Hybrid Heat Pump Solutions for Industrial Energy Savings

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Hybrid Heat Pump Solutions for Industrial Energy Savings

DTU International Energy Conference
September 10th-12th 2013

Jonas Kjær Jensen
PhD Student
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 $T_{\text{supply}} < 110^\circ\text{C}$.
• Conclusion & future work
The Hybrid Heat Pump

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

\[\dot{m}_{vapour}\]

\[\dot{W}_{comp}\]

\[\dot{W}_{pump}\]

\[m_{lean}\]

\[Q_{IHEX}\]

\[m_{rich}\]

\[Q_{des}\]
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 and temperature for zeotropic mixtures. The graph includes a legend indicating different concentrations (x) of mixtures and two critical points: R717 at 28 bar and 63-230°C, and R718 at 130 bar and 155-330°C. The graph also highlights the temperature range for each component.]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Diagram showing temperature vs. heat load for Pure Refrigerant and Zeotropic Mixtures]

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Sink
Source
Temperature [°C]
Heat Load [kW]
Pure Refrigerant
Pure Refrigerant
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Pure Refrigerant
Zeotropic Mixture
Zeotropic Mixture
Pure Refrigerant

Sink
Source

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

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

Sink

Source

Pure Refrigerant

Zeotropic Mixture

Zeotropic Mixture

Reduced ΔT => Reduced Entropy Generation
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

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

Absorber

$x=0.7$

$T \ [^\circ C]$

$\dot{Q} \ [kW]$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ T [^\circ C] \]
\[ \dot{Q} [kW] \]

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

Absorber

\( x=0.5 \)

\( T \text{ [°C]} \)

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

Absorber

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

Absorber

$\dot{Q} \text{ [kW]}$

$T \text{ [°C]}$

$x=0.3$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

Absorber

\( Q \) [kW] vs. \( T \) [°C]

\( x = 0.1 \)
The Hybrid Heat Pump: Design parameters $x_r$ & $f$
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>$m_{sink} = 1\text{kg/s}$</td>
<td>$\eta_{is,pump} = 0.7$</td>
</tr>
<tr>
<td>$m_{source} = 10\text{kg/s}$</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 $x_r \& f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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 $x_r$ & $f$: $T_{sink, out} = 110^{\circ}C$, $\Delta T_{lift} = 40^{\circ}C$
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>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP &gt; 4[-]$</td>
<td>Economic</td>
</tr>
<tr>
<td>$P_H &lt; 25[bar]$</td>
<td>Standard refrigeration equipment</td>
</tr>
<tr>
<td>$P_L &gt; 1[bar]$</td>
<td>No entrainment of air from ambient</td>
</tr>
<tr>
<td>$VHC &gt; 2[MJ/m^3]$</td>
<td>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</td>
</tr>
<tr>
<td>$T_H &lt; 160[^\circ C]$</td>
<td>Thermal stability of oil</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

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

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

Possible design options:
- \( \text{COP} < 4 \)
- \( P_H > 25 \) [bar]
Working domain hybrid heat pumps

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

Possible design options:
- \( \text{COP} < 4 \)
- \( P_H > 25 \text{[bar]} \)
- \( P_L < 1 \text{[bar]} \)
Working domain hybrid heat pumps

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

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

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

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

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

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

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

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

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

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

$T_{out}=130[^{\circ}C]$  $T_{lift}=30[^{\circ}C]$
Working domain hybrid heat pumps: $T_{\text{sink, out}}$

$T_{\text{out}} = 140[^\circ C]$ \hspace{0.1cm} $T_{\text{lift}} = 30[^\circ C]$

- 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: \( T_{\text{sink, out}} \)

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

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: $T_{sink, out}$

$T_{out} = 160[^\circ C]$  $T_{lift} = 30[^\circ C]$
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: $T_{sink, out}$

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

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

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

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

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: $\Delta T_{lift}$

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

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

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

Possible design options:
- COP $< 4$ $[\text{--}]$
- $P_H > 130$ $[\text{bar}]$
- $P_L < 1$ $[\text{bar}]$
- VHC $< 4$ $[\text{MJ/m}^3]$
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 $x_T$ and $f$.
• Standard refrigeration components can be used upto $110[^\circ C]$.
• Supercritical CO$_2$ components can be used upto $200[^\circ C]$.
• $\Delta T_{lift}$ upto $45[^\circ C]$ 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?