Supercritical Organic Rankine Cycle for waste heat recovery at high temperatures
Waste Heat Utilization (WHU) Potential

- Enova study (Norway): 7 TWh\(_{th}\) industrial waste heat with temperatures above 140 °C (mainly in cement/iron industry)
- Enova study applied on Germany gives a potential of 90 TWh\(_{th}\) > 140 °C
- Hamm et al.:
  - Germany: 42 TWh\(_{th}\)/a
  - Worldwide: 1530 TWh\(_{th}\)/a
- Companies are willing to use waste heat due to
  - increasing energy costs and
  - emission trading.
Waste Heat Utilization (WHU)
Supercritical vs. Subcritical Organic Rankine Cycle

→ Non-isothermal heating

→ Lower exergy destruction
Methods
Simulation scheme within Aspen Plus V7.2

Supercritical Organic Rankine Cycle for waste heat recovery | Markus Preißinger
Methods

Boundary conditions

- Temperature range:
  - Heat source: 633.15 K ... 823.15 K
  - Heat sink: 353.15 K
  - ORC: maximum temperature according to $s_{\text{max}}$

- Minimum internal temperature approach
  - Heat source/ORC: 30 K
  - Internal recuperator, condenser: 10 K

- ORC working pressure range
  - Subcritical: 0.2 MPa ... $p(s_{\text{max}})$ (within 50 steps)
  - Supercritical: $1.01 \cdot p_{\text{crit}}$ ... $1.30 \cdot p_{\text{crit}}$ (within 30 steps)

- Efficiencies: 0.7 (pump), 0.8 (turbine/generator-unit)

- Pressure and radiation losses are neglected
Methods

Maximum pressure and temperature

Turbine

Temperature vs. Entropy Graph:
- $T_{\text{max,SC}}$
- $p_{\text{max,sub}}$
- $s_{\text{max}}$
Methods
Working fluids, equation of state and validation

• Homologous series of 3 alkanes, 3 alkylbenzenes, 3 siloxanes and 2 cyclic siloxanes

• Peng-Robinson equation of state
  – Validation 1: PENG-ROB in comparison with BACKONE (Lai et al., 2011)
  
<table>
<thead>
<tr>
<th></th>
<th>( V_{\text{ORC-B-T}} ) [l/s]</th>
<th>( V_{\text{ORC-A-R}} ) [l/s]</th>
<th>( \eta_{\text{th}} ) [%]</th>
<th>( Q' ) [MW]</th>
<th>( C' ) [kW/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation with Peng-Robinson</td>
<td>51</td>
<td>1810</td>
<td>18.6</td>
<td>5.37</td>
<td>23.3</td>
</tr>
<tr>
<td>Simulation with BACKONE</td>
<td>51</td>
<td>1778</td>
<td>18.6</td>
<td>5.37</td>
<td>23.4</td>
</tr>
<tr>
<td>Relative deviation [%]</td>
<td>0.0</td>
<td>1.8</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

  – Validation 2: PENG-ROB in comparison with further equation of states in Aspen Plus
Methods
Working fluids, equation of state and validation

Relative deviation within 1%
Similar results can be found for the thermal efficiency (deviation < 2%)
Similar results can be found for further working fluids
Thermodynamic results
Net power output vs. working pressure

Efficiency increase/decrease depends on temperature of heat source

\[ T_{\text{heat source}} = 663.15 \, \text{K} \]
Thermodynamic results
Net power output vs. working pressure

→ Efficiency increase/decrease depends on temperature of heat source
→ The higher the temperature the more fluids show maximum net power output in supercritical mode

\[ T_{\text{heat source}} = 723.15 \, \text{K} \]
Thermodynamic results
Net power output vs. working pressure

Efficiency increase/decrease depends on temperature of heat source.
The higher the temperature the more fluids show maximum net power output in supercritical mode.
At a certain temperature all fluids show best performance in supercritical mode.

\[ T_{\text{heat source}} = 793.15 \text{ K} \]
Thermodynamic results
Correlation of net power output and critical pressure

$T_{\text{heat source}} = 663.15 \text{ K}$

→ Strong correlation of net power output from critical pressure at low heat source temperatures
Thermodynamic results
Correlation of net power output and critical pressure

$T_{heat\ source} = 693.15\ K$

→ Strong correlation of net power output from critical pressure at low heat source temperatures
→ Correlation weakens for higher heat source temperatures
Thermodynamic results
Correlation of net power output and critical pressure

\[ T_{\text{heat source}} = 823.15 \text{ K} \]

