High temperature heat pumps using zeotropic working fluids

Demonstration of Integration in a Spray Drying Facility

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Waste Heat Potential in Industry

Food Industry:
- Food Industry has the highest potential of excess heat
- Large temperature bandwidth
- 33 % of total fuel consumption for drying
- 42 % of total excess heat from drying

Drying Processes:
- Share on total fuel consumption of drying processes in other industries:
  - 19 % on average in industries
  - 26 % in wood and paper
  - 10 % in building material
# Drying Processes in Food Industry

<table>
<thead>
<tr>
<th>Drying Technology</th>
<th>Industry</th>
<th>$T_{in}$ [°C]</th>
<th>$T_{out}$ [°C]</th>
<th>Share [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spray Dryer</td>
<td>Milk/ Coffee/ Starch</td>
<td>200 - 270</td>
<td>60 - 110</td>
<td>25</td>
</tr>
<tr>
<td>Drum Dryer/ Kiln Dryer/ Rotary Dryer</td>
<td>Sugar¹</td>
<td>500</td>
<td>120</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Fruits/ Vegetables</td>
<td>65 – 105</td>
<td>20 – 40</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Fishmeal</td>
<td>500 – 600</td>
<td>80 – 120</td>
<td>9</td>
</tr>
<tr>
<td>Direct Contact Dryer (steam)</td>
<td>Bone meal</td>
<td>180</td>
<td>133</td>
<td>16</td>
</tr>
<tr>
<td>Fluidized Bed- / Fixed Bed- / Conveyer-/ Tray Dryer</td>
<td>Milk/ Coffee/ Starch</td>
<td>60 – 90</td>
<td>40 – 70</td>
<td>5</td>
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<tr>
<td></td>
<td>Cereals/ Sugar</td>
<td>40 – 70</td>
<td>20 – 30</td>
<td>23</td>
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<tr>
<td></td>
<td>Fruits/ Vegetables</td>
<td>40 – 60</td>
<td>20 – 30</td>
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</tr>
</tbody>
</table>

¹ In Denmark largely covered by superheated steam dryers
Case Study: Waste Heat Recovery from Spray Dryer (Arla)

<table>
<thead>
<tr>
<th>Flow</th>
<th>Temperature [°C]</th>
<th>Mass Flow [kg/s]</th>
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</thead>
<tbody>
<tr>
<td>Drying Air</td>
<td>1 15</td>
<td>43.7</td>
</tr>
<tr>
<td></td>
<td>2 70</td>
<td>43.7</td>
</tr>
<tr>
<td></td>
<td>4 210</td>
<td>43.7</td>
</tr>
<tr>
<td>Excess Air</td>
<td>5 70</td>
<td>61.5</td>
</tr>
</tbody>
</table>

High temperature HP using zeotropic working fluids: 18. Mai 2017
Integration in Spray Drying Facility
Case Study: Waste Heat Recovery from Spray Dryer (Arla)

High temperature HP using zeotropic working fluids:
Integration in Spray Drying Facility

<table>
<thead>
<tr>
<th></th>
<th>$T$ [°C]</th>
<th>$m$ [kg/s]</th>
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</thead>
<tbody>
<tr>
<td>Drying Air</td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>43.7</td>
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<tr>
<td>2</td>
<td>70</td>
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<td>3</td>
<td>125</td>
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<td>4</td>
<td>210</td>
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<td>Excess Air</td>
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<td>5</td>
<td>70</td>
<td>61.5</td>
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<tr>
<td>6</td>
<td>≈45</td>
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<tr>
<td>Secondary Cycle Source</td>
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<td>7</td>
<td>65</td>
<td>14.8</td>
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<tr>
<td>8</td>
<td>≈40</td>
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<tr>
<td>Secondary Cycle Sink</td>
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</tr>
<tr>
<td>9</td>
<td>75</td>
<td>10.6</td>
</tr>
<tr>
<td>10</td>
<td>130</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Heat Pump Model

