Thermische Kraftwerke höchsten Wirkungsgrades ohne CO2-Ausstoss

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12. SYMPOSIUM ENERGIEINNOVATION
Alternativen für die Energiezukunft Europas
15. – 17. Februar 2012
TU Graz, Österreich
Cycle Scheme for 600 MW net output

- **O2**
- **Fuel (methane)**
- **50 bar**
- **1500°C**
- **Combustor**
- **554°C**
- **180 bar**
- **557°C**
- **HPT**
- **Deaerator**
- **1 bar 572°C**
- **HRSG**
- **177°C**
- **572°C**
- **LPST**
- **Condenser**
- **172°C 0.75 bar**
- **0.021 bar**
- **CO2**
- **Cycle Fluid 79% H2O 21% CO2**
- **Cycle Fluid**
- **C0, C1, C2**
- **Cycle Fluid Compressors**
- **C3, C4**
- **Cycle Fluid Compressors**
- **HRSG**
- **Heat Recovery Steam Generator**

**Symbols and Units**:
- **HTT**: High Temperature Turbine
- **HPT**: High Pressure Steam Turbine
- **LPST**: Low Pressure Steam Turbine
- **C0, C1, C2**: Cycle Fluid Compressors
- **C3, C4**: Cycle Fluid Compressors
- **HRSG**: Heat Recovery Steam Generator
<table>
<thead>
<tr>
<th></th>
<th>400 MW</th>
<th>600 MW</th>
<th></th>
<th>400 MW</th>
<th>600 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTT power [MW]</td>
<td>617.9</td>
<td>908</td>
<td>Net shaft power [MW]</td>
<td>504.7</td>
<td>746</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>w/o mechanical losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HPT power [MW]</td>
<td>49.9</td>
<td>62</td>
<td>Total heat input Q_{zu} [MW]</td>
<td>758.6</td>
<td>1100</td>
</tr>
<tr>
<td>LPST power [MW]</td>
<td>71.6</td>
<td>101</td>
<td><strong>Thermal cycle efficiency [%]</strong></td>
<td>66.52</td>
<td>67.6</td>
</tr>
<tr>
<td><strong>Total turbine power P_T [MW]</strong></td>
<td>739.4</td>
<td>1071</td>
<td>Electrical power output [MW] incl. mechanical, electrical &amp; auxiliary loss</td>
<td>490.7</td>
<td>724.6</td>
</tr>
<tr>
<td>C0 power [MW]</td>
<td>-</td>
<td>8.8</td>
<td><strong>Net electrical cycle efficiency [%]</strong></td>
<td>64.68</td>
<td>65.71</td>
</tr>
<tr>
<td>C1 power [MW]</td>
<td>131.1</td>
<td>178</td>
<td>O_2 generation &amp; compression P_{O_2} [MW]</td>
<td>74.7</td>
<td>109</td>
</tr>
<tr>
<td>C2 power [MW]</td>
<td>82.6</td>
<td>108</td>
<td><strong>Efficiency considering O_2 supply [%]</strong></td>
<td>54.83</td>
<td>55.83</td>
</tr>
<tr>
<td>C3+C4 power [MW]</td>
<td>15.5</td>
<td>23</td>
<td>CO_2 compression to 100 bar P_{CO_2} [MW]</td>
<td>13.0</td>
<td>18.6</td>
</tr>
<tr>
<td>Pump power [MW]</td>
<td>5.5</td>
<td>7.2</td>
<td><strong>Net power output [MW]</strong></td>
<td>403.0</td>
<td>597</td>
</tr>
<tr>
<td><strong>Total compression power P_C [MW]</strong></td>
<td>234.7</td>
<td>325</td>
<td><strong>Net efficiency [%]</strong></td>
<td>53.12</td>
<td>54.14</td>
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</tbody>
</table>
• Main gas turbine components on two shafts for **600 MW** net output
• Compression shaft of 8500 rpm: cycle compressors C0, 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
Main Turbo Shaft

- Main gas turbine components on two shafts for **600 MW** net output
- Higher power obtained by design improvements (higher compression ratio, higher peak temperature)

Single stage transonic turbine drives compressor shaft (C0, C1 and C2)

Power turbine HTTP –
5 subsonic stages at 50 Hz
4 subsonic stages at 60 Hz
C0 and C1 compressor details

- Pre-arranged loading compressor C0 serves for higher mass flow to combustion chamber keeping volume flow to C1 equal to previous layout
- Speed change allows to keep tip Mach number at 1.3
High Speed Shaft (8500 rpm)