- Strong correlation of net power output from critical pressure at low heat source temperatures
- Correlation weakens for higher heat source temperatures
- Correlation vanishes for even higher heat source temperatures
Thermodynamic results
Correlation of net power output and critical temperature

\[ T_{\text{heat source}} = 663.15 \, \text{K} \]
Thermodynamic results
Correlation of net power output and critical temperature

\[ T_{\text{heat source}} = 753.15 \text{ K} \]

→ Correlation of net power output from critical temperature within a chemical class at low heat source temperatures
→ Correlation can just be seen for alkylbenzenes for higher heat source temperatures
Thermodynamic results
Correlation of net power output and critical temperature

\[ T_{\text{heat source}} = 823.15 \text{ K} \]

- Correlation of net power output from critical temperature within a chemical class at low heat source temperatures
- Correlation can just be seen for alkylbenzenes for higher heat source temperatures
- Correlation vanishes for even higher heat source temperatures
Constructional results
Comparison within chemical classes I

\[ T_{\text{heat source}} = 663.15 \, \text{K} \]

OMCTS shows highest volume flow rates at turbine outlet.
Volume flow rates of OMTS and n-nonane are similar.
Ethylbenzene has lowest volume flow rates.
Constructional results
Comparison within chemical classes I

\[ T_{\text{heat source}} = 753.15 \, \text{K} \]

- OMCTS shows highest volume flow rates at turbine outlet
- Volume flow rates of OMTS and n-nonane are similar
- Ethylbenzene has lowest volume flow rates
- Same trends can be seen at higher heat source temperature
Constructional results
Comparison within chemical classes II

\[ T_{\text{heat source}} = 753.15 \text{ K} \]

At fixed working pressure siloxanes show highest volume flow rate ratios within the turbine.

OMCTS has steepest slope, volume flow rate ratio of ethylbenzene increases slightly.

An inflexion point can be observed between sub- and supercritical mode of operation for all fluids.
Comparison of chemical classes
Heat exchanger size

![Graph showing comparison of heat exchanger size for different chemical classes](image)
Heat transfer results
Nusselt number

Miropol’skiy-Shitsman

\[ Nu_b = 0.023 \operatorname{Re}_b^{0.8} \operatorname{Pr}_{\text{min}}^{0.8} \]

Yamagata

\[ Nu_b = 0.0135 \operatorname{Re}_b^{0.85} \operatorname{Pr}_b^{0.8} F_c \]

\[ F_c = 1.0 \text{ for } E > 1 \]

\[ F_c = 0.67 \operatorname{Pr}_{pc}^{-0.05} \left( \frac{c_p}{c_{pb}} \right)^{n_1} \text{ for } 0 \leq E \leq 1 \]

\[ F_c = \left( \frac{c_p}{c_{pb}} \right)^{n_2} \text{ for } E < 0 \]

\[ E = \left( \frac{T_{pc} - T_b}{T_w - T_b} \right) \]

\[ n_1 = -0.77 \left( 1 + \frac{1}{\operatorname{Pr}_{pc}} \right) + 1.49 \]

\[ n_2 = -1.44 \left( 1 + \frac{1}{\operatorname{Pr}_{pc}} \right) - 0.53 \]

Jackson and Hall

\[ Nu = 0.0183 \operatorname{Re}_b^{0.82} \operatorname{Pr}_b^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{c_p}{c_{pb}} \right)^n \text{ with } n = f(T_w, T_b, T_{pc}) \approx 0.4 \]
Heat transfer results
Case 1: $T_{wall}=\text{const.}$

- Jackson and Hall
- Miropol'skiy and Shitsman
- Yamagata
Heat transfer results
Case 1: $T_{\text{wall}} = \text{const.}$
Heat transfer results
Case 2: $T_{\text{wall}} = T_{\text{heat source}}$

- Jackson and Hall
- Miropol'skiy and Shitsman
- Yamagata
Heat transfer results

Case 2: $T_{\text{wall}} = T_{\text{heat source}}$

![Graph showing heat transfer results for different cases](image)
Summary

- Study on supercritical Organic Rankine Cycle for waste heat utilization
- 11 fluids out of 4 chemical classes (alkanes, alkylbenzenes, linear siloxanes, cyclic siloxanes) were investigated.
- Net power output increase strongly depends on heat source temperature.
- Correlation between net power output and physico-chemical properties depends on heat source temperature and chemical class.
- Alkylbenzenes show highest net power output, lowest volume flow rate but highest working pressure.
- Linear siloxanes show smaller volume flow rates and heat transfer capacities UA than cyclic siloxanes for similar net power output.
- Prediction of heat transfer coefficients is quite complicated.
Future work

- Integration of pressure and radiation losses
- More detailed evaluation of heat transfer mechanism
- Fluid-to-Fluid modelling for heat transfer correlations
- Measurement of heat transfer coefficients in laboratory
- Economic evaluation of supercritical Organic Rankine Cycle
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Thank you