Challenges in using fuel-fired heaters for \( \text{sCO}_2 \) closed Brayton Cycle

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4 STRATEGIC PRIORITIES

DEVELOP & TEST
new energy services for customers

PREPARE
the electrical systems and networks of the future

CONSOLIDATE AND DEVELOP
competitive and zero-carbon production mixes

SUPPORT the Group’s international growth by developing research partnerships
## EDF R&D activities on supercritical sCO\textsubscript{2}

### The sCO\textsubscript{2} cycle is an opportunity to:
- Improve power plant efficiency
- Reduce the fossil plant impact
- Enhance renewable heat sources

### Main goals about sCO\textsubscript{2} cycles are to:
- Scale-up the sCO\textsubscript{2} Brayton cycle maturity level
- Prove the sustainability of this technology
- Optimize processes at any load

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Review for nuclear power cycles (GenIV)</td>
</tr>
<tr>
<td>2012</td>
<td>Preliminary study: performance assessment with CCS</td>
</tr>
<tr>
<td>2014</td>
<td>sCO\textsubscript{2}-BC for coal power plant – study + starting of PhD</td>
</tr>
<tr>
<td>2016</td>
<td>European project constitution: efficiency &amp; flexibility</td>
</tr>
<tr>
<td>2018</td>
<td>Start of the sCO\textsubscript{2}-Flex European project</td>
</tr>
</tbody>
</table>
Outline

1. Context
2. Adaptation of sCO₂ Brayton cycle to current coal-fired heater constraints
3. Methodology and results
4. Conclusion and Perspectives
The supercritical CO$_2$ Brayton cycle

- **Advantages**
  - Compactness
  - High performance at high temperature
  - No water consumption (if air cooled)
  - Simplified layout
  - Expected cost reduction
  - Expected to fit many heat sources
  - Expected to fit several heat sink technologies

- **Cycle characteristics**
  - Highly regenerative cycle (heat available at the turbine outlet)
  - Very sensitive to pressure drops, heat sink temperature

Source: Cengel & Boles, 2015
Many publications on **nuclear applications** (non-exhaustive list):

- Yoonhan Ahn, Seong Jun Bae, Minseok Kim, Seong Kuk Cho, Seungjoon Baik, Jeong Ik Lee, Jae Eun Cha, *Review of supercritical CO₂ power cycle technology and current status of research and development*, Nuclear Engineering and Technology, Volume 47, Issue 6, 2015, Pages 647-661, ISSN 1738-5733, [http://dx.doi.org/10.1016/j.net.2015.06.009](http://dx.doi.org/10.1016/j.net.2015.06.009)

and many many others…

Prototypes/demo on several other applications:

- Concentrated Solar: Sunshot, STEP
- Direct fossil fuel cycles (Allam Cycle): NetPower
- Waste Heat Recovery: ECHOGEN
- …
(non-exhaustive list)

2013
✓ Conceptual study of a high efficiency coal fired power plant with CO₂ capture using a supercritical CO₂ Brayton cycle, Le Moullec

2015
✓ Supercritical CO₂ Brayton cycles for coal-fired power plants, Mecheri & Le Moullec

2017
✓ Thermodynamic and economic investigation of coal-fired power plant combined with various supercritical CO₂ Brayton power cycle, Park et al.

2018
✓ A supercritical CO₂ Brayton cycle with a bleeding anabranch used in coal-fired power plants, Bai et al.
✓ 300 MW Boiler Design Study for Coal-fired Supercritical CO₂ Brayton Cycle, Bai et al.

