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

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

\( m_{\text{vapour}} \)

\( m_{\text{rich}} \)

\( \dot{Q}_{\text{abs}} \)

\( m_{\text{lean}} \)

\( Q_{\text{IHEX}} \)

\( Q_{\text{des}} \)
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure
Advantages of Zeotropic Mixtures

Reduction of Vapor Pressure

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Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the vapor pressure of mixtures for different temperatures and compositions. The graph illustrates the reduction in vapor pressure for different mixtures compared to single components.](image)

- R717: Temp. Range 63-230°C
- R718: Temp. Range 155-330°C

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**DTU International Energy Conference 11.9.2013**
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Sink

Source

Temperature [°C]

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

![Graph showing temperature vs. heat load for sink and source with pure refrigerant lines.

- Pure Refrigerant
- Sink
- Source

Source:
- Pure Refrigerant

Sink:
- Pure Refrigerant

Heat Load [kW]

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

![Diagram showing temperature vs. heat load for Pure Refrigerant, Zeotropic Mixture, and Sink/Source comparison.](image-url)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Reduction of ΔT => Reduced Entropy Generation

Temperature [°C]

Heat Load [kW]

Pure Refrigerant
Zeotropic Mixture
Sink
Source

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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

\( x=0.8 \)

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

Absorber

\( x = 0.7 \)

\( T \ [^\circ C] \)

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

Absorber

\( x=0.6 \)

\( T \ [^\circ C] \)

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

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

Absorber

\[ x=0.5 \]

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

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

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

Absorber

\[ x = 0.3 \]

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

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

Absorber

\( x = 0.3 \)

<table>
<thead>
<tr>
<th>Tempreature ( T ) [°C]</th>
<th>Q [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

\[ 0 \leq x \leq 1 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x = 0.2 \)

\( T \) [°C]

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

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

Absorber

\[ x = 0.1 \]

\[
\begin{array}{c|c|c|c|c|c}
Q [kW] & T [\degree C] & \hline
0 & 50 & \hline
20 & 50 & \hline
40 & 70 & \hline
60 & 90 & \hline
80 & 100 & \hline
100 & 100 & \hline
\end{array}
\]
The Hybrid Heat Pump: Design parameters $x_r$ & $f$

- Absorber
- Desorber
- IHEX
- Liquid/vapour separator
- Mixer
- $m_{vapour}$
- $m_{rich}$
- $Q_{abs}$
- $Q_{IHEX}$
- $m_{lean}$
- $W_{pump}$
- $W_{comp}$
- $Q_{des}$

Equations:

1. $Q_{abs}$
2. $m_{vapour}$
3. $m_{rich}$
4. $Q_{IHEX}$
5. $m_{lean}$
6. $W_{pump}$
7. $W_{comp}$
8. $Q_{des}$
9. $x_r$
10. $f$
**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_{pinch,\text{abs}} = 5^\circ C )</td>
</tr>
<tr>
<td>( T_{sink,\text{out}} = 110^\circ C )</td>
<td>( \Delta T_{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>( m_{sink} = 1\text{kg/s} )</td>
<td>( \eta_{is,\text{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>COP</th>
<th>PH</th>
<th>PL</th>
<th>VHC</th>
<th>TH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard refrigeration equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No entrainment of air from ambient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economic (\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal stability of oil</td>
<td></td>
<td></td>
<td></td>
<td></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[−]

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Working domain hybrid heat pumps

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

Possible design options
- 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

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

Constraints corresponding to supercritical CO₂ refrigeration components and new synthetic oils

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$ &gt; 4[−]</td>
<td>Economic</td>
</tr>
<tr>
<td>$P_H$ &lt; 130[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; 4[MJ/m³]</td>
<td>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</td>
</tr>
<tr>
<td>$T_H$ &lt; 250[°C]</td>
<td>Thermal stability of oil</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

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

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

Possible design options

\[ \text{COP} < 4[^\text{-}] \]

\[ P_H > 130[^\text{bar}] \]

\[ P_L < 1[^\text{bar}] \]
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
- \( P_H > 130 \) [bar]
- \( P_L < 1 \) [bar]
- VHC < 4 [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: $T_{\text{sink,out}}$

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

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

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

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: $T_{sink, out}$

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

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: $T_{sink, out}$

$T_{out} = 150[°C]$  $T_{lift} = 30[°C]$

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: $T_{sink, out}$

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

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

Possible design options
Working domain hybrid heat pumps: $T_{sink,out}$

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

$T_{\text{out}} = 190^\circ\text{C}$  $T_{\text{lift}} = 30^\circ\text{C}$

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: $T_{sink,out}$

$T_{out} = 200[°C] \quad T_{lift} = 30[°C]$

- 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: $\Delta T_{lift}$

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

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

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

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

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

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
- $P_H > 130$[bar]
- $P_L < 1$[bar]
- VHC < 4[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 $x_T$ 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?