\text{C}]$  $T_{\text{lift}} = 30[^\circ\text{C}]$
Working domain hybrid heat pumps

\[ T_{\text{out}} = 110[^{\circ}\text{C}] \quad T_{\text{lift}} = 30[^{\circ}\text{C}] \]

Possible design options
- \( \text{COP} < 4 \)
- \( P_H > 25[^{\text{bar}}] \)
- \( P_L < 1[^{\text{bar}}] \)
- \( \text{VHC} < 2[^{\text{MJ/m}^3}] \)
Working domain hybrid heat pumps

\[ T_{\text{out}} = 110[^\circ C] \quad T_{\text{lift}} = 30[^\circ C] \]

Possible design options:
- \( \text{COP} < 4 [-] \)
- \( P_H > 25 [\text{bar}] \)
- \( P_L < 1 [\text{bar}] \)
- \( \text{VHC} < 2 [\text{MJ/m}^3] \)
- \( T > 160[^\circ C] \)
Working domain hybrid heat pumps

Constraints corresponding to supercritical CO$_2$ refrigeration components and new synthetic oils

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$</td>
<td>$&gt; 4[-]$</td>
</tr>
<tr>
<td>$P_H$</td>
<td>$&lt; 130[bar]$</td>
</tr>
<tr>
<td>$P_L$</td>
<td>$&gt; 1[bar]$</td>
</tr>
<tr>
<td>$V_HC$</td>
<td>$&gt; 4[M J/m^3]$</td>
</tr>
<tr>
<td>$T_H$</td>
<td>$&lt; 250[^\circ C]$</td>
</tr>
</tbody>
</table>

Economic

Standard refrigeration equipment

No entrainment of air from ambient

Economic ($\dot{Q}_{abs}/\dot{V}_{suc,comp}$)

Thermal stability of oil
Working domain hybrid heat pumps

\[ T_{\text{out}} = 110[^\circ\text{C}] \quad T_{\text{lift}} = 30[^\circ\text{C}] \]
Working domain hybrid heat pumps

$T_{\text{out}} = 110[^\circ\text{C}] \quad T_{\text{lift}} = 30[^\circ\text{C}]$

Possible design options
- $\text{COP} < 4$ [−]
- $P_H > 130$ [bar]
Working domain hybrid heat pumps

\[ T_{\text{out}} = 110[^{\circ}\text{C}] \quad T_{\text{lift}} = 30[^{\circ}\text{C}] \]
**Working domain hybrid heat pumps**

\[ T_{\text{out}} = 110[^\circ C] \quad T_{\text{lift}} = 30[^\circ C] \]

Possible design options:
- COP < 4
- \( P_H > 130[^\text{bar}] \)
- \( P_L < 1[^\text{bar}] \)
- \( VHC < 4[^\text{MJ/m}^3] \)
Working domain hybrid heat pumps

\[ T_{out} = 110[^\circ C] \quad T_{lift} = 30[^\circ C] \]
Working domain hybrid heat pumps: $T_{sink,out}$

$T_{out}=120[^\circ C]$ $T_{lift}=30[^\circ C]$
Working domain hybrid heat pumps: $T_{sink, out}$

$T_{out}=130[^{\circ}C] \quad T_{lift}=30[^{\circ}C]$

Possible design options:
- COP $< 4$ [−]
- $P_H > 130$ [bar]
- $P_L < 1$ [bar]
- VHC $< 4$ [MJ/m$^3$]
- $T > 250[^{\circ}C]$
Working domain hybrid heat pumps: $T_{\text{sink,out}}$

$$T_{\text{out}} = 140[\degree C] \quad T_{\text{lift}} = 30[\degree C]$$

Possible design options:
- $\text{COP} < 4[-]$
- $P_H > 130[\text{bar}]$
- $P_L < 1[\text{bar}]$
- $VHC < 4[\text{MJ/m}^3]$
- $T > 250[\degree C]$
Working domain hybrid heat pumps: $T_{sink, out}$

$T_{out} = 150[\degree C]$  $T_{lift} = 30[\degree C]$
Working domain hybrid heat pumps: $T_{sink,out}$

$T_{out} = 160[^\circ C]$  $T_{lift} = 30[^\circ C]$
Working domain hybrid heat pumps: $T_{sink, out}$

$T_{out} = 170[\degree C]$  $T_{lift} = 30[\degree C]$
Working domain hybrid heat pumps: $T_{\text{sink, out}}$

$T_{\text{out}} = 180[^\circ\text{C}]$ $T_{\text{lift}} = 30[^\circ\text{C}]$

Possible design options:
- COP $< 4$ [-]
- $P_H > 130$ [bar]
- $P_L < 1$ [bar]
- VHC $< 4$ [MJ/m$^3$]
- $T > 250[^\circ\text{C}]$
Working domain hybrid heat pumps: $T_{sink, out}$

$T_{out} = 190[^\circ C]$ $T_{lift} = 30[^\circ C]$
Working domain hybrid heat pumps: $T_{sink,\text{out}}$

$T_{\text{out}} = 200[^\circ\text{C}]$  $T_{\text{lift}} = 30[^\circ\text{C}]$

Possible design options

- COP $< 4$ [-]
- $P_H > 130$ [bar]
- $P_L < 1$ [bar]
- VHC $< 4$ [MJ/m$^3$]
- $T > 250[^\circ\text{C}]$
Working domain hybrid heat pumps: $\Delta T_{lift}$

$T_{out} = 180[^\circ C] \quad T_{lift} = 30[^\circ C]$
Working domain hybrid heat pumps: $\Delta T_{lift}$

$T_{out}=180[^\circ C] \ T_{lift}=35[^\circ C]$
Working domain hybrid heat pumps: $\Delta T_{lift}$

$T_{out}=180[^{\circ}C]$ $T_{lift}=40[^{\circ}C]$
Working domain hybrid heat pumps: $\Delta T_{lift}$

$T_{out} = 180[^\circ C]$ $T_{lift} = 45[^\circ C]$
Working domain hybrid heat pumps: $\Delta T_{lift}$

$T_{out} = 180[^\circ C]$  $T_{lift} = 50[^\circ C]$
Future work

• Heat transfer characteristics, influence of $x_r$.
• Identification of suitable oils.
• Material compatibility with NH$_3$/H$_2$O should be investigated.
• Two-stage concepts should be evaluated, this could reduce compressor discharge temperature and increase COP.
• Thermoeconomic analysis and optimization should be applied to find cost efficient designs.
Conclusion

- COP and design parameters are highly dependent on $x_r$ and $f$.
- Standard refrigeration components can be used upto 110[°C].
- Supercritical CO$_2$ components can be used upto 200[°C].
- $\Delta T_{lift}$ upto 45[°C] can be attained.
- Dominating constraint is the compressor discharge temperature.
- Hence thermal stability of oil should be tested.
- Case studies should be performed to show the feasibility of the hybrid heat pump implementation.
Thank you for your attention. Questions?