→ Late interest for coal-fired power plant application?
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Current “steam coal-fired boiler” constraints

- Heat available:
  - ✔ Combustion chamber
  - ✔ Flue gases

- Boiler performances → depends on the heat recovered

- Limitations:
  - ✔ Combustion chamber → working fluid must protect material from very high temperatures
  - ✔ Flue gases → flue gas temperature at the stack > condensation temperature ~120°C (~248°F)

- Specificities of the “water steam Rankine cycle” (vs CO₂ Brayton cycle)
  - ✔ Phase change → low water temperature at the turbine outlet + latent heat (vaporization/condensation)
  - ✔ Low water temperature at the boiler inlet → use of low temperature heat of the boiler
“Optimized” recompression sCO₂ Brayton Cycle

- High cycle performance
- Low enthalpy rise in the “boiler”
- Optimized cycle is not able to recover “low temperature heat” of the heat source

Note: approximate values
Main issues (using CO₂ instead of water)

Reduction of the “Boiler” performance due to wasted “low temperature heat” available in flue gases

→ How to recover “low temperature heat”?
Foreseen solutions to keep high heater performance without impacting the “main” sCO$_2$ Brayton cycle

- Combination of an “optimized sCO$_2$ Brayton cycle” (denoted “reference cycle”) with:
  - a sCO$_2$ bottom cycle (cascaded cycles) [Thimsen and Weitzel, 2016]
  - an Organic Rankine Cycle (ORC)
  - a very high temperature air-preheating process
  - low Temperature Recuperator (LTR Bypass) sCO$_2$ Brayton cycle configuration
  - high Temperature Recuperator (HTR Bypass) sCO$_2$ Brayton cycle configuration
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Methodology

1. Inlet data (cycle configuration, study boundaries, models...) and assumptions (numerical values...)

2.1 Process flow simulation (thermodynamic simulation)
   - Cycle performances, maximal temperature and pressure, heat duty, power output...

2.2 Economic assessment (simplified economic model)
   - Power cycle CAPEX and specific cost

3. Flexibility qualitative assessment
   - Start/stop frequency
   - Part-load interval
   - Time-response

4. Comparison of each foreseen solution
Disclaimer: this study does not deal with sCO₂ coal-heater design purposes: only simplified assumption are made
2.1. Performances assessment (thermodynamic simulations)

- Process simulator: Aspen Plus v8.6 (aspentech)
- Simplified “heater” construction: heat duty at given temperature level for each “heater heat exchanger”
- Thermodynamic models:
  - NIST RefProp for modeling CO₂
  - SRK for hydrocarbons (ORC)
  - Water steam table for water
- Indicator: net cycle efficiency defined as:

\[
\eta_{\text{power cycle}} = \frac{\text{Turbine work} - \text{Compressor (or pump) work} (MW_{el})}{\text{Recovered heater duty} (MW_{th})}
\]
2.2. Economic assessment (model based on main component costs)

Main components:
- turbines/compressors,
- heat exchangers (recuperators, coolers)
- pump (ORC)

"a" and "b" empirical parameters that depend on component

Impact of the pressure and temperature on the costs (material aspects)

\[
\text{Component cost (\$)} = a \times (\text{electrical power or duty in MW})^b \times f_p \times f_T
\]

CAPEX ($)

Direct costs = 1.26 \times \sum \text{Component cost}

Indirect costs = 8\% \times \text{direct costs}

Impact of pressure and temperature on costs:

\[
f_p = \begin{cases} 
1 & \text{if } P_{\text{max}} < 100 \text{ bar} \\
\alpha \times P_{\text{max}} + \beta & \text{otherwise}
\end{cases}
\]

\[
f_T = \begin{cases} 
1 & \text{if } T_{\text{max}} < 400 \degree C \\
\gamma \times T_{\text{max}}^2 + \delta \times T_{\text{max}} + \varepsilon & \text{otherwise}
\end{cases}
\]

CAPEX ($) = 1.3608 \times \sum \text{Component cost}

\[
\times \frac{1}{\text{Net power}}
\]

Specific costs ($/\text{kW}_e$)

Sources: [Caputo et al., 2004], [Park et al. 2017], [Kumar et al, 2015]
3. Flexibility qualitative assessment

