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 10\textsuperscript{th}-12\textsuperscript{th} 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

Absorber

Desorber

IHEX

Liquid/vapour separator

Mixer

\[ \dot{Q}_{abs} \]

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

\[ \dot{m}_{mess} \]

\[ \dot{Q}_{IHEX} \]

\[ \dot{W}_{pump} \]

\[ \dot{W}_{comp} \]

\[ \dot{Q}_{des} \]
Advantages of Zeotropic Mixtures

Reduction of Vapor Pressure

![Graph showing vapor pressure vs temperature for different compositions of zeotropic mixtures (R717 and R718). The graph indicates how the vapor pressure decreases with an increase in temperature for various compositions.](image)
Advantages of Zeotropic Mixtures

Reduction of Vapor Pressure

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Advantages of Zeotropic Mixtures
Reduction of Vapor Pressure

![Graph showing the vapor pressure curves of zeotropic mixtures with temperature.]

- **R717**
- **R718**

**X**-axis: Temperature [°C]
**Y**-axis: Vapor Pressure [bar]

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

**Note:** This graph illustrates the vapor pressure curves for different zeotropic mixtures over a range of temperatures, showcasing their unique properties and advantages in industrial applications.
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

![Graph showing temperature vs heat load for sink and source.]

- Temperature [°C]
- Heat Load [kW]

Source
Sink
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Sink
Source
Temperature [°C]
Heat Load [kW]

Pure Refrigerant

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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>

Sink

Source
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Reduced ΔT => Reduced Entropy Generation

Sink
Source
Temperature [°C]
Heat Load [kW]
Pure Refrigerant
Zeotropic Mixture
Zeotropic Mixture
Pure Refrigerant
Reduced ΔT => Reduced Entropy Generation

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

Absorber

x=0.8

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

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

x=0.5

\[ T \ [^\circ\mathrm{C}] \]

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

Absorber

x=0.3

T [°C]

Q [kW]

0 20 40 60 80 100

0 50 60 70 80 90 100
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation
Advantages of Zeotropic Mixtures
Reduction of Entropy Generation

Absorber

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

Absorber

$T \ [\degree C]$

$\dot{Q} \ [kW]$

$x=0.1$

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The Hybrid Heat Pump: Design parameters $x_r$ & $f$
Influence of $x_r$ & $f$: $T_{\text{sink,out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$

Inputs and Assumptions

<table>
<thead>
<tr>
<th>External Inputs</th>
<th>Internal Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{sink,in}} = 80^\circ C$</td>
<td>$\Delta T_{\text{pinch,abs}} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{\text{sink,out}} = 110^\circ C$</td>
<td>$\Delta T_{\text{pinch,des}} = 5^\circ C$</td>
</tr>
<tr>
<td>$T_{\text{source,in}} = 80^\circ C$</td>
<td>$\eta_{\text{is,comp}} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{\text{sink}} = 1\text{kg/s}$</td>
<td>$\eta_{\text{is,pump}} = 0.7$</td>
</tr>
<tr>
<td>$\dot{m}_{\text{source}} = 10\text{kg/s}$</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 $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink, out} = 110^\circ C$, $\Delta T_{lift} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{\text{sink, out}} = 110^\circ C$, $\Delta T_{\text{lift}} = 30^\circ C$
Influence of $x_r$ & $f$: $T_{sink,\text{out}} = 110^\circ \text{C}$, $\Delta T_{lift} = 40^\circ \text{C}$

COP

$P_H \ [\text{bar}]$

$P_L \ [\text{bar}]$

$T_H \ [\text{C}]$

$VHC \ [\text{kJ/m}^3]$
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>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$ &gt; 4[−]</td>
<td></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/m³]</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

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

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

Possible design options

- \( \text{COP} < 4 [-] \)
- \( P_H > 25 [\text{bar}] \)
- \( P_L < 1 [\text{bar}] \)
Working domain hybrid heat pumps

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

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

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

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

<table>
<thead>
<tr>
<th>Design Constraints</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$COP$  &gt; 4[—]</td>
<td>Economic</td>
</tr>
<tr>
<td>$P_H$  &lt; 130[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>$V_HC$ &gt; 4[MJ/m$^3$]</td>
<td>Economic ($\dot{Q}<em>{abs}/\dot{V}</em>{suc,comp}$)</td>
</tr>
<tr>
<td>$T_H$  &lt; 250[°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

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

\[ x_r \text{ [kg/kg]} \]
Working domain hybrid heat pumps

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

Possible design options:
- \( \text{COP} < 4 \)
- \( P_H > 130 \text{ bar} \)
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
- \( P_H > 130[^\text{bar}] \)
- \( P_L < 1[^\text{bar}] \)

\( f \) vs. \( x_r \) [kg/kg]
Working domain hybrid heat pumps

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

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

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

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

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

$T_{out} = 140[^\circ C]$  $T_{lift} = 30[^\circ C]$
Working domain hybrid heat pumps: \( T_{\text{sink, out}} \)

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

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

- $T_{out} = 160[^\circ C]$  
- $T_{lift} = 30[^\circ C]$  

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: $T_{sink,out}$

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

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

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

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

- 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: $\Delta T_{lift}$

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

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

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

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

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: $\Delta T_{lift}$

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

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: $\Delta T_{lift}$

$T_{out} = 180[°C]$ $T_{lift} = 50[°C]$

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