Optimal Design of Gas Turbine-Solid Oxide Fuel Cell Hybrid Plant

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Solid Oxide Fuel Cells

Common electrolyte:
Yttria stabilized zirconia

Operating temperature:
600-1000°C

System output:
1kW-3kW

Electrical efficiency:
35-43%

Combined heat and power efficiency:
<90%
Solid Oxide Fuel Cells

**Advantages:**
- High efficiency
- Fuel flexibility
- Can use a variety of catalysts
- Solid electrolyte reduces electrolyte management problems
- Suitable for CHP
- Suitable for Hybrid GT/cycle

**Application:**
- Auxiliary power
- Electric utility
- Large distributed generation
PLANTS’ CONFIGURATION

1. Air
2. Fuel (CH₄)
3. SOFC
4. Combustor
5. Gas Turbine
6. Power Turbine
7. DC
8. Recuperator
## Thermodynamic modeling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine efficiency</td>
<td>0.84</td>
</tr>
<tr>
<td>Compressor efficiency</td>
<td>0.81</td>
</tr>
<tr>
<td>Power turbine efficiency</td>
<td>0.89</td>
</tr>
<tr>
<td>Recuperator effectiveness</td>
<td>0.8</td>
</tr>
<tr>
<td>Combustor efficiency</td>
<td>0.98</td>
</tr>
<tr>
<td>Air utilization factor</td>
<td>0.25</td>
</tr>
<tr>
<td>Fuel utilization factor</td>
<td>0.85</td>
</tr>
<tr>
<td>Steam to carbon ratio</td>
<td>2.5</td>
</tr>
<tr>
<td>Stack temperature (K)</td>
<td>1273</td>
</tr>
<tr>
<td>Current density (A/cm$^2$)</td>
<td>0.3</td>
</tr>
<tr>
<td>Cell area (cm$^2$)</td>
<td>834</td>
</tr>
<tr>
<td>Ambient temperature (K)</td>
<td>288</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>1</td>
</tr>
<tr>
<td>Lower heating value of CH4 (kJ/kg)</td>
<td>50050</td>
</tr>
</tbody>
</table>
Thermodynamic modeling

**Recuperator**

\[
\dot{m}_{R} = \dot{m}_{2} + \frac{\dot{m}_{3}}{h_{21}^{+}} (\ldots)
\]

\[
\chi_{\text{rec}}^T = \frac{\epsilon + 1}{\epsilon} \frac{T_{2}^{+}}{T_{1}^{+}} + 2
\]

\[
\dot{W}_{\text{ehh}} = + \frac{1}{12} (\ldots)
\]
Thermodynamic modeling

**SOFC**

**Anode:**

\[
\begin{align*}
\text{Net cell reaction} & \quad 2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O} + 2 e^- \\
\text{Anode} & \quad \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O} + 2 e^- \\
\text{Electrode} & \quad \text{H}_2 \rightarrow 2 \text{H}^+ + 2 e^- \\
\text{Cathode} & \quad \text{O}_2 \rightarrow 2 \text{O}^- + 4 e^- \\
\text{Net cell reaction} & \quad 2 \text{H}_2 + \text{O}_2 \rightarrow 2 \text{H}_2\text{O} + 2 e^- \\
\end{align*}
\]
Thermodynamic modeling

\[ \dot{W}_{\text{Comb}} = \dot{m}_{\text{in}} C_{\text{m}} \frac{\dot{m}_{\text{in}}}{\dot{m}_{\text{fuel,Comb}}} \]  

\[ \phi_{\text{GT}} = \frac{\dot{m}_{\text{fuel,Comb}}}{6} \]  

\[ \dot{m}_{\text{in}} C_{\text{m}} = \dot{W}_{\text{in}} \]  

\[ \dot{Q}_{\text{loss fuel, Comb}} = \frac{6}{6s} \]  

\[ \dot{W}_{\text{m,th, PT}} = -\dot{m}_{\text{in}} C_{\text{m}} \]
Thermodynamic modeling

$$\phi_{th}^{cycle} = \frac{\dot{W}_{net}}{\dot{Q}_{tot}}$$

$$\dot{W}_{net} = FC_{acGen}$$

$$\dot{W}_{FC_{ac}} = \phi_{invert}\dot{W}_{FC_{dc}}$$

$$\dot{W}_{Gen} = \phi W_{PT}$$

$$\dot{Q}_{ion} = fuelFC_{comb} \rightarrow ULHVQ CH_4$$

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COST EVALUATION

\[ \frac{C_{AT \ SOFC}}{C_{SOFC}} = 2.961907 \quad \text{stack} \]

