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

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Background, Past Studies and Present Problems

Special Points of HTGR

- Inherent Safety
  → Easy to be accepted.
- Very high temperature coolant
  → For a cogeneration system with multiple products (hydrogen and electricity).

Past Studies

- 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;

Present Problems

- 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;

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

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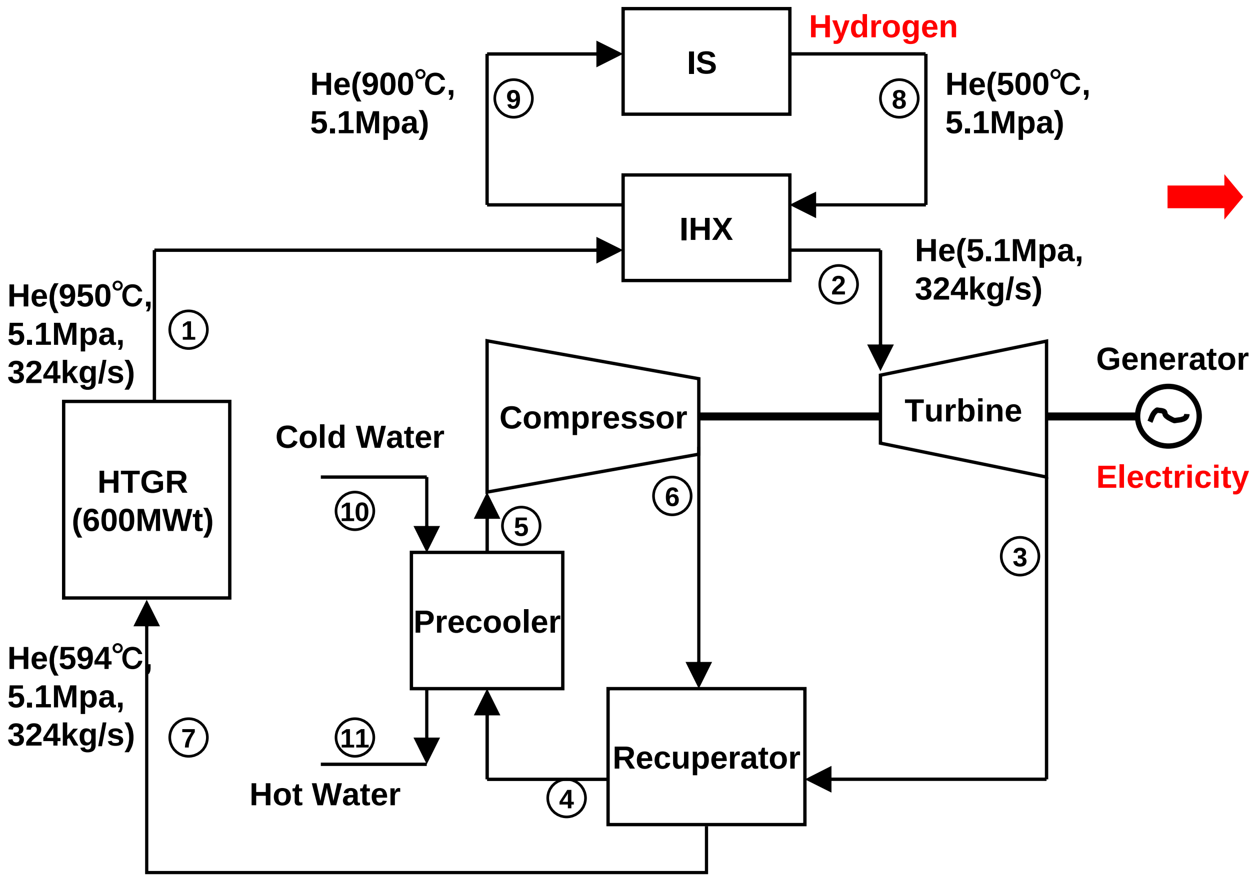
- Proposing optimum scenarios from the analysis results at all operating conditions, and then testing the feasibility and profitability of them.

