Design Concept for Large Output Graz Cycle Gas Turbines

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How do you want your egg(s)?  - Sunny side up?
But do not have it burned!
• Toronto Conference 1988, a Call for Action
• **Kyoto Protocol** demands the reduction of greenhouse gases, mainly CO2
• In EU: strong pressure on utilities and companies to reduce CO2 emissions
• In 2005: emission allowances to about 10 000 companies within the EU covering about 46 % of the overall EU CO2 emissions
• As emission allowances become scarce: CO2 generates costs (European Emission Allowances in March 2006: 27 €/ton CO2)
• CO2 and N2 from ASU can be utilized for **Enhanced Oil Recovery (EOR)**
  Return: 20 – 40 $/ton CO2
Oxy-Fuel Cycles

- **Oxy-fuel cycles** with internal combustion with pure oxygen are a very promising technology (Global Gas Turbine News 10/2005)

  + CO2 can be easily separated by condensation from working fluid consisting of CO2 and H2O, no need for very penalizing scrubbing

  + Very low NOx generation (fuel bound N2)

  + Flexibility regarding fuel: natural gas, syngas from coal, biomass or refinery residue gasification

- New equipment required

- Additional high costs of oxygen production

+ These new cycles show higher efficiencies than current air-based combined cycles (Graz Cycle, Matiant cycle, Water cycle,...)
History of the Graz Cycle

• **1985**: presentation of a power cycle without any emission (CIMAC Oslo)
  • H2/O2 internally fired steam cycle, as integration of top Brayton steam cycle and bottom Rankine cycle
  • efficiency 6 % - points higher than state-of-the art CC plants

• **1995**: Graz cycle adopted for the combustion of fossil fuels like methane (CH4) (CIMAC Interlaken & ASME Cogen Vienna)
  • cycle fluid is a mixture of H2O and CO2
  • thermal cycle efficiency: 64 %

• **2000**: thermodynamically optimized cycle for syngas from coal gasification (VDI Essen)

• **2002/2003**: conceptual layout of prototype Graz Cycle power plant: detailed design of components (ASME Amsterdam, VDI Leverkusen, ASME Atlanta)

• **2004/2005**: presentation of S-Graz Cycle with 69% thermal efficiency and 57 % net efficiency for syngas firing (ASME Vienna, ASME Reno)
Graz Cycle Basic Configuration (ASME 04/05)

Cycle Fluid
77 % H2O
23 % CO2

HTT High Temperature Turbine
HRSG Heat Recovery Steam Gen.
LPT Low Pressure Turbine
C3/C4 CO2 Compressors
C1/C2 Cycle Fluid Compressors
HPT High Pressure Turbine

Fuel (methane)

Combustor

O2

40 bar

1400°C

HPT

180 bar

565°C

Cond. P.

C3/C4

CO2

600°C

C1/C2

water injection

573°C

Feed Pump

Deaerator

Condenser

H2O

water injection

for cooling

0.04 bar
• Electrical cycle efficiency for methane firing:
  **Efficiency: 64.6 %** (same for syngas firing)

• Oxygen production (0.15 - 0.3): 0.25 kWh/kg
  Oxygen compression (2.38 to 40 bar, inter-cooled): 325 kJ/kg
  **Efficiency: 54.8 %**

• Compression of separated CO2 for liquefaction
  (1 to 100 bar, inter-cooled): 270 kJ/kg (3.7 MW)
  **Efficiency: 52.7 %**
Condensation/Re-Vaporization at around 1 bar

Cycle Fluid
79 % H2O
21 % CO2

Compressors C3 and C4 raise partial steam pressure for condensation and deliver CO2
• Constant re-evaporation pressure of 0.75 bar for the bottoming steam cycle

• LPST inlet temperature of 175 °C; expansion line crosses Wilson line at last blade inlet, thus low humidity losses
## S-Graz Cycle Power Balance for 400 MW net power

<table>
<thead>
<tr>
<th></th>
<th>Basic Layout</th>
<th>New Layout</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTT power [MW]</td>
<td>635</td>
<td>638</td>
</tr>
<tr>
<td>Total turbine power [MW]</td>
<td>753</td>
<td>739</td>
</tr>
<tr>
<td>Total compression power [MW]</td>
<td>249</td>
<td>235</td>
</tr>
<tr>
<td><strong>Net shaft power [MW]</strong></td>
<td><strong>504</strong></td>
<td><strong>505</strong></td>
</tr>
<tr>
<td>Total heat input [MW]</td>
<td>759</td>
<td>759</td>
</tr>
<tr>
<td><strong>Thermal cycle efficiency [%]</strong></td>
<td><strong>66.5</strong></td>
<td><strong>66.5</strong></td>
</tr>
<tr>
<td><strong>Electrical cycle efficiency [%]</strong></td>
<td><strong>64.6</strong></td>
<td><strong>64.6</strong></td>
</tr>
</tbody>
</table>
Additional Losses and Expenses

