A Study on the Performance of the HTGR Cogeneration System at Various Operating Conditions for Proposing Optimum Scenarios

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Several studies on the concept and safety of the HTGR cogeneration system have been conducted (T. Nishihara, 2006, K. Ohashi, 2007);
The economical investigation for the GTHTR300 with only one product – electricity (M. Takei, 2006) has been conducted;

Several future development scenarios of the HTGR cogeneration system with multiple products have been proposed, the performance of them need to be calculate for proposing the optimum scenarios while have never been done due to the lack of feasible method.
Objectives of this Study

- Modeling the target HTGR cogeneration system with multiple products and the identifying independent parameters to form various operating conditions;

- Study the thermodynamic and economic performances of the HTGR cogeneration system with multiple products at various operating conditions using exergy and exergy costing analyses;

- Proposing optimum scenarios from the analysis results at all operating conditions, and then testing the feasibility and profitability of them.
A Typical HTGR Cogeneration System and Its Initial Parameters

HTGR (600MWt)

1. He(950°C, 5.1Mpa, 324kg/s)

2. He(900°C, 5.1Mpa)

3. He(500°C, 5.1Mpa)

4. He(5.1Mpa, 324kg/s)

5. He(594°C, 5.1Mpa, 324kg/s)

6. Cold Water

7. Hot Water

8. IHX

9. IS

10. Compressor

11. Precooler

12. Generator

Products
- Hydrogen
- Electricity
**Exergy and Exergy Costing Analyses based on EXCEM Model**

**EXCEM**

\[
\begin{align*}
\text{Ex}_\text{Fuel} - \text{Ex}_\text{Product} - \text{Ex}_\text{Consumption} &= M_{\text{accumulation}} \\
C_{\text{Fuel}} + C_{\text{generation}} - C_{\text{Product}} &= C_{\text{accumulation}} \\
E_{\text{Fuel}} - E_{\text{Product}} &= E_{\text{accumulation}} \\
M_{\text{Fuel}} - M_{\text{Product}} &= M_{\text{accumulation}}
\end{align*}
\]

- Due to the exergy destruction and loss
- Due to the capital and MO costs
- Conservation
- Conservation

**Exergy Analysis**

- Can identify the location, magnitude and source of the thermodynamic losses, thus can assess the thermodynamic performance of the system comprehensively.

\[
\epsilon = \frac{\text{Ex}_p}{\text{Ex}_F} = 1 - \frac{(\text{Ex}_D + \text{Ex}_L)}{\text{Ex}_F}
\]

Ex: Exergy, F: Fuel, P: Product
D: Destruction L: Loss

**Exergy Costing Analysis**

- Can estimate the cost of each product in a cogeneration system by allocating the cost based on exergy.

\[
\begin{align*}
c_F &= \frac{C_F}{\text{Ex}_F} \\
c_P &= \frac{C_p}{\text{Ex}_p} = \frac{C_F + Z}{\text{Ex}_p}
\end{align*}
\]

C: Cost per unit exergy, C: Cost, F: Fuel, P: Product, Z: Cost information of the component
The reactor can be simply modeled as a heat source, adiabatic and constant pressure.

\[ E_{HTGR} = m_{he}C_{pHe}(T_1 - T_7) \]

\[ m_{he,Main}C_{pHe}(T_1 - T_2) = m_{he,IS}C_{pHe}(T_9 - T_8) \]

HTGR

IHX

The IHX in this study are considered as adiabatic

Generating hydrogen through IS process using the HTGR heat.

\[ P_{Hydrogen} = m_{He,IS}C_{pHe}(T_9 - T_8) \times 0.5 / 286 \times 22.4 \times 10^{-3} \times 3600 \text{ (m}^3 / \text{h)} \]

From H. Karasawa, 2005
Basic Thermodynamic Analysis of Component(2)

The compressor are described as polytrophic processes with the efficiency due to the frictions.

\[ E_6 - E_5 = m_{He} C_{P_{He}} (T_6 - T_5) = W \]

\[ \frac{T_{6s}}{T_5} = PR^{\frac{k-1}{k}} \quad \frac{T_{6s} - T_5}{T_6 - T_5} = \eta_{comp} \]

The turbine are described as polytrophic processes with the efficiency \( \eta_{turb} \) due to the frictions.

\[ T_{3s} = \frac{1}{PR} \left( \frac{k-1}{k} \right) \quad \frac{T_2 - T_3}{T_2 - T_{3s}} = \eta_{turb} \]

\[ E_2 - E_3 = m_{He} C_{p_{He}} (T_2 - T_3) = \text{Electricity} \]
Basic Thermodynamic Analysis of Component(3)

**Precooler**

The heater for water stream in this study are considered as adiabatic

\[ m_{\text{water}}(h_{11} - h_{10}) = m_{\text{he,Main}}Cp_{He}(T_4 - T_5) \]

\[ T_4 - T_{10} \geq \Delta T \]

**Recuperator**

The thermodynamic analysis of the recuperator is similar with the IHX

\[ m_{\text{he,Main}}Cp_{He}(T_3 - T_4) = m_{\text{he,Main}}Cp_{He}(T_7 - T_6) \]

\[ T_3 - T_7 \geq \Delta T, T_4 - T_6 \geq \Delta T \]
Exergy and Exergy Costing Analyses for the HTGR System