\[ \dot{m}_{\text{sink}} = 10.61 \text{ kg/s} \]
\[ T_{\text{sink,in}} = 75 \, ^\circ\text{C} \]
\[ T_{\text{sink,out}} = 125 \, ^\circ\text{C} \]

\[ \dot{m}_{\text{source}} = 14.81 \text{ kg/s} \]
\[ T_{\text{source,in}} = 65 \, ^\circ\text{C} \]
\[ T_{\text{source,out}} \approx 40 \, ^\circ\text{C} \]

\[ \dot{Q}_{\text{sink}} \]
\[ \dot{Q}_{\text{source}} \]
\[ W_{\text{comp}} \]

Butane:
\[ \text{COP} = 2.92 \]
\[ p_{\text{evap}} = 2.9 \text{ bar} \]
\[ p_{\text{cond}} = 27.4 \text{ bar} \]
Heat Pump Model

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Butane:
- \( \text{COP} = 2.92 \)
- \( p_{\text{evap}} = 2.9 \text{ bar} \)
- \( p_{\text{cond}} = 27.4 \text{ bar} \)
- \( y_{D,\text{source}} = 22 \% \)
- \( y_{D,\text{sink}} = 23 \% \)
Heat Pump Model

\[ \dot{m}_{\text{sink}} = 10.61 \text{ kg/s} \]
\[ T_{\text{sink,in}} = 75 \degree C \]
\[ T_{\text{sink,out}} = 125 \degree C \]

Butane:
\[ \text{COP} = 2.92 \]
\[ p_{\text{evap}} = 2.9 \text{ bar} \]
\[ p_{\text{cond}} = 27.4 \text{ bar} \]
\[ \gamma_{D,\text{source}} = 22 \% \]
\[ \gamma_{D,\text{sink}} = 23 \% \]
\[ \gamma_{D,\text{source,Fluid}} = 12 \% \]
\[ \gamma_{D,\text{sink,Fluid}} = 13 \% \]

\[ \dot{Q}_{\text{sink}} \]
\[ \dot{Q}_{\text{source}} \]
\[ W_{\text{comp}} \]
Heat Pump Model

40 % DME – 60 % Pentane:
COP = 3.26

Butane:
COP = 2.92
p_{evap} = 2.9 \text{ bar}
p_{cond} = 27.4 \text{ bar}
\gamma_{D,source} = 22 \%
\gamma_{D,sink} = 23 \%
\gamma_{D,source,Fluid} = 12 \%
\gamma_{D,sink,Fluid} = 13 \%

Find suitable mixture
# List of considered Fluids

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of Fluid</th>
<th>Ref. No.:</th>
<th>Type</th>
<th>ODP</th>
<th>GWP</th>
<th>Normal Boiling Point, °C</th>
<th>Crit. Temp. °C</th>
<th>Crit. Pressure bar</th>
<th>Safety Class</th>
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<tbody>
<tr>
<td>1</td>
<td>Methane</td>
<td>R-50</td>
<td>HC</td>
<td>0</td>
<td>25</td>
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<td>-82.6</td>
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<td>2</td>
<td>Ethylene</td>
<td>R-1250</td>
<td>HC</td>
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<td>6.8</td>
<td>-103.8</td>
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<tr>
<td>3</td>
<td>Ethane</td>
<td>R-170</td>
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<td>R-744</td>
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<td>Iso-Butane</td>
<td>R-600a</td>
<td>HC</td>
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<td>n-Butane</td>
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<td>98.4</td>
<td>267.0</td>
<td>27.4</td>
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</tbody>
</table>
Results - COP

DME/i-Pentane  Propane/i-Pentane  DME/Pentane

Butane/Hexane  DME/DEE

Butane  DME  DEE

COP

Composition of Component 2, kg/kg

Propylene/Isopentane
Propane/Isobutane
Propane/Butane
Propane/i-Pentane
DME/Isobutane
DME/i-Pentane
DME/Pentane
DME/DEE
DME/Hexane
Isobutane/Pentane
Butane/Pentane
Butane/Hexane

