Techno-economic comparison of different cycle architectures for high temperature waste heat to power conversion systems using CO$_2$ in supercritical phase

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Waste Heat Recovery: some data

- The energy rejected from industry under the form of heat is estimated to be the 20-50% of its overall energy consumption.

- The recovery of industrial waste could bring a saving of 1800 TeraBTU/year with an economic value of $6 billion/year (US DOE, 2004).

- In the UK 163 TeraBTUs/year are rejected in the environment, almost one sixth of the overall industrial energy consumption.
Waste Heat Recovery: some data

- Particular industrial sectors reject a more significant percentage of the overall energy consumption to the environment.

- Main relevance in energy intensive industrial plants.

- In many cases this energy is rejected in form of high thermal grade heat (steel, cement, chemical industry).

- The heat recovered has to be used or stored, not always is possible.
Waste Heat Recovery: technologies

- Heat re-use and storage
  - Steam production
  - Heat pumps

- Heat adsorption

- Thermochemical conversion

- Thermal water desalination

- Heat to power conversion
  - Thermoacoustic
  - Thermoelectricity
  - Thermodynamic cycles
## WHR: Heat to power conversion

<table>
<thead>
<tr>
<th>WHR applications</th>
<th>Range of temperatures</th>
<th>Heat to power conversion technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra Low</td>
<td>T&lt;120 °C</td>
<td>Kalina, TFC</td>
</tr>
<tr>
<td>Low</td>
<td>120 °C &lt; T &lt; 230 °C</td>
<td>ORC, Kalina, Goswami</td>
</tr>
<tr>
<td>Medium</td>
<td>230 °C &lt; T &lt; 650 °C</td>
<td>ORC (up to 500 °C)</td>
</tr>
<tr>
<td>High</td>
<td>650 °C &lt; T &lt; 870 °C</td>
<td>Rankine (from 700 °C)</td>
</tr>
<tr>
<td>Ultra High</td>
<td>T &gt; 870 °C</td>
<td>Rankine</td>
</tr>
</tbody>
</table>

There is a gap…
Supercritical carbon dioxide Brayton cycle

- Carbon dioxide (CO2) in supercritical phase
  - Liquid-like density
  - Gas-like viscosity
- Joule-Brayton cycle
- Critical point of CO2 (30.98 °C, 73.8 bar)
- High pressures and high temperatures
Why sCO2: other reasons

- Far from the critical point the sCO2 density decreases
- High efficiencies if the goal of higher turbine inlet temperatures can be achieved
- Not toxic, Eco-friendly and abundant
- High thermal stability
- Lower compression work near the critical point
- High number of possible applications
sCO2 vs Rankine cycle

- Heat supplied and rejected at a higher averaged values of temperature;
- Better thermal matching between the working fluid and the hot source;
- Higher density allows downsized and less complex turbomachines

CONS

- High thermal load in the regenerators lower expansion ratio

Simple Regenerated (SR) layout
Reheating (RH) layout
Recompression (RC) layout
Recompression Reheating (RCRH) layout
Methodology: CycleTempo

1. Reading parameters
2. Creation of system matrix
3. Calculating thermodynamic properties ($p$, $T$, $h$)
4. Solving system matrix
5. Checking for convergence: $|\varphi_{m+1} - \varphi_m| < 0.001$
6. Output and Exergy analysis

If not converged, return to step 3.
Cycle Tempo: governing equations

- Steady state analysis

- Governing equations:

\[ \sum_i m_i = 0 \quad (mass\ balance) \]

\[ \sum_i m_i h_i = 0 \quad (energy\ balance) \]

\[ \sum_i m_i [(h_i-h_0) - T_0(s_i - s_0)] = 0 \quad (exergy\ equation) \]
### Cycle Tempo: Creation of system matrix

<table>
<thead>
<tr>
<th>Components</th>
<th>nr</th>
<th>Balance</th>
<th>Number of pipes</th>
<th>Components</th>
<th>nr</th>
<th>Balance</th>
<th>Number of pipes</th>
<th>Mass flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater</td>
<td>2</td>
<td>mass</td>
<td>1   -1</td>
<td>Turbine</td>
<td>3</td>
<td>mass</td>
<td>1   -1</td>
<td>0</td>
</tr>
<tr>
<td>Turbine</td>
<td>3</td>
<td>mass</td>
<td>1   -1</td>
<td>Regenerator</td>
<td>5</td>
<td>mass</td>
<td>1   -1 1   -1</td>
<td>0</td>
</tr>
<tr>
<td>Regenerator</td>
<td>5</td>
<td>mass</td>
<td>-1  1</td>
<td>Compressor</td>
<td>1</td>
<td>mass</td>
<td>-1  1</td>
<td>0</td>
</tr>
<tr>
<td>Compressor</td>
<td>1</td>
<td>mass</td>
<td>1   -1 1   -1</td>
<td>Chiller</td>
<td>4</td>
<td>mass</td>
<td>-1  1</td>
<td>0</td>
</tr>
<tr>
<td>Chiller</td>
<td>4</td>
<td>mass</td>
<td>h₂   -h₃</td>
<td>Heater</td>
<td>2</td>
<td>energy</td>
<td>h₁   -h₂</td>
<td>p_gas</td>
</tr>
<tr>
<td>Heater</td>
<td>2</td>
<td>energy</td>
<td>h₅   -h₆ h₇   -h₁₀</td>
<td>Chiller</td>
<td>4</td>
<td>energy</td>
<td>h₅   -h₆ h₇   -h₁₀</td>
<td>0</td>
</tr>
<tr>
<td>Chiller</td>
<td>4</td>
<td>energy</td>
<td>h₄   -h₅</td>
<td>Regenerator</td>
<td>5</td>
<td>energy</td>
<td>h₁   -h₂</td>
<td>0</td>
</tr>
</tbody>
</table>