- Oxygen production: $0.25 \text{ kWh/kg} = 900 \text{ kJ/kg}$
  Oxygen compression (2.38 to 42 bar, inter-cooled): $325 \text{ kJ/kg}$

  **Efficiency: 54.8 %**

- Compression of separated CO2 for liquefaction
  (1.9 to 100 bar): $13 \text{ MW}$ (1 to 100 bar: 15.6 MW)

  **Efficiency: 53.1 %** (compared to 52.7 %)
490 MW Turbo Shaft Configuration

- Main gas turbine components on two shafts for **400 MW** net output
- Compression shaft of 8500 rpm: cycle compressors C1 and C2, driven by first part of HTT, the compressor turbine HTTC
- Power shaft of 3000/3600 rpm: power turbine HTTP as second part of HTT drives the generator
  Four-flow LPST at the opposite side of the generator
- Shafts on same spring foundation
  Intercooler between C1 and C2 on fixed foundation connected to HRSG
Working Fluid Compressor C1

- Compression 1 -> 13 bar, 106° -> 442°C
- Speed of 8500 rpm leads to inlet tip Mach number of 1.3
- 7 axial and 1 radial stage, 8500 rpm
- Uncooled drum rotor of ferritic steel (high temperature 9 %-chrome steel)
Working Fluid Compressor C2

- Compression 13 -> 40 bar, 380° -> 580°C, 7 stages, 8500 rpm
- Cooled drum rotor of ferritic steel with counterflow of cooling steam
- Blade length of 90 to 40 mm, small radial tip clearances

[Diagram of the compressor with labels for From Intercooler, Inlet scroll, Steam injection for meridional flow improvement, Cooling steam, and Combustor]
Intercooler between C1 and C2

- Heat transfer between working fluid and high pressure steam from HRSG
- Outer shell is a solid tube with internal insulation

Vertical section

From C1

Guiding plates

To C2

To HRSG

From HRSG

Side view

180 tubes of 3.1 m length

Internal insulation
Combustion Chamber

- Design as presented at ASME 2003, scaled up from 75 to 400 net power
- Stoichiometric combustion of fossil fuel and O2 at 40 bar
- Combustor exit temperature: 1400 °C
- Oxidizer is not cooling medium, thus risk of incomplete combustion. So fuel and O2 inflow have to be kept in close contact in burner vortex
- Cooling of burner by steam wrapping around burner head, limits flame temperature and prevents acoustic vibrations excitation
- Annular flame casing with 6 quadruples of burner tubes
- Cooling of annular flame cage by recompressed working fluid flow
- Tangential arrangement provides additional flow path length for better mixture and pre-swirl for first turbine stage
Compressor Turbine HTTC for 50 Hz

- HTTC: reaction turbine with 2 subsonic stages and blade length of 100 mm and 164 mm
- Rotor cooling steam along the drum surface
- Nozzles and blades are cooled in conventional serpentine passage design with holes
HTTC alternative design

- Alternative HTTC expansion with one transonic stage
- Blade length of 120 mm at higher radius and loading
- Application of innovative cooling design developed for transonic flows using underexpanded jets from slots (ASME 2004)
Power Turbine HTTP for 50 Hz

- 5 stages with strong change of inner radius
- Last blade length of 750 mm at 1300 mm inner radius
- Internal insulation of intermediate bearing casing, design similar to HP steam turbine presented at ASME 1988, Amsterdam
- Necessary thrust equalization and drum surface cooling on the exhaust side by steam
Power Turbine HTTP for 60 Hz

- 4 stages with strong change of inner radius
- Last blade length of 600 mm at 1300 mm inner radius
- HTTC outlet and HTTP inlet at the same radius