- Complete and accurate flexibility analysis requires specific dynamic calculations! Not achieved here.
- This study is only given a qualitative assessment of the flexibility of the foreseen solutions regarding 3 criteria:
  - ✓ Start/stop
  - ✓ Part-load range (maximal and minimal acceptable load)
  - ✓ Time-response
- The final results table is qualitatively assessing these 3 criteria within “positive”, “neutral” or “negative” impact on the global power plant flexibility compared to the reference cycle.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>-</th>
<th>=</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start/Stop</td>
<td>Not recommended: only if no other option</td>
<td>Usual frequency</td>
<td>Adapted to high frequency</td>
</tr>
<tr>
<td>Part-load range</td>
<td>Narrow range</td>
<td>Usual range</td>
<td>Wide range</td>
</tr>
<tr>
<td>Time response</td>
<td>Slow</td>
<td>Usual</td>
<td>Rapid</td>
</tr>
</tbody>
</table>
## 4. Results

<table>
<thead>
<tr>
<th></th>
<th>Reference (R)</th>
<th>R + Air preheating</th>
<th>R + LTR bypass</th>
<th>R + HTR bypass</th>
<th>R + ORC</th>
<th>R + Cascaded</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cycle Efficiencies (%)</strong></td>
<td>51.36</td>
<td>51.36</td>
<td>49.88</td>
<td>51.12</td>
<td>51.36 and 35.8</td>
<td>49.9 and 36.6</td>
</tr>
<tr>
<td><strong>Net Production (MWₑ)</strong></td>
<td>899</td>
<td>899</td>
<td>994.6</td>
<td>1018.2</td>
<td>899</td>
<td>480.3</td>
</tr>
<tr>
<td><strong>Secondary net Production (MWₑ)</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>86</td>
<td>377</td>
</tr>
<tr>
<td><strong>Total net production (MWₑ)</strong></td>
<td>899 (=)</td>
<td>899</td>
<td>994.6 (+95.6)</td>
<td>1018.2 (+119.2)</td>
<td>985 (+86)</td>
<td>857.3 (-41.7)</td>
</tr>
<tr>
<td><strong>CO₂ temperature at the FWH inlet (°C)</strong></td>
<td>477</td>
<td>477 (=)</td>
<td>488 (+11)</td>
<td>497 (+20)</td>
<td>477 (=)</td>
<td>415 (-62)</td>
</tr>
<tr>
<td><strong>Recovered heat (%)</strong></td>
<td>87.9 %</td>
<td>100 %</td>
<td>100 %</td>
<td>100%</td>
<td>100 %</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>Ratio (%) : Power / Recovered heat</strong></td>
<td>43.74 (=)</td>
<td>48.39 (+4.7)</td>
<td>49.54 (+5.8)</td>
<td>47.92 (+4.2)</td>
<td>41.71 (-2)</td>
<td></td>
</tr>
<tr>
<td><strong>Fired-heater</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Start/stop</strong></td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
<tr>
<td><strong>Load range</strong></td>
<td>=</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td><strong>Time-response</strong></td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

### Performances and costs

- **CAPEX (M€)**: 789 (=), 823 (+34), 851 (+62), 857 (+68), 711 (-78)
- **Specific cost ($/kWₑ)**: 878 (=), 827 (-51), 835.5 (-42.5), 870 (-8), 829.4 (-48.6)
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Conclusions of this study
Limitations and perspectives

Many **boiler design** challenges to heat CO₂ are not taken into account here (pressure drops management, furnace cooling, material choice, high mass flow rate, structural support...) see [Thimsen and Weitzel, 2016]

Simplified cost model: work in progress to **improve these correlations** (to go from “flux based” correlations to “characteristic parameter design” correlations (e.g. for heat exchangers: “UA” instead of “heat duty”))...

Flexibility of the sCO₂ – Brayton cycle: necessitate accurate dynamic models and simulations. One of the objectives of the sCO₂ Flex project

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*Context*  *Methodology & Results*  *Conclusion & Perspectives*
Thank you for your attention

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References

[1] Yoonhan Ahn, Seong Jun Bae, Minseok Kim, Seong Kuk Cho, Seungjoon Baik, Jeong Ik Lee, Jae Eun Cha, Review of supercritical CO\textsubscript{2} power cycle technology and current status of research and development, Nuclear Engineering and Technology, Volume 47, Issue 6, 2015, Pages 647-661, ISSN 1738-5733, http://dx.doi.org/10.1016/j.net.2015.06.009


Simplified diagrams of tested configurations