Hybrid Heat Pump Solutions for Industrial Energy Savings

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Publication date:
2013

Citation (APA):

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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

\[ Q_{abs} \]

\[ Q_{IHEX} \]

\[ m_{vapour} \]

\[ m_{lean} \]

\[ m_{rich} \]

\[ W_{pump} \]

\[ W_{comp} \]

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

![Graph showing the reduction of vapor pressure for different compositions of Zeotropic Mixtures. The graph plots temperature against vapor pressure for various mole fractions (x) of the mixture. The critical point of R717 and R718 is also indicated.]
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the relationship between temperature and vapor pressure for Zeotropic Mixtures.

- **Temperature**: Range 63-230°C
- **Vapor Pressure**: Range 0-220 bar

The graph depicts the vapor pressure of different compositions (x) of Zeotropic Mixtures R717 and R718. The critical points are marked with dashed lines, and the temperature and vapor pressure ranges are highlighted.

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Graph showing temperature vs. heat load for sink and source](image)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

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

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

<table>
<thead>
<tr>
<th>Pure Refrigerant</th>
<th>Zeotropic Mixture</th>
<th>Zeotropic Mixture</th>
<th>Pure Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sink [°C]</td>
<td>Heat Load [kW]</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Source [°C]</td>
<td></td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

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

Reduced ΔT => Reduced Entropy Generation

Sink
Source

Temperature [°C]
Heat Load [kW]

Pure Refrigerant
Zeotropic Mixture

Reduced ΔT => Reduced Entropy Generation

Pure Refrigerant
Zeotropic Mixture

Sink
Source

Heat Load [kW]
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

\( x = 0.8 \)

\[ T \text{[°C]} \]

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

Absorber

\( x = 0.7 \)

\[ T \ [\degree C] \]
\[ Q \ [\text{KW}] \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.6 \]

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

Absorber

\( x=0.5 \)

![Graph showing the relationship between temperature (T) and heat flow (Q)](image-url)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

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

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

Absorber

\[ T \left[{^\circ}C\right] \]
\[ Q \left[\text{kW}\right] \]

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

Absorber

$\dot{Q}$ [kW]  $T$ [°C]

$x=0.2$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
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 $x_r$ & $f$: $T_{sink,out} = 110\degree C$, $\Delta T_{lift} = 30\degree C$
Influence of $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$ &gt; 4[–]</td>
</tr>
<tr>
<td>$P_H$ &lt; 25[bar]</td>
</tr>
<tr>
<td>$P_L$ &gt; 1[bar]</td>
</tr>
<tr>
<td>$V_{HC}$ &gt; 2[MJ/m$^3$]</td>
</tr>
<tr>
<td>$T_H$ &lt; 160[°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

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

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

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

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

- COP < 4
- \( P_H > 130 \text{[bar]} \)

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

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

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

Possible design options

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

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

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

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

- **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: $T_{sink,out}$

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

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

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: $T_{sink, out}$

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

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: $T_{sink,out}$

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

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

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

\[ T_{\text{sink,out}} \]

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

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

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

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

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: $\Delta T_{lift}$

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

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

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: $\Delta T_{lift}$

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

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

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

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

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.

![Graph showing possible design options with COP, $P_H$, $P_L$, VHC, and $T$.]
Conclusion

• COP and design parameters are highly dependent on \( x_r \) 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?