Exergy Analysis for whole system

\[ \varepsilon_{\text{whole}} = \frac{Ex_{10} + Ex_{12}}{Ex_0 + Ex_9} \times 100\% \]

- Ex0 = 600MWt

Exergy Costing Analysis

Hydrogen Cost

Hydrogen Cost = Water Cost + Components + Reactor(Ex1-Ex2)/(Ex1-Ex7)

Electricity Cost

Electricity Cost = Components + Reactor(Ex2-Ex7)/(Ex1-Ex7)
Determining the Independent Parameters and Their Valid ranges

Preconditions

Independent Parameters
T2, T5 and PR

Valid Ranges

740°C ≤ T2 ≤ 850°C
30°C ≤ T5 ≤ 160°C
1.5 ≤ PR ≤ 2

Constrains

\[ T_3 = \left( T_2 - \eta_{\text{tur}} \times \left( T_2 - T_2 PR^{1-k} \right) \right) > T_7 \]

\[ T_4 < T_6 \]

......
Conducting the Exergy and Exergy Costing Analyses at Various Operating Conditions

- Independent Parameters: T2, T5, and PR

Exergy and Exergy Costing Analyses Of HTGR Cogenreation System

Performance:
- Production
- Efficiency
- Cost

Optimum Result:
- Select optimum scenarios
EXCEM Studio for Conducting the Exergy and Exergy Costing Analyses at Various Operating Conditions

Exergy and Exergy Costing analyses of HTGR Cogeneration system
Results of Exergy and Exergy Costing Analyses
Productions of Hydrogen and Electricity at Various Operating Conditions

- **HTGR (600MWt)**
- **Compressor**
- **Recuperator**
- **IHX**
- **Precooler**
- **Generator**
- **Electricity**

**He** (990°C, 5.1Mpa, 324kg/s)

**He** (950°C, 5.1Mpa, 324kg/s)

**He** (594°C, 5.1Mpa, 324kg/s)

**Cold Water**

**Hot Water**

**Hydrogen**

**PR = P6/P5**

**Electricity Production at PR = 1.5**

**Electricity Production at PR = 1.7**

**Electricity Production at PR = 2**

Graph showing the relationship between T2 (°C) and Hydrogen production (m³/h).
Exergy Efficiency at Various Operating Conditions by Exegy Analysis

Exergy efficiency

Exergy Efficiency at PR=1.5

Exergy Efficiency at PR=1.7

Exergy Efficiency at PR=2

T5 T2

T5 T2

T5 T2
Costs of Hydrogen and Electricity at Various Operating Conditions by Exergy Costing Method

Hydrogen Producing Cost $/(1000M3) at PR=1.5

Electricity Producing Cost $/(KWh) at PR=1.5

Hydrogen Producing Cost $/(1000M3) at PR=1.7

Electricity Producing Cost $/(KWh) at PR=1.7

Hydrogen Producing Cost $/(1000M3) at PR=2

Electricity Producing Cost $/(KWh) at PR=2

T2(°C)

T2(°C)

T2(°C)

T2(°C)

T5=30  T5=50  T5=100  T5=150

T5=30  T5=50  T5=100  T5=150

T5=30  T5=50  T5=100  T5=150

T5=30  T5=50  T5=100  T5=150
Based on the previous analysis results of the exergy and exergy costing analyses, three optimum scenarios are proposed here as three examples for satisfying different hydrogen demand scenarios.

<table>
<thead>
<tr>
<th>Case</th>
<th>T2</th>
<th>T5</th>
<th>PR</th>
<th>Production E (MWe)</th>
<th>Production H2 (Nm3/h)</th>
<th>Cost E($/Kwh)</th>
<th>Cost H2 ($/Nm3)</th>
<th>ExEf(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>740</td>
<td>30</td>
<td>1.5</td>
<td>130.2</td>
<td>49897.1</td>
<td>0.0251</td>
<td>0.100</td>
<td>46.03</td>
</tr>
<tr>
<td>Case2</td>
<td>790</td>
<td>30</td>
<td>1.7</td>
<td>174.2</td>
<td>38016.8</td>
<td>0.0246</td>
<td>0.102</td>
<td>47.58</td>
</tr>
<tr>
<td>Case3</td>
<td>850</td>
<td>30</td>
<td>2.0</td>
<td>231.2</td>
<td>23760.5</td>
<td>0.0239</td>
<td>0.106</td>
<td>50.13</td>
</tr>
</tbody>
</table>

**Graphs:**
- Hydrogen Cost ($/1000M3)
- Electricity Cost (Cent/Kwh)
Conclusion

- The **thermodynamic and economic** performances of the HTGR cogeneration system with multiple products have been investigated by using **exergy and exergy costing analysis** methods at various operating conditions;

- The analysis results show that the HTGR cogeneration system is **thermodynamic efficient and economical competitive** system comparing with other hydrogen and electricity generation systems, thus the HTGR is a **promising** reactor in the near future;