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 NH₃/H₂O
- Evaluation of important design parameters.
- Prospect for high temperature development $T_{supply} < 110^\circ$C.
- Conclusion & future work
The Hybrid Heat Pump

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

Absorber

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

IHEX

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

Mixer

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

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

Liquid/vapour separator

\[ Q_{\text{abs}} \]

\[ Q_{\text{des}} \]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing vapor pressure vs. temperature for zeotropic mixtures with different compositions (x). R717 to R718 are marked. Critical points are indicated.](image-url)
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

Temperature [°C]

Vapor Pressure [bar]

Temp. Range 63-230°C

R717 → ← R718

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

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

- R717
- R718

Temp. Range 63-230°C
Temp. Range 155-330°C

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

Temperature [°C]

Source
Sink

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

![Graph showing temperature vs. heat load comparison between pure refrigerant, sink, source, and zeotropic mixtures.]

Temperature [°C] vs. Heat Load [kW] graph displaying the advantages of zeotropic mixtures over pure refrigerants.
Advantages of Zeotropic Mixtures

Reduction of Entropy Generation

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

| Sink            |                  |                |
| Pure Refrigerant|                  |                |
| Zeotropic Mixture|                |                |
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>Zeotropic Mixture</td>
</tr>
<tr>
<td>Zeotropic Mixture</td>
<td>Pure Refrigerant</td>
</tr>
</tbody>
</table>

Reduced ΔT => Reduced Entropy Generation

Sink
Source
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

$\dot{Q}$ [kW]

$T$ [°C]

$x=0.9$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x=0.8 \]

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

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

Absorber

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

\( T \) [°C]

\( x=0.7 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

x=0.6

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

\[ x = 0.5 \]
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

\[ x = 0.3 \]

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

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

\( Q \) [kW]

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

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

\[ x=0.2 \]

Absorber

\[ \begin{array}{c|c|c}
\text{T }[^{\circ}\text{C}] & \text{Q }[\text{kW}] \\
\hline
50 & 0 \\
60 & 20 \\
70 & 40 \\
80 & 60 \\
90 & 80 \\
100 & 100 \\
\end{array} \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x=0.1 \]

\[
\begin{align*}
T [^\circ C] & \quad \dot{Q} [kW] \\
0 & \quad 0 \\
50 & \quad 50 \\
60 & \quad 60 \\
70 & \quad 70 \\
80 & \quad 80 \\
90 & \quad 90 \\
100 & \quad 100 \\
\end{align*}
\]
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>$\dot{m}_{sink} = 1kg/s$</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 $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$
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Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 40^\circ C$
Influence of $x_r$ & $\dot{f}$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 50^\circ C$
## 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>$COP$ $&gt; 4[-]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_H$ $&lt; 25[bar]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_L$ $&gt; 1[bar]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$VHC$ $&gt; 2[MJ/m^3]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_H$ $&lt; 160[^\circ C]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

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

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

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

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

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

\[ f \quad [\text{−}] \]
Working domain hybrid heat pumps

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

Possible design options:
- \( \text{COP} < 4 \)
- \( P_H > 25 \text{[bar]} \)
- \( P_L < 1 \text{[bar]} \)
- \( VHC < 2 \text{[MJ/m}^3\text{]} \)
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\(^3\)]
- \( T > 160[^\circ\text{C}] \)
## 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>$V_{HC}$ $&gt; 4[\text{MJ/m}^3]$</td>
</tr>
<tr>
<td>$T_H$ $&lt; 250[\text{°C}]$</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

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

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

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

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

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

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: $T_{sink,out}$

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

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

$T_{out} = 140[\degree C]$  $T_{lift} = 30[\degree C]$
Working domain hybrid heat pumps: $T_{sink,out}$

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

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

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

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

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

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

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

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

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

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

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

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