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

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

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

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

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

\( Q_{\text{abs}} \)

\( Q_{\text{des}} \)

\( W_{\text{comp}} \)

\( W_{\text{pump}} \)
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing vapor pressure vs. temperature for different compositions of mixtures R717 and R718. The graph includes curves for x=0.0 to x=1.0, showing the change in vapor pressure with temperature for each composition. The critical point is also indicated on the graph.](image-url)
Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Temperature vs. Vapor Pressure Graph]

- X-axis: Temperature [°C]
- Y-axis: Vapor Pressure [bar]
- Curves represent different values of x:
  - Red: x=0.0
  - Purple: x=0.1
  - Orange: x=0.2
  - Pink: x=0.3
  - Green: x=0.4
  - Blue: x=0.5
  - Light blue: x=0.6
  - Dark blue: x=0.7
  - Purple: x=0.8
  - Light purple: x=0.9
  - Dark purple: x=1.0
- Critical point at 28 [bar]
- Temp. Range: 63-230 °C

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Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing vapor pressure vs. temperature for zeotropic mixtures.
Different mixtures are denoted by different colors, with
x-values ranging from 0.0 to 1.0.

Legend:
- Red: x=0.0
- Orange: x=0.1
- Yellow: x=0.2
- Green: x=0.3
- Blue: x=0.4
- Purple: x=0.5
- Magenta: x=0.6
- Cyan: x=0.7
- Teal: x=0.8
- Light blue: x=0.9
- Dark blue: x=1.0

Key:
- Critical point
- R717
- R718

Temperature Range:
- 63-230°C
- 155-330°C

Vapor Pressure Range:
- 28 bar
- 130 bar

Note: The graph illustrates the vapor pressure of zeotropic mixtures at various temperatures, highlighting the differences between pure R717 and R718.
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Temperature [°C] vs. Heat Load [kW]

Sink
Source
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Source
Sink

Temperature [°C]

Heat Load [kW]

Pure Refrigerant

Pure Refrigerant

8
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Reduced $\Delta T \Rightarrow$ Reduced Entropy Generation

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

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

Absorber

\[ x = 0.9 \]

\[ T [\degree C] \]

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

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

x=0.8

T [°C] vs. Q [kW]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.6 \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

\( Q \) [kW]

\( x=0.5 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

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

Absorber

x=0.3

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

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

\( 0 \)

\( 100 \)
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.2 \]

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

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

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Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
The Hybrid Heat Pump: Design parameters $x_r$ & $f$

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

$\dot{Q}_{abs}$

$\dot{W}_{pump}$

$\dot{W}_{comp}$

$m_{vapour}$

$m_{rich}$

$m_{lean}$

$Q_{IHEX}$

$Q_{des}$

$Q_{abs}$

$Q_{des}$

$W_{comp}$

$W_{pump}$

$\dot{Q}_{abs}$

$\dot{Q}_{IHEX}$

$\dot{m}_{vapour}$

$\dot{m}_{rich}$

$\dot{m}_{lean}$
**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 $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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Influence of $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,\,out} = 110°C$, $\Delta T_{lift} = 40°C$
Influence of $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 50^\circ C$
### Design Constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COP</td>
<td>$&gt; 4[-]$</td>
<td>Economic</td>
</tr>
<tr>
<td>$P_H$</td>
<td>$&lt; 25[\text{bar}]$</td>
<td>Standard refrigeration equipment</td>
</tr>
<tr>
<td>$P_L$</td>
<td>$&gt; 1[\text{bar}]$</td>
<td>No entrainment of air from ambient</td>
</tr>
<tr>
<td>$V_{HC}$</td>
<td>$&gt; 2 [MJ/m^3]$</td>
<td>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</td>
</tr>
<tr>
<td>$T_H$</td>
<td>$&lt; 160[^\circ\text{C}]$</td>
<td>Thermal stability of oil</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

Possible design options

COP < 4 [−]

Possible design options

COP < 4 [−]
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]

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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/m\(^3\)
Working domain hybrid heat pumps

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

Constraints corresponding to supercritical CO$_2$ refrigeration components and new synthetic oils

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$COP &gt; 4[-]$</strong></td>
<td>Economic</td>
</tr>
<tr>
<td><strong>$P_H &lt; 130[bar]$</strong></td>
<td>Standard refrigeration equipment</td>
</tr>
<tr>
<td><strong>$P_L &gt; 1[bar]$</strong></td>
<td>No entrainment of air from ambient</td>
</tr>
<tr>
<td><strong>$VHC &gt; 4[MJ/m^3]$</strong></td>
<td>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</td>
</tr>
<tr>
<td><strong>$T_H &lt; 250[^{\circ}C]$</strong></td>
<td>Thermal stability of oil</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

Possible design options

COP<4[−]
Working domain hybrid heat pumps

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

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

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

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

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

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

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

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

$\rho \quad \rho$
Working domain hybrid heat pumps: $T_{sink,out}$

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

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

$T_{out} = 190[^{\circ}C] \quad T_{lift} = 30[^{\circ}C]$

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: $T_{sink,out}$

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

### 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: $\Delta T_{lift}$

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

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

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

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