9 %
Results - NPV

Butane/Hexane
DME/i-Pentane
Propane/i-Pentane
DME/Pentane
Propylene/i-Pentane

DME
Butane

NPV, Mio. €:

Composition of Component 2, kg/kg
## Results

<table>
<thead>
<tr>
<th>Component 1</th>
<th>Component 2</th>
<th>(x_1)</th>
<th>(x_2)</th>
<th>COP</th>
<th>(P_{\text{evap}}) (bar)</th>
<th>(P_{\text{cond}}) (bar)</th>
<th>(\frac{P_{\text{cond}}}{P_{\text{evap}}})</th>
<th>(T_{\text{comp, out}}) (°C)</th>
<th>NPV (10^3 €)</th>
<th>PBT (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DME</td>
<td>Pentane</td>
<td>0.4</td>
<td>0.6</td>
<td>3.26</td>
<td>2.63</td>
<td>20.89</td>
<td>7.94</td>
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<td>Pentane</td>
<td>0.7</td>
<td>0.3</td>
<td>3.24</td>
<td>5.03</td>
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<td>6.61</td>
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<td>0.5</td>
<td>3.24</td>
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<td>27.61</td>
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<td>143.8</td>
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<td>-</td>
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<td>0.5</td>
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<td>4.01</td>
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<td>979.03</td>
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<td>Propylen</td>
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<td>0.6</td>
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<td>9.54</td>
<td>137.3</td>
<td>486.10</td>
<td>7.7</td>
</tr>
</tbody>
</table>
Best solution - COP

\[ \text{COP} = 3.26, \quad \dot{Q}_{\text{sink}} = 2.23 \text{ MW} \]

\[ \text{TCI} = 0.792 \text{ Mio. €}, \quad \text{NPV} = 1.05 \text{ Mio. €}, \quad \text{PBT} = 5.4 \text{ years} \]
Best solution - NPV

70 % DME – 30 % Pentane

COP = 3.24, \( \dot{Q}_{\text{sink}} = 2.23 \) MW

TCI = 0.642 Mio. €, NPV = 1.20 Mio. €, PBT = 4.4 years
Economics with Arla’s Boundary Conditions

Main Assumptions: Economic best case: 70 % DME – 30 % Pentane

Total investment: \(2 \times TCI_{hp}\)

Electricity: 0.074 €/kWh

Steam: 0.047 €/kWh

Subsidy: 0.051 €/kWh (first year)

Interest Rate: 10 %

Loan Duration: 5 years at 100 %

Results without Subsidy:

NPV: 5.29 Mio. €

Payback Time: 4 Years

Heating price: 0.042 €/kWh

Results with Subsidy:

NPV: 5.857 Mio. €

Payback Time: 3 Years

Heating price: 0.040 €/kWh
Conclusions

- **Possible application:** Simple Heat Pump with 70% DME – 30 % Pentane
  - Recovered waste heat: **1.53 MW** from exhaust air at 70 °C – 45 °C
  - Supplied heat: **2.23 MW** to heat air from 70 °C – 125 °C
  - Natural gas consumption: Decreased by ~**36 %** (2 Mio. m³/year)
  - Economically feasible:
    - **PBT = 4 – 5 years**, **NPV = 1.20 Mio. €**
    - **PBT = 3 years**, **NPV = 5.86 Mio. €** for complete investment considering subsidy in DK
  - Solution is technically feasible (according to manufacturer)
  - …but still needs to be validated in experimental setups

- **Heat pumps utilizing mixtures:**
  - Significant performance increase possible (**9 %**)
  - Requires a comprehensive screening
  - Considering mixtures can enhance the range of application for limited set of fluids
Thank you for your attention!

More about High Temperature Heat Pumps:
**Workshop on 11.09.2017 in Copenhagen**
http://www.conferencemanager.dk/HighTemperatureHeatPumps