**Kind of equation:**

- Sum of mass flows equals zero:
  - \( \mathbf{m} = \mathbf{0} \)

**Thermal power supplied by the exhaust gases:**

- Expressed as \( p_{gas} \) in the system matrix.
Methodology: Overall analysis

Cycle-Tempo

MATLAB
The Language of Technical Computing

REFPROP

OUTPUT

- Heat exchangers' transfer area
- sCO2 mass flows
- Net power output
- Cycle efficiency
- Exergy efficiency
Results: Assumptions

- Pressure and temperatures assumed accordingly with the limits of the currently material technology
- Isentropic efficiencies of the turbomachines have been assumed accordingly with the experimental tests carried out by SNL
- High grade Waste Heat Recovery applications

### Thermodynamic conditions

<table>
<thead>
<tr>
<th></th>
<th>Turbine</th>
<th>Compressor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet Pressure</td>
<td>250</td>
<td>75</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>500</td>
<td>32</td>
</tr>
<tr>
<td>Outlet pressure</td>
<td>75</td>
<td>250</td>
</tr>
<tr>
<td>Isentropic efficiencies</td>
<td>0.85</td>
<td>0.7</td>
</tr>
<tr>
<td>Mechanical efficiencies</td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>Generator efficiency</td>
<td></td>
<td>0.95</td>
</tr>
</tbody>
</table>

### Sources

<table>
<thead>
<tr>
<th></th>
<th>Flue gases</th>
<th>Cooling water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temp [°C]</td>
<td>900</td>
<td>15</td>
</tr>
<tr>
<td>Outlet temp [°C]</td>
<td>500</td>
<td>45</td>
</tr>
<tr>
<td>Mass flow [kg/s]</td>
<td>1</td>
<td>Not fixed</td>
</tr>
</tbody>
</table>

### Heat exchangers

<table>
<thead>
<tr>
<th></th>
<th>Heater</th>
<th>Regenerators</th>
<th>Cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>U [W/m²K]</td>
<td>100</td>
<td>1700</td>
<td>2900</td>
</tr>
<tr>
<td>Cost coefficient $k$</td>
<td>7.0</td>
<td>1.8</td>
<td>8.0</td>
</tr>
<tr>
<td>Pinch point</td>
<td></td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
Results: parametric analysis

![Graph showing net power output and back work ratio as functions of cycle pressure ratio. The graph compares the performance of different systems labeled SR, RC, RH, and RCRH.](image-url)
Results: 1st Principle analysis

- SR
- RC
- RH
- RCRH

<table>
<thead>
<tr>
<th></th>
<th>Electrical Net Power Output [kW$_e$]</th>
<th>Energy Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>155</td>
<td>32%</td>
</tr>
<tr>
<td>RC</td>
<td>160</td>
<td>34%</td>
</tr>
<tr>
<td>RH</td>
<td>170</td>
<td>36%</td>
</tr>
<tr>
<td>RCRH</td>
<td>175</td>
<td>38%</td>
</tr>
</tbody>
</table>
Results: Exergy analysis

The diagram shows the irreversibility breakdown and exergy efficiency for different processes labeled as SR, RC, RH, and RCRH. The processes are categorized into various components such as SENS, CLR, REC_LT, REC_HT, HEAT_HP, HEAT_LP, TRB_HP, TRB_LP, CMP_MAIN, and CMP_SPLIT. The irreversibility breakdown is represented by colored bars, and the exergy efficiency is indicated on the right side of the diagram.
Investment cost analysis

To calculate the CAPEX for each layout component and then for the overall cost of the different cycle schemes, the following correlations have been adopted:

\[ c_T = 479.34m \left( \frac{1}{0.93 - \eta_T} \right) \ln(\beta)(1 + \exp(0.036T_{in} - 54.4)) \]

\[ c_C = 71.10m \left( \frac{1}{0.92 - \eta_C} \right) \beta \ln(\beta) \]

\[ c_{HX} = k \ 2681 A^{0.59} \]

\[ c_{HX} = k \ 130 \left( \frac{A}{0.093} \right)^{0.78} \]

Where:

- the temperature is expressed in °C
- the mass flow in kg/s
- the heat transfer area in m²
Results: Investment cost analysis

Cost Breakdown:
- SR
- RC
- RH
- RCRH

Cost Distribution:
- SENS
- CLR
- REC_LT
- REC_HT
- HEAT_HP
- HEAT_LP
- TRB_HP
- TRB_LP
- CMP_MAIN
- CMP_SPLIT

Cost Range: $800 - 1800/kW_e
Questions?