Hybrid Heat Pump Solutions for Industrial Energy Savings

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Publication date:
2013

Citation (APA):
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DTU International Energy Conference
September 10\textsuperscript{th}-12\textsuperscript{th} 2013

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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

\[ Q_{abs} \]

\[ Q_{IHEX} \]

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

\[ \dot{m}_{\text{pump}} \]

\[ \dot{m}_{\text{comp}} \]

\[ \dot{m}_{\text{rich}} \]

\[ \dot{m}_{\text{lean}} \]
Advantages ofzeotropic mixtures
Reduction of vapor pressure

![Diagram showing the reduction of vapor pressure with different compositions of zeotropic mixtures.](image-url)
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the reduction of vapor pressure for different compositions of a zeotropic mixture. The graph includes lines for different mole fractions (x) of component R717 in the mixture, with critical points and temperature range indicated.]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Graph showing the temperature in °C vs heat load in kW for Pure Refrigerant, Sink, Source, and Pure Refrigerant.](Image)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

<table>
<thead>
<tr>
<th>Source Temperature [°C]</th>
<th>Pure Refrigerant</th>
<th>Zeotropic Mixture</th>
<th>Zeotropic Mixture</th>
<th>Pure Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Load [kW]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Temperature [°C]

Heat Load [kW]

Sink

Source

Pure Refrigerant

Zeotropic Mixture

Reduced $\Delta T$ $\Rightarrow$ Reduced Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x=0.9 \]

\[ T [\degree C] \]

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

\[ 0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \]

\[ 50 \quad 70 \quad 90 \quad 100 \]

\[ 0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

\[ T \text{ [°C]} \]

\( x = 0.8 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[
x = 0.7
\]

\[
\begin{array}{c|c|c}
\hline
Q [kW] & T [^\circ C] \\
\hline
50 & 70 \\
60 & 75 \\
70 & 80 \\
80 & 85 \\
90 & 90 \\
100 & 95 \\
\hline
\end{array}
\]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x=0.6 \)

\( T \) [°C]

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

Absorber

$x=0.5$

$T \, [^\circ C]$ vs. $\dot{Q} \, [kW]$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.3 \]

\[ T \ [^\circ C] \]

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

\[ Q \ [kW] \]

\[ T \ [^\circ C] \]

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

\[ x = 0.3 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

\[ x=0.3 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

x=0.2

Absorber

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

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

0 20 40 60 80 100

50 60 70 80 90 100

0 20 40 60 80 100

50 60 70 80 90 100

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

Absorber

$\dot{Q}$ [kW] vs. $T$ [$^\circ\text{C}$]

x=0.1

$\dot{Q}$ [kW]

$T$ [$^\circ\text{C}$]
The Hybrid Heat Pump: Design parameters $x_r$ & $f$

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

Symbols:
- $\dot{Q}_{abs}$
- $m_{rich}$
- $Q_{IHEX}$
- $m_{lean}$
- $Q_{des}$
- $m_{vapour}$
- $W_{pump}$
- $W_{comp}$

Notes:
- [1] $m_{vapour}$
- [2] $W_{comp}$
- [3] $m_{vapour}$
- [4] $W_{pump}$
- [5] $m_{vapour}$
- [6] $Q_{IHEX}$
- [7] $Q_{des}$
- [8] $m_{lean}$
- [9] $m_{lean}$
- [10] Liquid
- [11] $m_{vapour}$
- [12] $W_{pump}$
- [13] $Q_{des}$
- [14] $m_{vapour}$
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 $x_r \& f$: $T_{sink,\text{out}} = 110^{\circ}C$, $\Delta T_{lift} = 30^{\circ}C$
Influence of $x_r$ & $f$: $T_{\text{sink,out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$
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 $x_r$ & $f$: $T_{\text{sink,out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 40^\circ C$
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[°C]</td>
<td>Thermal stability of oil</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

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

Possible design options

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

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

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

Possible design options:

- COP < 4
- \( P_H > 25 \) [bar]
- \( P_L < 1 \) [bar]
- \( VHC < 2 \) [MJ/m\(^3\)]
Working domain hybrid heat pumps

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

Possible design options:
- COP < 4
- \( P_H > 25 \) [bar]
- \( P_L < 1 \) [bar]
- VHC < 2 [MJ/m³]
- \( T > 160[^\circ C] \)
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>$T_H &lt; 250[^{\circ}C]$</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

\[ \text{COP} < 4[^{-}] \]
Working domain hybrid heat pumps

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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: $T_{sink,out}$

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

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

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

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

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

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

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

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: $\Delta T_{lift}$

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