Process Integration of High-Temperature Heat Pumps

Dr.-Ing. Florian Schlosser
Industrial Process Heat Demand

Final Energy Demand
Worldwide 2019: 116,111TWh

- Industry (other) 13%
- Industry (process heat) 21%
- Transport 19%
- Household 36%
- Commerce, Trade, Services 11%

Temperatures:
- > 500 °C: 53%
- 200 - 500 °C: 9%
- 100 - 200 °C: 27%
- < 100 °C: 11%

Process Integration Principles

Wrong! Integration below Pinch

Wrong! Integration above Pinch

Correct! Integration around Pinch

\[
\dot{Q}_{\text{HU}} - P_{\text{el}} = \dot{Q}_{\text{ev}} + P_{\text{el}} \\
\dot{Q}_{\text{ev}} + P_{\text{el}} = \dot{Q}_{\text{CU}} + P_{\text{el}}
\]

Break-even Targeting of High-Temperature Heat Pump Integration

- Just 14 case studies collected within the Annex 58 in the temperature range > 100 °C

- Rising target temperatures mean rising temperature lifts and degreasing COPs

- Matching the process requirements in terms of \( T-\dot{H} \)-profile with HTHPs in different development levels

- Identification of economic break-even conditions within the technical potential of the corresponding heat pump types quantified by the Heat Pumping Recovery Rate (HPRR) and the economic electricity-to-reference price ratio.
Performance-Model of High-Temperature Heat Pumps

Market-available drying VHTHPs
- Schlosser et al. (2020)

Stirling VHTHPs
- R704, Zühlsdorf et al. (2022)

Prototypes – Transcritical VHTHPs:
- R1336mzz(Z), HFE356mmZ, R600
- Kimura et al. (2021), Suemitsu et al. (2021), Hasegawa et al. (2021), Verdnik et al. (2019)

Simulation studies - Transcritical VHTHPs:
- R1234ze(Z), R1233zd(E), R1224yd(Z), R601, R600
- Arpagaus et al. (2020)

Simulation studies VHTHPs:
- Cascade: Bottom: R600, Top: R718
- Reversed Brayton Cycle: R744
- Zühlsdorf et al. (2019)

Simulation studies – Transcritical Cascade VHTHPs:
- R744
- Kong et al. (2022)
## Break-even Targeting based on LCOH

\[
r_p = \frac{p_{el}}{p_{ref}}
\]

\[
a \cdot c_{i,ref} + p_{ref} \cdot \frac{1}{\eta_{ref}} \cdot t_{FL} + f_{M,ref} \cdot c_{I,ref} = a \cdot c_{I,HP} + p_{el} \cdot \frac{1}{\text{COP}(\Delta T_{lift})} \cdot t_{FL} + f_{M,HP} \cdot c_{I,HP}
\]

\[
\frac{LCOH_{HP}}{LCOH_{ref}} = \frac{A_{HP}}{A_{ref}}
\]

\[
a = \frac{(1 + i)^N \cdot i}{(1 + i)^N - 1}
\]

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VHTHP</th>
<th>Ref. boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment costs (c_i)</td>
<td>500 EUR/kW(_{th})</td>
<td>0 EUR/kW(_{th})</td>
</tr>
<tr>
<td>Reference energy carrier price</td>
<td>(r_p \cdot p_{ref})</td>
<td>0.0306 EUR/kWh</td>
</tr>
<tr>
<td>Full-load hours (t_{FL})</td>
<td>6000 h/a (three-shift operation)</td>
<td></td>
</tr>
<tr>
<td>Interest factor (i)</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Depreciation period (N)</td>
<td>20 a</td>
<td></td>
</tr>
<tr>
<td>Factor maintenance costs (f_{M,i})</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Efficiency ratios (full-load) (\eta_j)</td>
<td>COP ((\Delta T_{lift}))</td>
<td>0.87</td>
</tr>
</tbody>
</table>
COP Targeting

\[ \dot{Q}_{ev} = \dot{Q}_{co} \cdot \left(1 - \frac{1}{COP}\right) \]

\[ \dot{Q}_{co}(T_{t,St}) = \dot{Q}_{ev}(T_{t,So}) \cdot \left(1 - \frac{1}{COP(\Delta T_{lift,crit})}\right)^{-1} \]
Retrofit approach

Heat Pump Bridge Analysis

Construction of Modified Energy Transfer Diagram (METD)


Retrofit approach
Heat Pump Bridge Analysis

Retrofit approach

Heat Pump Bridge Analysis


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Modelling of high-temperature process requirement
Modelling of high-temperature process requirement

Targeting results for milk spray drying

Targeting based on the (a) Grand Composite Curve and (b) Modified Energy Transfer Diagram

Conclusions

Findings
- Temperature lift is opposed to the electricity-to-gas price ratio as setting screw
- Technological concepts available to reach 210 °C
  - $r_p = 1.20$ to $1.57$
  - COP = 1.61 to 2.14

Outlook
- Further adaption to specific process profile needed to improve (economic) efficiency
- Promising results for the simulation studies of transcritical, cascade and Brayton cycle HP
  - Further development to reach higher TRL levels
  - Extension of HP performance dataset
- Application of method to other high-temperature processes
- Extension of method for LCOH-based optimisation of HP cycle configuration
References


