Hybrid Heat Pump Solutions for Industrial Energy Savings

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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 NH$_3$/H$_2$O
• Evaluation of important design parameters.
• Prospect for high temperature development $T_{supply} < 110^\circ$C.
• Conclusion & future work
The Hybrid Heat Pump

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

\[ m_{\text{vapour}} \rightarrow W_{\text{comp}} \]

\[ Q_{IHEX} \]

\[ m_{\text{rich}} \rightarrow \text{Absorber} \]

\[ \text{Mixer} \]

\[ \text{IHEX} \]

\[ \text{Desorber} \]

\[ m_{\text{lean}} \]

\[ m_{\text{vapour}} \rightarrow W_{\text{pump}} \]

\[ \dot{Q}_{\text{des}} \]

\[ \text{Liquid/vapour separator} \]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the relationship between temperature and vapor pressure for zeotropic mixtures. The graph includes curves for different compositions (x=0.0 to x=1.0) and highlights the critical point. The mixtures R717 and R718 are indicated.]
Advantages of Zeotropic Mixtures

Reduction of Vapor Pressure
Advantages of Zeotropic Mixtures

Reduction of Vapor Pressure

![Graph showing the temperature and vapor pressure relationship for R717 and R718 mixtures.](graph)

- **R717**
  - Temperature: 63-230°C
  - Vapor Pressure: 28 bar

- **R718**
  - Temperature: 155-330°C
  - Vapor Pressure: 130 bar

The graph illustrates the critical points for each mixture, showing how the vapor pressure changes with temperature.
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Graph showing temperature vs. heat load for a sink and source system.](image-url)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

- Pure Refrigerant

Heat Load [kW]
Temperature [°C]

Sink
Source

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

<table>
<thead>
<tr>
<th>Sink</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature [°C]</td>
<td>Heat Load [kW]</td>
</tr>
<tr>
<td>Pure Refrigerant</td>
<td>Zeotropic Mixture</td>
</tr>
<tr>
<td>Reduced ΔT =&gt; Reduced Entropy Generation</td>
<td></td>
</tr>
</tbody>
</table>

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.9 \]

\[ T [^\circ C] \]

\[ Q [kW] \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x = 0.8 \)

\( T \text{ [°C]} \)

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

Absorber

\[ T \ [\degree C] \]
\[ Q \ [\text{kW}] \]

\( x = 0.7 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

$\dot{Q}$ [kW] vs. $T$ [°C]

$\times=0.6$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

\[ x=0.5 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

$x = 0.3$

$\dot{Q} [kW]$ vs. $T [^\circ C]$ for $x = 0.3$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

\[x = 0.3\]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( T \text{ [°C]} \)

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

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

Absorber

\( T [^\circ C] \)

\( Q [kW] \)

x=0.1

0 20 40 60 80 100

0 50 60 70 80 90 100

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The Hybrid Heat Pump: Design parameters $x_r$ & $f$
Influence of \( x_r \) & \( f \): \( T_{\text{sink, out}} = 110^\circ C, \Delta T_{\text{lift}} = 30^\circ C \)

Inputs and Assumptions

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

Pressure drops are neglected.
Influence of $x_r$ & $f$:

$T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r \ & f$: $T_{sink.out} = 110^\circ C, \Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$  &gt;  4$[-]$</td>
</tr>
<tr>
<td>$P_H$  &lt;  25[bar]</td>
</tr>
<tr>
<td>$P_L$  &gt;  1[bar]</td>
</tr>
<tr>
<td>$VHC$  &gt;  2[MJ/m$^3$]</td>
</tr>
<tr>
<td>$T_H$  &lt;  160[°C]</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

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

Plot showing possible design options:
- \( \text{COP} < 4 \) in cyan
- \( P_H > 25 \) bar in red
- \( P_L < 1 \) bar in blue

\( x_r \) in [kg/kg] on the x-axis,
\( f \) in [-] on the y-axis.
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
- \( P_H > 25 \text{[bar]} \)
- \( P_L < 1 \text{[bar]} \)
- \( \text{VHC} < 2 \text{[MJ/m}^3\text{]} \)
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

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

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th>COP</th>
<th>$&gt; 4[-]$</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_H$</td>
<td>$&lt; 130[bar]$</td>
<td></td>
<td>Standard refrigeration equipment</td>
</tr>
<tr>
<td>$P_L$</td>
<td>$&gt; 1[bar]$</td>
<td></td>
<td>No entrainment of air from ambient</td>
</tr>
<tr>
<td>$V HC$</td>
<td>$&gt; 4[MJ/m^3]$</td>
<td></td>
<td>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</td>
</tr>
<tr>
<td>$T_H$</td>
<td>$&lt; 250[^\circ C]$</td>
<td></td>
<td>Thermal stability of oil</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

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

Possible design options
- COP < 4
- $P_H > 130$ bar
Working domain hybrid heat pumps

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

Possible design options:
- \( \text{COP} < 4 \)
- \( P_H > 130 \text{[bar]} \)
- \( P_L < 1 \text{[bar]} \)

\[ x_r \text{[kg/kg]} \]

\[ f \]
Working domain hybrid heat pumps

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

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

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

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

\[ T_{out} = 120[^\circ C] \quad T_{lift} = 30[^\circ C] \]

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

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

Possible design options:
- $\text{COP} < 4[-]$,
- $P_H > 130[\text{bar}]$,
- $P_L < 1[\text{bar}]$,
- $VHC < 4[\text{MJ/m}^3]$,
- $T > 250[^\circ C]$.

$\rho_r [\text{kg/kg}]$
Working domain hybrid heat pumps: $T_{sink,out}$

$$T_{out} = 140^\circ C \quad T_{lift} = 30^\circ C$$

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: $T_{sink,out}$

$T_{out} = 150[^\circ C]$ $T_{lift} = 30[^\circ C]$

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: $T_{sink, out}$

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

\[
T_{out} = 170[^\circ C] \quad T_{lift} = 30[^\circ C]
\]

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

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

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: $T_{sink,out}$

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

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

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

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

$T_{out} = 180[^\circ C]$  $T_{lift} = 35[^\circ C]$

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: \( \Delta T_{\text{lift}} \)

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

$T_{out} = 180[^{\circ}\text{C}]$  $T_{lift} = 45[^{\circ}\text{C}]$

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

$T_{out} = 180[^{\circ}\text{C}]$  $T_{lift} = 50[^{\circ}\text{C}]$
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 $x_T$ 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?