- Compressors C1 und C2 for working fluid (79% H2O/ 21 % CO2) and HTTC
Steam Cooling Details of HTTC and C2

- HTTC and C2 on common shaft with a disk of constant stress
- Disk is cooled on both sides with cooling steam of 300 °C
- Cooling steam on right-hand-side: balancing of axial thrust
- C2 rotor: cooling to avoid creep
Transonic Stage Steam Cooling

- Cooling steam entry through hollow nozzles
- Collection in inner annular chamber
- Jet in partly tangential direction to provide optimal inflow into blade root
- Radial outflow of cooling steam through fir-tree root into hollow blade in innovative cooling system (ICS)

Exit of under-expanded transonic steam flow covering whole blade surface by a coherent layer of steam

ICS cooling slits

High-reaction high-flow-efficiency blade channel
3D cooling arrangement of HTTC stage (previous work)

Blade with ICS steam cooling as proposed for 75 MW Graz Cycle presented at ASME Turbo Expo Atlanta 2003
• Power Plants using photovoltaics, tidal flow, wind, ... produce electricity at different time periods and different locations
• Electrolysers split water and H2 and O2 are delivered to storage tanks which feed several new hybrid plants in generating peak power

Wind power (see e.g. proposal Max Platzer, 2009)

High-pressure tanks allow peak power generation

New Hybrid FC-GT Plant

Electrolyser

H2

O2

Electrolyser

Electrolyser

Photovoltaics
(see work of Princeton Univ. 1984)

Solar thermal plant

Tidal power
Principle Flow Scheme

**Electric Power**

- **O₂**
- **H₂**

**Combustion of H₂ surplus**

**H₂O – hot steam**

**H₂O – hot steam**

**Motor/Generator**

**Start + Peak power**

41 bar 600°C

**Gear**

**CC**

**HTT1** High Temperature Compressor Turbine

**HTT2** High Temperature Power Turbine

**HPT** High Pressure Steam Turbine

**LPT** Low Pressure Steam Turbine

**C** Steam Compressors

**FC** Fuel Cells

**HRSG** Heat Recovery Steam Generator

**Feed water**

**Deaerator**

0.05 bar

**Condenser**

**Main Generator**

**Start + Peak power**

40 bar 1550°C

**Gear**
Hybrid Plant

- High-speed shaft of 22432 rpm with high-pressure turbine, steam compressor and HTTC
- HTTP runs at 9400 rpm and drives generator via a gear box
- Low-pressure turbine at 3000 rpm
- Arrangement of fuel cells between compressor outlet and turbine combustion chamber inlet
## Power Balance

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Fuel input</td>
<td>1.568 kg/s H2, 12.44 kg/s O2</td>
</tr>
<tr>
<td>Total heat input</td>
<td>188 MW</td>
</tr>
<tr>
<td>HTT power</td>
<td>123.1 MW</td>
</tr>
<tr>
<td>HPT power</td>
<td>22.4 MW</td>
</tr>
<tr>
<td>LPT power</td>
<td>14.3 MW</td>
</tr>
<tr>
<td>Compressor power</td>
<td>47.8 MW</td>
</tr>
<tr>
<td>Total pump power</td>
<td>0.7 MW</td>
</tr>
<tr>
<td>Generator power</td>
<td>109.6 MW</td>
</tr>
<tr>
<td>Fuel cell DC power</td>
<td>30 MW</td>
</tr>
<tr>
<td>Fuel cell AC power</td>
<td>29.1 MW</td>
</tr>
<tr>
<td>Net electrical power</td>
<td>138.7 MW</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>73.8 %</td>
</tr>
</tbody>
</table>
• **Compressor**: double flow rotor with two axial stages on each side connected to a radial disk. Symmetric arrangement creates an optimal flow situation in the radial diffuser. Axial stages: half of the compressor pressure head, first axial stages have a maximum tip Mach number of 1.4.

• High rotational speed of **22432 rpm** to achieve a reasonable enthalpy drop for the HTT1 and especially for the HPT despite their small dimensions as a result of the low volume flow.

• **HTT2 at 9400 rpm**: reasonable stage number of five at bearable disk stresses at the same time. Solid rotor design with blade lengths from 90 mm to 350 mm attached in fir-tree roots on small elongation disks on the rotor drum. For the cooling: innovative cooling system ICS is applied.

• **HPT**: 50 % reaction blading and multiple stages at low rotor diameter. A balance piston is arranged in the usual way.