Hybrid Heat Pump Solutions for Industrial Energy Savings

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Hybrid Heat Pump Solutions for Industrial Energy Savings

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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

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

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

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

\( m_{\text{rich}} \)

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

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

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

\( W_{\text{pump}} \)

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

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Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the vapor pressure of zeotropic mixtures as a function of temperature. The graph includes curves for different compositions (x) and a critical point.]
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

![Graph showing the reduction of vapor pressure for R717 and R718 mixtures. The graph includes different concentrations (x) of the mixtures, with critical and temperature range markings.]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

<table>
<thead>
<tr>
<th>Pure Refrigerant</th>
<th>Pure Refrigerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature [°C]</td>
<td>Heat Load [kW]</td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Source
Sink

Temperature [°C] vs. Heat Load [kW] graph showing the performance of pure refrigerants compared to zeotropic mixtures.
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
## 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>Reduced ΔT =&gt; Reduced Entropy Generation</td>
<td>Pure Refrigerant</td>
<td>Zeotropic Mixture</td>
<td>Pure Refrigerant</td>
</tr>
<tr>
<td>Sink</td>
<td>Source</td>
<td>Sink</td>
<td>Source</td>
</tr>
<tr>
<td>10</td>
<td>DTU Mechanical Engineering, Technical University of Denmark</td>
<td>11.9.2013</td>
<td>DTU International Energy Conference</td>
</tr>
</tbody>
</table>
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x = 0.9 \]

\[
\begin{align*}
T [\degree C] & \quad \dot{Q} [kW] \\
50 & \quad 0 \\
60 & \quad 10 \\
70 & \quad 20 \\
80 & \quad 30 \\
90 & \quad 40 \\
100 & \quad 50 \\
\end{align*}
\]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

Absorber

x=0.7

T [°C]

Q [kW]

0 20 40 60 80 100

0 50 60 70 80 90 100

x=0.7
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Graph showing the relationship between temperature (T) and Q (kW) for x=0.6]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\( x = 0.5 \)

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

\( T \text{ [°C]} \)

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

Absorber

\[ T [\degree C] \]

\[ Q [kW] \]

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

Absorber

\( x = 0.3 \)

\[ \begin{align*}
\dot{Q} \, [\text{kW}] & \quad T \, [\text{C}^\circ] \\
0 & \quad 50 \\
20 & \quad 60 \\
40 & \quad 70 \\
60 & \quad 80 \\
80 & \quad 90 \\
100 & \quad 100
\end{align*} \]
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

$T \text{ [C]}$

$x=0.2$

$0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100$

$50 \quad 60 \quad 70 \quad 80 \quad 90 \quad 100$
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

\[ x=0.1 \]

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

\[ T \text{ [°C]} \]
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>$m_{sink} = 1\text{kg/s}$</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 $x_r$ and $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$

COP

$P_H$ [bar]

$P_L$ [bar]
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 $x_r \& f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
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>
<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>$T_H &lt; 160[^{\circ}C]$</td>
<td>Thermal stability of oil</td>
</tr>
</tbody>
</table>
Working domain hybrid heat pumps

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

Possible design options

COP < 4[–]

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

\[ f \text{ [–]} \]
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

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

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

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

Possible design options:
- COP < 4
- \( P_H > 25 \text{[bar]} \)
- \( P_L < 1 \text{[bar]} \)
- VHC < 2 \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:
- \( \text{COP} < 4 [-] \)
- \( P_H > 25 [\text{bar}] \)
- \( P_L < 1 [\text{bar}] \)
- \( \text{VHC} < 2 [\text{MJ/m}^3] \)
- \( T > 160[^{\circ}\text{C}] \)
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>
</table>
| $COP$ > 4[−]      | Economic  
| $P_H$ < 130[bar]  | Standard refrigeration equipment  
| $P_L$ > 1[bar]    | No entrainment of air from ambient  
| $V_{HC}$ > 4[MJ/m$^3$] | Economic ($\dot{Q}_{abs}/\dot{V}_{suc,comp}$)  
| $T_H$ < 250[°C]  | Thermal stability of oil  

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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

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

\[ f [-] \]

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

[Diagram showing possible design options with COP < 4 and other conditions.]
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
- \( P_H > 130 \) [bar]
Working domain hybrid heat pumps

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

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

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

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

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

$T_{\text{out}} = 150[^\circ\text{C}]$ $T_{\text{lift}} = 30[^\circ\text{C}]$
Working domain hybrid heat pumps: $T_{sink, out}$

\[ T_{out} = 160 \, ^\circ C \quad T_{lift} = 30 \, ^\circ C \]

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: $T_{sink,out}$

$T_{out} = 170[^\text{°C}]$ $T_{lift} = 30[^\text{°C}]$
Working domain hybrid heat pumps: $T_{\text{sink},\text{out}}$

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

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: $T_{sink, out}$

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

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

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

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

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

$T_{out} = 180[{°C}]$  $T_{lift} = 35[{°C}]$

Possible design options:

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

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

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

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: $\Delta T_{lift}$

$T_{out}=180[\degree C]$ $T_{lift}=50[\degree C]$
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].
• $\Delta T_{liq}$ 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?