Partial Load Characteristics of the Supercritical CO₂ Gas Turbine System for the Solar Thermal Power System with the Na-Al-CO₂ Heat Exchanger

Yasushi Muto, Noriyuki Watanabe, Masanori Aritomi, Takao Ishizuka
Tokyo Institute of Technology
Objective of this study
To show the technical feasibility of the new solar power system for the partial load operation

Contents
1. The design of the new solar thermal power generation system provided with a Na cooled receiver, an Al heat storage heat exchanger and the supercritical CO$_2$ gas turbine.
2. Partial load calculation method
3. Results of partial load calculation.
4. Conclusions
New Solar Thermal Power Generation with a S-CO₂ Gas Turbine

Incident Sunbeam
Thermal Energy = 125 MW
- Heliostat field diameter 800m
- Number of heliostats (φ3.4m) 42,519
- Central receiver height from the ground 100m

Due to the reference (Hasuike)

Na–Al–CO₂ Heat Exchanger
Aluminum
- Thermal conductivity 237 W/m/K
- Melting point 660°C
- Heat of fusion 397 kJ/kg
- Specific heat 0.897 kJ/kg.K

Na is an excellent heat transfer fluid.
- Thermal conductivity 70 W/m/K
- Thermal conductivity of molten salt 0.6 W/m/K
- Specific heat 1.3 kJ/kg.K
Receiver

Na Flow channel

800H Shell

Thermal Energy transferred to Na = 83.94 MW

Radiation loss 25.24 MW

Convection loss 3.32 MW

Reflection loss 12.5 MW

Solar Radiation 125 MW
Na-Al-CO₂ Heat Exchanger

Na (700°C)
CO₂ (650°C, 20.17 MPa)
Aluminum (3360 ton)
Latent heat capacity (103 MW.hr)
Sensible heat capacity (292 MW.hr)

CO₂ (460°C, 20.2 MPa)
Ar-gas Na (600°C)

Tube pitches
PH=0.3025m
PB=0.26m
Number of rows
NH=7
NB=160

7 arrays with 0.30 m pitch

Na tubes
φ60.5 mm, ID53.5 mm

CO₂ tubes
φ60.5 mm, ID34.7 mm

8.41 m
83.14 m
160 rows with 0.26m pitch
2.22 m
83.14 m
Daily Power Demand and Aluminum Volume for the Heat Storage

• 50% of total solar thermal energy are needed to be stored (Reference Dunn).

• Demand assumed
  Daytime       7:30 a.m. - 4:30 p.m.  100% of full power × 9 hr
  Night         4:30 p.m. - 8:00 p.m.  90% of full power × 3.5 hr
                8:00 p.m. - 10:00 p.m.  80% of full power × 2 hr
                10:00 p.m. - 6:00 a.m.  38% of full power × 8 hr
                6:00 a.m. - 7:30 a.m.  80% of full power × 1.5 hr

• Aluminum volume for the heat storage
  Melting of 30% is assumed.
  Aluminum vessel dimensions = W8.41 m x H2.22 m x D83.1 m
  weight = 3,360 ton
  Heat storage capacity
  Latent heat = 103 MW.hr
  Sensible heat = 292 MW.hr for the temperature difference of 300°C
Supercritical CO₂ GT Cycle

Assumptions

• Turbine adiabatic efficiency 92%
• Compressor adiabatic efficiency 88%
• Pressure loss (ratios over the inlet pressure)
  ① Heat source 1.0%
  ② Recuperator high temperature side 1.2%
  ③ Recuperator low temperature side 0.4%
  ④ Precooler 1.0%
  ⑤ Intercooler 0.8%
• Recuperator average temperature effectiveness 89%

Cycle Thermal Efficiency = 48.2%
Recuperator Designs

PCHE (Printed Circuit Heat Exchanger)

S-shaped fins

Length (1.0m)

Width (0.26m)

Height (parameters)

