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

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

\[ m_{rich} \]

Absorber

IHEX

\[ Q_{IHEX} \]

Desorber

\[ Q_{des} \]

\[ m_{vapour} \]

\[ m_{lean} \]

Liquid/vapour separator

Mixer

\[ W_{pump} \]

\[ W_{comp} \]

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

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

![Graph showing the reduction of vapor pressure for zeotropic mixtures]

- Temperature [°C]
- Vapor Pressure [bar]

- Curves for different compositions:
  - 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 point

DTU Mechanical Engineering, Technical University of Denmark
DTU International Energy Conference 11.9.2013
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

Temperature [°C]

Vapor Pressure [bar]

R717 → ← R718

Temp. Range 63-230°C

28[bar]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

R717
R718

Temperature \[ {\degree} C \]
Vapor Pressure [bar]

Temp. Range 63-230\degree C
6

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

130[bar]

28[bar]

Temp. Range 155-330\degree C
8

20
40
60
80
100
120
140
160
180
200
220
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Graph showing the comparison between pure refrigerant and zeotropic mixture in terms of temperature and heat load. The graph illustrates how zeotropic mixtures can reduce entropy generation compared to pure refrigerants.]
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></td>
</tr>
<tr>
<td>Zeotropic Mixture</td>
<td></td>
</tr>
<tr>
<td>Zeotropic Mixture</td>
<td></td>
</tr>
<tr>
<td>Pure Refrigerant</td>
<td></td>
</tr>
</tbody>
</table>

Reduced ΔT => Reduced Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.9 \]

\[ T \text{[°C]} \]

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

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

Absorber

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

Absorber

\[ x=0.6 \]

\[ T \, [\degree C] \]

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

Absorber

\( x=0.5 \)

\( T [^\circ C] \)

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

Absorber

\[ x = 0.3 \]

\[ T \text{ [°C]} \]

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

Absorber

\[ x = 0.3 \]

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

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

Absorber

\[ x = 0.2 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x=0.1 \]

\[ T \text{ [°C]} \]

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

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02 0 40 60 80 100

50 60 70 80 90 100

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The Hybrid Heat Pump: Design parameters $x_r$ & $f$

Diagram:
- **Absorber**
- **Desorber**
- **IHEX**
- **Mixer**
- **Liquid/vapour separator**

Symbols:
- $m_{vapour}$
- $m_{lean}$
- $Q_{IHEX}$
- $Q_{abs}$
- $Q_{des}$
- $W_{pump}$
- $W_{comp}$

Equations:
- $\dot{Q}_{abs}$
- $m_{rich}$

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°C</td>
<td>$\Delta T_{pinch,abs} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{sink,out}$ = 110°C</td>
<td>$\Delta T_{pinch,des} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{source,in}$ = 80°C</td>
<td>$\eta_{is,comp} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{sink}$ = 1kg/s</td>
<td>$\eta_{is,pump} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{source}$ = 10kg/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 $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$
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 $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 40^\circ C$
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>( VHC )</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[°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
COP < 4

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

\[ f [-] \]

Possible design options

COP < 4 [–]
Working domain hybrid heat pumps

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

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

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

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

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

Possible design options:
- \( \text{COP} < 4 \)
- \( P_H > 25 [\text{bar}] \)
- \( P_L < 1 [\text{bar}] \)
- \( \text{VHC} < 2 [\text{MJ/m}^3] \)
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 [-]
- \( P_H > 25 \text{[bar]} \)
- \( P_L < 1 \text{[bar]} \)
- 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[−]</td>
</tr>
<tr>
<td>$P_H$ &lt; 130[bar]</td>
</tr>
<tr>
<td>$P_L$ &gt; 1[bar]</td>
</tr>
<tr>
<td>$V_HC$ &gt; 4[MJ/m$^3$]</td>
</tr>
<tr>
<td>$T_H$ &lt; 250[°C]</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

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

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

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

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

$T_{out} = 110[^\circ C]$  $T_{lift} = 30[^\circ C]$
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: $T_{sink,out}$

$T_{out}=140[^\circ C]$  $T_{lift}=30[^\circ C]$
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$^3$]
- $T > 250^\circ C$
Working domain hybrid heat pumps: $T_{sink, out}$

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

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

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

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

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

$T_{out}=180[\degree C] \quad T_{lift}=40[\degree C]$
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[°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?