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

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

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

\[ m_{\text{vapour}} \]

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

\[ Q_{\text{IHEX}} \]

\[ Q_{\text{des}} \]

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

\[ W_{\text{pump}} \]

\[ W_{\text{comp}} \]

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

\[ m_{\text{lean}} \]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

The diagram illustrates the vapor pressure of zeotropic mixtures as a function of temperature for different compositions, denoted by $x$. The x-axis represents temperature in °C, ranging from 0 to 400, and the y-axis represents vapor pressure in bar, ranging from 0 to 220. The diagram shows multiple curves corresponding to different compositions, with $x=0.0$ to $x=1.0$, each curve indicating the vapor pressure at a specific temperature. The critical point is also indicated on the diagram.
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing vapor pressure and temperature relationships for zeotropic mixtures, with curves representing different compositions (x) and critical temperatures.]

- Temperature Range 63-230°C
- Temp. Range 155-330°C
- Vapor Pressure Range 28-130 bar

R717 → x=0.0
R718 ← x=1.0

x=0.0
x=0.1
x=0.2
x=0.3
x=0.4
x=0.5
x=0.6
x=0.7
x=0.8
x=0.9
x=1.0

Critical

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

- Pure Refrigerant
- Sink
- Source

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

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

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Reduced $\Delta T \Rightarrow$ Reduced Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.9 \]

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

\[ Q \text{ [kW]} \]
\[ T \text{ [°C]} \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( T \ [\degree C] \)

\( x=0.8 \)

\( Q \ [kW] \)

\( 0 \)

\( 100 \)

\( 50 \)

\( 70 \)

\( 90 \)

\( 100 \)

\( 0 \)

\( 20 \)

\( 40 \)

\( 60 \)

\( 80 \)

\( 100 \)

\( 0 \)

\( 20 \)

\( 40 \)

\( 60 \)

\( 80 \)

\( 100 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

Absorber

\[ T \text{ [\degree C]} \]
\[ Q \text{ [kW]} \]
\[ x=0.6 \]

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

$x = 0.3$

\[ T [\degree C] \]

\[ Q [kW] \]

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x=0.3 \)

\( T \text{ [°C]} \)

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

\( x=0.3 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

Absorber

\( x=0.1 \)

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

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

Inputs and Assumptions

<table>
<thead>
<tr>
<th>External Inputs</th>
<th>Internal Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{sink,\text{in}} = 80^\circ C$</td>
<td>$\Delta T_{\text{pinch},\text{abs}} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{sink,\text{out}} = 110^\circ C$</td>
<td>$\Delta T_{\text{pinch},\text{des}} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{source,\text{in}} = 80^\circ C$</td>
<td>$\eta_{is,\text{comp}} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{sink} = 1\text{kg/s}$</td>
<td>$\eta_{is,\text{pump}} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{source} = 10\text{kg/s}$</td>
<td>$\epsilon_{IHEX} = 0.8$</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 $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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 $x_r \& f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$

[COP, PH, PL, PR, TH, VHC] plots for different $x_r$ values.
Influence of $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 40^\circ C$
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>Economic</th>
<th>Standard refrigeration equipment</th>
<th>No entrainment of air from ambient</th>
<th>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</th>
<th>Thermal stability of oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$</td>
<td>$&gt; 4[-]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_H$</td>
<td>$&lt; 25[bar]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_L$</td>
<td>$&gt; 1[bar]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V_{HC}$</td>
<td>$&gt; 2[MJ/m^3]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_H$</td>
<td>$&lt; 160[^\circ C]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

Possible design options

\[ \text{COP} < 4 [-] \]
Working domain hybrid heat pumps

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

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

Possible design options

- \( \text{COP} < 4[-] \)
- \( P_H > 25[\text{bar}] \)
- \( P_L < 1[\text{bar}] \)

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

\[ f [-] \]
Working domain hybrid heat pumps

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

Possible design options:
- \( \text{COP} < 4 \)[−]
- \( P_H > 25[\text{bar}] \)
- \( P_L < 1[\text{bar}] \)
- \( \text{VHC} < 2[\text{MJ/m}^3] \)
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>Economic</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>$&gt; 4[MJ/m^3]$</td>
</tr>
<tr>
<td>$T_H$</td>
<td>$&lt; 250[^{\circ}C]$</td>
</tr>
</tbody>
</table>

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

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

Possible design options

\( \text{COP} < 4 \quad f \quad x_r \quad [\text{kg/kg}] \)

Possible design options
\( \text{COP} < 4 \quad [\text{–}] \)
Working domain hybrid heat pumps

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

Possible design options

\[ \text{COP} < 4[-] \]
\[ P_H > 130[\text{bar}] \]
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
- \( P_H > 130 \) [bar]
- \( P_L < 1 \) [bar]
Working domain hybrid heat pumps

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

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

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

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

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

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

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

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

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

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: $T_{sink,out}$

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

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

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

$T_{out} = 200[^\circ C]$  $T_{lift} = 30[^\circ C]$
Working domain hybrid heat pumps: $\Delta T_{lift}$

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

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

$T_{out} = 180[^\circ C]$, $T_{lift} = 40[^\circ C]$

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

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

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: $\Delta T_{\text{lift}}$

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

- Possible design options
  - $\text{COP}<4$ [−]
  - $P_{\text{H}} > 130$ [bar]
  - $P_{\text{L}} < 1$ [bar]
  - $VHC < 4$ [MJ/m$^3$]
  - $T > 250$ [°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 up to 110[°C].
• Supercritical CO$_2$ components can be used up to 200[°C].
• $\Delta T_{lift}$ up to 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?