1st and 2nd stage cooling

Rotor cooling

Thrust equalization and drum cooling
Comparison of turbo set 50 - 60 Hz

60 Hz: one-stage transonic HTTC

50 Hz: two-stage subsonic HTTC
Low Pressure Steam Turbine

- Inlet: 0.75 bar and 175°C
- Condensation pressure of 0.021 bar leads to a high volume flow
- At 50 Hz a four-flow design with three stages
- Transonic last stage with a blade length of 970 mm
- Expansion line crosses Wilson line at last stage inlet; thus formation of small droplets only in the exhaust
## Investment costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Scale parameter</th>
<th>Specific costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Plant [13]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment costs</td>
<td>Electric power</td>
<td>$/kW&lt;sub&gt;el&lt;/sub&gt; 414</td>
</tr>
<tr>
<td>S-Graz Cycle Plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment costs</td>
<td>Electric power</td>
<td>$/kW&lt;sub&gt;el&lt;/sub&gt; 414</td>
</tr>
<tr>
<td>Air separation unit [14]</td>
<td>O&lt;sub&gt;2&lt;/sub&gt; mass flow</td>
<td>$(/kg O&lt;sub&gt;2&lt;/sub&gt;/s) 1 500 000</td>
</tr>
<tr>
<td>Other costs (Piping, CO&lt;sub&gt;2&lt;/sub&gt;-Recirc.) [14]</td>
<td>CO&lt;sub&gt;2&lt;/sub&gt; mass flow</td>
<td>$(/kg CO&lt;sub&gt;2&lt;/sub&gt;/s) 100 000</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;-Compression system [14]</td>
<td>CO&lt;sub&gt;2&lt;/sub&gt; mass flow</td>
<td>$(/kg CO&lt;sub&gt;2&lt;/sub&gt;/s) 450 000</td>
</tr>
</tbody>
</table>

- yearly operating hours: 8500 hrs/yr
- capital charge rate: 12%/yr
- natural gas is supplied at 1.3 ¢/kWh<sub>th</sub>
### Comparison of Component Size

<table>
<thead>
<tr>
<th>Component</th>
<th>Conventional CC Plant 400 MW</th>
<th>Graz Cycle Plant 400 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>turbine of &quot;gas turbine&quot;/ HTT</td>
<td>667 MW</td>
<td>618 MW</td>
</tr>
<tr>
<td>compressor of &quot;gas turbine&quot;/ C1+C2+C3+C4</td>
<td>400 MW</td>
<td>232 MW</td>
</tr>
<tr>
<td>steam turbine/ HPT+LSPT</td>
<td>133 MW</td>
<td>120 MW</td>
</tr>
<tr>
<td>HRSG</td>
<td>380 MW</td>
<td>360 MW</td>
</tr>
<tr>
<td>Generator</td>
<td>400 MW</td>
<td>490 MW</td>
</tr>
</tbody>
</table>

- Turbine power of same size
- Compressor power smaller
- Generator power higher
<table>
<thead>
<tr>
<th>Cost of Electricity</th>
<th>Reference plant [23]</th>
<th>S-GC new version</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant capital costs  [$/kW_{el}]</td>
<td>414</td>
<td>414</td>
</tr>
<tr>
<td>Addit. capital costs [$/kW_{el}]</td>
<td>288</td>
<td></td>
</tr>
<tr>
<td>CO$<em>2$ emitted [kg/kWh$</em>{el}$]</td>
<td>0.342</td>
<td>0.0</td>
</tr>
<tr>
<td>Net plant efficiency [%]</td>
<td>58.0</td>
<td>53.1</td>
</tr>
<tr>
<td>COE for plant amort. [$/kWh$_{el}$]</td>
<td>0.58</td>
<td>0.99</td>
</tr>
<tr>
<td>COE due to fuel [$/kWh$_{el}$]</td>
<td>2.24</td>
<td>2.45</td>
</tr>
<tr>
<td>COE due to O&amp;M [$/kWh$_{el}$]</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Total COE [$/kWh$_{el}$]</td>
<td>3.52</td>
<td>4.24</td>
</tr>
<tr>
<td>Comparison</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differential COE [$/kWh$_{el}$]</td>
<td></td>
<td>0.72 (+ 20 %)</td>
</tr>
<tr>
<td>Mitigation costs [$/ton CO$_2$ capt.]</td>
<td></td>
<td>21.0</td>
</tr>
</tbody>
</table>
Favorable assumption of Göttlicher (VDI): 70 % additional capital costs for air supply and CO2 compression

But large uncertainty in cost estimation:

- e.g.: ASU: cost estimates differ between 230 and 400 $/kW_el
Conclusions

- **Graz Cylce** is an oxy-fuel power cycle of highest efficiency.
- Modified cycle configuration with condensation in the range of 1 bar with re-evaporation of pure steam to feed LPST results in a high net cycle efficiency above 53%.
- Output raised from industrial size of 75 MW to 400 MW net output.
- A design concept for this size is presented with two shafts, a fast running compression shaft and the power shaft and LPST.
- Economic comparison with reference plant shows the strong influence of capital costs on CO2 mitigation costs.
- Mitigation costs vary between 20 - 30 $/ton CO2 depending on additional investment costs (ASU).
- Presentation of a design solution for an oxy-fuel CO2 retaining gas turbine system which can by acceptance of international gas turbine industry be put into operation within a few years.