High Temperature CO₂

Low Temperature CO₂

CO₂

CO₂
## Design Conditions of the Recuperators

<table>
<thead>
<tr>
<th>Items</th>
<th>Supercritical CO₂ Gas Turbine</th>
<th>RHX-1</th>
<th>RHX-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recuperator effectiveness %</td>
<td></td>
<td>89</td>
<td>89</td>
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<tr>
<td>Number of modules</td>
<td></td>
<td>5</td>
<td>5</td>
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<tr>
<td>Heat load (MW/ modules)</td>
<td></td>
<td>12.17</td>
<td>5.39</td>
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<tr>
<td>HT side</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Flow rate (kg/s)</td>
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<td>35.52</td>
<td>35.52</td>
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<tr>
<td>Inlet temperature (°C)</td>
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<td>509.9</td>
<td>210.7</td>
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<tr>
<td>Inlet pressure (MPa)</td>
<td></td>
<td>6.780</td>
<td>6.698</td>
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<tr>
<td>LT side</td>
<td></td>
<td></td>
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<tr>
<td>Flow rate (kg/s)</td>
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<td>35.52</td>
<td>22.84</td>
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<tr>
<td>Inlet temperature (°C)</td>
<td></td>
<td>190.3</td>
<td>69.0</td>
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<tr>
<td>Inlet pressure (MPa)</td>
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<td>20.283</td>
<td>20.365</td>
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# Results of the Recuperator Designs

<table>
<thead>
<tr>
<th>Items</th>
<th>Supercritical CO₂ Gas Turbine</th>
<th>RHX-1</th>
<th>RHX-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width × Length × module</td>
<td></td>
<td>0.26 × 1.0</td>
<td>0.26 × 1.0</td>
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<tr>
<td>Height m/ module</td>
<td></td>
<td>4.24</td>
<td>3.65</td>
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<tr>
<td>Weight ton/ module</td>
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<td>7.90</td>
<td>6.80</td>
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<tr>
<td>Total weight ton</td>
<td></td>
<td>39.5</td>
<td>34.0</td>
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<tr>
<td>Heat transfer capacity MW</td>
<td></td>
<td>12.19</td>
<td>5.42</td>
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<tr>
<td>Pressure loss ratio (dP/Pinlet) %</td>
<td>HT side</td>
<td>0.74</td>
<td>0.27</td>
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<tr>
<td></td>
<td>LT side</td>
<td>0.58</td>
<td>0.08</td>
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<tr>
<td>Effective heat transfer area m²</td>
<td>HT side</td>
<td>413.7</td>
<td>354.6</td>
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<tr>
<td></td>
<td>LT side</td>
<td>206.8</td>
<td>177.3</td>
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<td>Overall heat transfer coefficient J/m²/K/s</td>
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<td>909</td>
<td>1049</td>
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Partial Load Control
Inventory (pressure level) control
Partial Load Analysis Calculation Assumptions

1. The rotational speed is kept constant by the generator to meet the power grid frequency.

2. In this condition, the pressure ratio of both the turbine and the compressors should not be varied and should be kept in the rated values.

3. It is assumed that the bypass flow rate is kept constant.
Assumptions (Continued)

1. Pressure loss ratios of the components are assumed constant.
2. Inlet temperatures of both the low pressure compressor and the high pressure compressor are assumed to be kept constant by regulating the pre-cooler flow rate.
3. The inlet temperature of the RHX-1 high pressure side is calculated as the mixture of thermal energies of the RHX-2 high pressure side outlet gas and that of the bypass compressor outlet gas.
Fixed Input Data

1. Turbine pressure ratio (2.95), low pressure compressor pressure ratio (1.26)
2. Low pressure compressor inlet temperature (35°C), high pressure compressor inlet temperature (35°C)
3. Component pressure ratios, which are the same values with those for the design
4. Turbine adiabatic efficiency (92%), compressor adiabatic efficiency (88%), generator efficiency (98%)
5. Design turbine flow rate (166.72 kg/s)
6. Design bypass flow ratio (0.357)
7. Design turbine inlet temperature (650°C), Design turbine inlet pressure (20MPa)
8. Design turbine inlet CO₂ density (110 kg/m³)
9. Recuperators dimensions
Input Data Varied

