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 10\textsuperscript{th}-12\textsuperscript{th} 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 $T_{\text{supply}} < 110^\circ$C.
- Conclusion & future work
The Hybrid Heat Pump

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

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

\[ m_{vapour} \]

\[ m_{lean} \]

\[ Q_{IHEX} \]

\[ m_{rich} \]

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

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

\[ \dot{W}_{comp} \]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the vapor pressure vs. temperature for zeotropic mixtures with different compositions. The graph includes curves for x=0.0 to x=1.0, with critical points indicated.]
Advantages of Zeotropic Mixtures

Reduction of Vapor Pressure

---

Diagram showing the relationship between temperature and vapor pressure for different concentrations of R717 and R718 mixtures. The diagram includes a temperature range of 63-230°C and a vapor pressure range of 0-220 bar. The critical points and specific concentrations (x=0.0 to x=1.0) are marked on the graph.
Advantages of Zeotropic Mixtures

Reduction of Vapor Pressure

![Graph showing vapor pressure vs. temperature for zeotropic mixtures, with critical points and temperature ranges for R717 and R718.](image-url)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Temperature [°C] vs Heat Load [kW]

- Pure Refrigerant
- Sink
- Source
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Graph showing temperature vs. heat load for pure refrigerant and zeotropic mixture.]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Reduced $\Delta T$ => Reduced Entropy Generation

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Heat Load [kW]</th>
<th>Pure Refrigerant</th>
<th>Zeotropic Mixture</th>
<th>Zeotropic Mixture</th>
<th>Pure Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sink
Source
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x=0.9 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

x=0.8

T [°C]

0 20 40 60 80 100

Q [kW]

0 20 40 60 80 100
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x = 0.7 \)

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

\[ T \text{ [^\circ C]} \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

\[ x = 0.6 \]

Absorber

\[ T [\degree C] \]

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

\[ x = 0.6 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

Absorber

\( x = 0.3 \)

\[ T \ [\degree C] \]

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

Absorber

\[ x = 0.1 \]

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

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

\[ \dot{Q} \text{ [kW]} \]
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>$\dot{m}_{sink} = 1\text{kg/s}$</td>
<td>$\eta_{is,pump} = 0.7$</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 $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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>Constraint</th>
<th>Requirement</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$</td>
<td>$&gt; 4[\text{--}]$</td>
<td>Economic</td>
</tr>
<tr>
<td>$P_H$</td>
<td>$&lt; 25[\text{bar}]$</td>
<td>Standard refrigeration equipment</td>
</tr>
<tr>
<td>$P_L$</td>
<td>$&gt; 1[\text{bar}]$</td>
<td>No entrainment of air from ambient</td>
</tr>
<tr>
<td>$VHC$</td>
<td>$&gt; 2[\text{MJ/m}^3]$</td>
<td>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</td>
</tr>
<tr>
<td>$T_H$</td>
<td>$&lt; 160[^{\circ}\text{C}]$</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[−]

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DTU International Energy Conference 11.9.2013
Working domain hybrid heat pumps

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

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

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

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

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

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

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

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

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

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

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

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

\(T_{\text{out}} = 110[^\circ\text{C}]\)  \(T_{\text{lift}} = 30[^\circ\text{C}]\)
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]
- $P_L < 1$ [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 \]
- \( P_H > 130[\text{bar}] \)
- \( P_L < 1[\text{bar}] \)
- \( \text{VHC} < 4[\text{MJ/m}^3] \)
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
- \( P_H > 130 \text{[bar]} \)
- \( P_L < 1 \text{[bar]} \)
- VHC < 4 \text{[MJ/m}^3\text{]}
- \( T > 250[^\circ\text{C}] \)
Working domain hybrid heat pumps: $T_{sink, out}$

$T_{out} = 120[\degree C]$  $T_{lift} = 30[\degree C]$

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

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

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

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: $T_{sink,\text{out}}$

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

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

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

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

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

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

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

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

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: $\Delta T_{lift}$

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

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

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

Diagram showing 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: $\Delta T_{lift}$

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

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: $\Delta T_{lift}$

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

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