\[ C_{inverter} = 10^5 \times 0.7 \frac{W_{FCdc}}{500} \]

\[ C_{SOFC_{aux}} = 0.1 \]

\[ C_{turbine} = \left( \frac{W_{GTPT}}{GPT} \right) \times 18.598328 \ln ( \ ) \quad 0.67 \]

\[ C_{comp} = 91562 \times \frac{W_{comp}}{445} \]
Multi objective optimization

• Most of the real world optimization problems are dealing with more than one objective functions.
• These Objective functions can be conflicting
• Traditional optimization methods are not appropriate for these types of problems
• Genetic algorithm has been successfully tested for multiple objective problems
## Multi objective optimization

### Objective functions:
- Efficiency
- Cost

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure outlet of the compressor, $P_2$</td>
<td>40 2.10^8 Pa ( )</td>
</tr>
<tr>
<td>Flow rate of inlet air, $\dot{m}_1$</td>
<td>2.5-5 (kg/s)</td>
</tr>
<tr>
<td>Flow rate of inlet fuel to combustor, $\dot{m}_{fuel, Comb}$</td>
<td>0.01-0.03 (kg/s)</td>
</tr>
</tbody>
</table>

Population size and termination tolerance:
- Population size: 40
- Termination tolerance: $10^{-4}$

Optimization terminated after 124 generation
## Optimization results

<table>
<thead>
<tr>
<th>( \dot{m}_{\text{fuelComb}} )</th>
<th>( P_{\text{in}} )</th>
<th>( \dot{m}_1 ) (kg/s)</th>
<th>( \phi_{\text{th}} )</th>
<th>Cost (not specified)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01004</td>
<td>202144.7</td>
<td>2.77531</td>
<td>-0.568</td>
<td>5.39E+08</td>
</tr>
<tr>
<td>0.01019</td>
<td>201190.5</td>
<td>2.62401</td>
<td>-0.575</td>
<td>5.49E+08</td>
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<tr>
<td>0.01107</td>
<td>218338.7</td>
<td>2.512497</td>
<td>-0.578</td>
<td>5.86E+08</td>
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<tr>
<td>0.01073</td>
<td>233678.8</td>
<td>2.766003</td>
<td>-0.581</td>
<td>6.18E+08</td>
</tr>
<tr>
<td>0.01089</td>
<td>242689.1</td>
<td>2.817732</td>
<td>-0.588</td>
<td>6.5E+08</td>
</tr>
<tr>
<td>0.01077</td>
<td>238215.6</td>
<td>2.83126</td>
<td>-0.592</td>
<td>6.54E+08</td>
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<tr>
<td>0.01043</td>
<td>244868.2</td>
<td>2.920349</td>
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<td>6.75E+08</td>
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<tr>
<td>0.01135</td>
<td>257280.3</td>
<td>2.536014</td>
<td>-0.599</td>
<td>6.79E+08</td>
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<tr>
<td>0.01229</td>
<td>259090.6</td>
<td>2.691334</td>
<td>-0.605</td>
<td>7.23E+08</td>
</tr>
<tr>
<td>0.01139</td>
<td>324479.8</td>
<td>2.584347</td>
<td>-0.606</td>
<td>7.55E+08</td>
</tr>
<tr>
<td>0.01061</td>
<td>334861.1</td>
<td>2.5482</td>
<td>-0.617</td>
<td>7.7E+08</td>
</tr>
<tr>
<td>0.01052</td>
<td>396885.4</td>
<td>2.526984</td>
<td>-0.628</td>
<td>8.31E+08</td>
</tr>
<tr>
<td>0.01198</td>
<td>382681</td>
<td>2.502595</td>
<td>-0.629</td>
<td>8.5E+08</td>
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<tr>
<td>0.01086</td>
<td>415453.3</td>
<td>2.621838</td>
<td>-0.633</td>
<td>8.72E+08</td>
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<tr>
<td>0.01101</td>
<td>498681</td>
<td>2.549965</td>
<td>-0.635</td>
<td>9.17E+08</td>
</tr>
</tbody>
</table>
Optimization results
Thank You for Your Attention!
Questions