1. Turbine inlet pressure (MPa)
2. Turbine inlet temperature (°C)

*To adjust the daily power demands.*

*Dependent on them, CO₂ density changes and then, CO₂ mass flow rate change.*
Partial Load Analysis Procedure

Step 1
Receiver calculation

Q sun 125 MW

700° C, 0.15 MPa

Na-Al-CO₂ Heat Exchanger

Na Pump

Solar Receiver

Q transfer 41.97 MW

Q store 41.97 MW

600° C, 0.16 MPa

Step 2
HX Calculation

Adiabatic at night

Na 83.94 MW

600° C, 0.11 MPa

Step 2+
S-CO₂ Cycle Calculation

T_{CO₂} P_{CO₂} m_{CO₂}

S-CO₂ Gas Turbine

Determine the turbine inlet CO₂ pressure and temperature so as to adjust the demand

Q store 41.97 MW

Determine the turbine inlet CO₂ pressure and temperature so as to adjust the demand

Q sun 125 MW

125 MW

83.94 MW

41.97 MW

41.97 MW

Na 600° C, 0.16 MPa

Na Pump

Adiabatic at night

T_{CO₂} P_{CO₂} m_{CO₂}

S-CO₂ Gas Turbine

Determine the turbine inlet CO₂ pressure and temperature so as to adjust the demand
Results of Partial Load Analyses
Turbine inlet pressure and temp. (Input data)

Pressure (MPa)

Temperature (°C)

Time (hr)
Heater load, Generator power and cycle thermal efficiency

Cycle thermal efficiency (%)
Minimum efficiency 26.3 %
Heater load (MW)
Generator power (MWe)

Time (hr)
End temperature differences of recuperator 1 and 2

Too low pressure results in the too small temperature difference

Minimum 1.6°C
Energy Balance

- **Average thermal efficiency** = \( \frac{303.1 \text{ MWe}.\text{hr}}{1125 \text{ MW}.\text{hr}} = 26.9\% \)
- **Average power generating efficiency** = \( \frac{303.1 \text{ Mwe}.\text{hr}}{755 \text{ MW}.\text{hr}} = 40.2\% \)

Receiver efficiency = 67.15%

Mean gross efficiency = 18.1%

*(Zhang, H. L. et. al., Renewable and Sustainable Energy Reviews 22 (2013) 466-481)*

- From heliostat 125MW
- Reflection 12.5MW
- Radiation 25.24 MW

**Daytime**
- 153.9 MWe hr
- 14.31 MWe to 18.62 MW

**Night**
- 149.2 MWe hr
- 4.70 MWe to 12.36 MWe

**From S-CO2**
- 377.7 MW hr

**Energy Flow**

- Sodium 83.94 MW X9 hr
- Al 41.97 MW X9 hr
- Convection 3.32 MW
- Latent 103.4 MWh
- Sensible 274.3 MWh
Conclusions

1. 50% solar thermal energy should be stored in aluminum for the night power demand. The aluminum inventory becomes 3,000 tons, where the latent and sensible heat storages are 103.4 MW.hr and 274.9 MW.hr, respectively. The aluminum vessel dimensions are 8.41 m width, 2.22 m height and 83.14 m depth.

2. From the sunset (4:30 p.m.) to 7:15 p.m., the power is supplied by the latent heat. In the midnight, the turbine inlet pressure falls to the minimum of 9.1 MPa. Minimum temperature difference of the recuperater becomes 1.6°C. The turbine inlet temperature becomes the minimum of 371°C at 7:30 a.m. early in the morning.

3. Total 303.1MWe.hr are produced. The average thermal efficiency and the average cycle efficiency are 26.9% and 40.12%, respectively.

4. The partial operation of this system is technically feasible though more comprehensive studies including turbomachinery are needed.