A Typical HTGR Cogeneration System and Its Initial Parameters



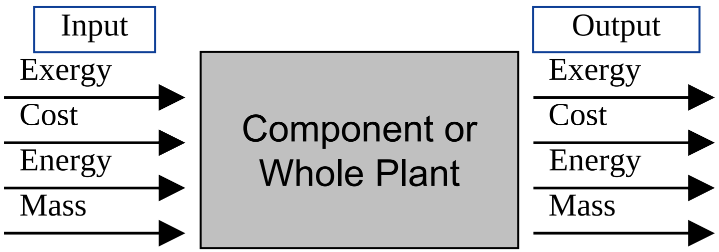
Products

- Hydrogen
- Electricity

Exergy and Exergy Costing Analyses based on EXCEM Model

From G. Tsatsaronis, 1996

EXCEM



$$Ex_{Fuel} - Ex_{Product} - Ex_{consumption} = M_{accumulation}$$ Due to the exergy destruction and loss

$$C_{Fuel} + C_{generation} - C_{Product} = C_{accumulation}$$ Due to the capital and MO costs

$$E_{Fuel} - E_{Product} = E_{accumulation}$$ Conservation

$$M_{Fuel} - M_{Product} = M_{accumulation}$$ Conservation

Exergy Analysis

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

$$\varepsilon = \frac{Ex_P}{Ex_F} = 1 - \frac{(Ex_D + Ex_L)}{Ex_F}$$

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.

$$c_F = \frac{C_F}{Ex_F} \qquad c_P = \frac{C_P}{Ex_P} = \frac{C_F + Z}{Ex_p}$$

C: Cost per unit exergy, C: Cost,

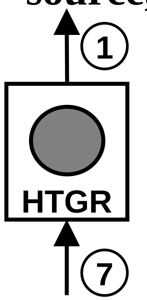
F: Fuel, P: Product,

Z: Cost information of the component

Basic Thermodynamic Analysis of Component(1)

HTGR

The reactor can be simply modeled as a heat source, adiabatic and constant pressure.



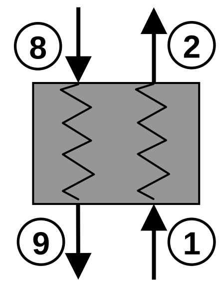
$$E_{HTGR} = m_{he} Cp_{He} (T_1 - T_7)$$

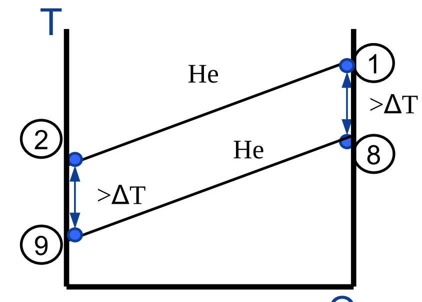
Mhe: mass of the helium
Cphe: the specific heat in J kg^{-1}K^{-1}

IHX

The IHX in this study are considered as adiabatic

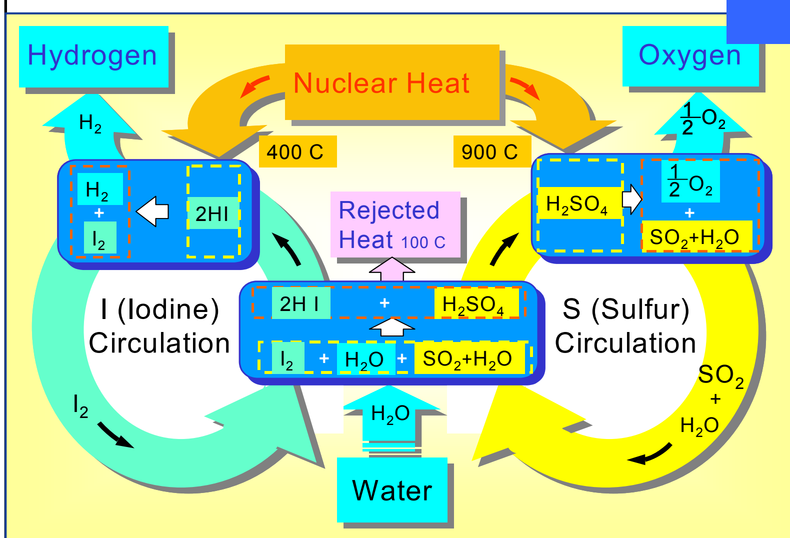
$$m_{he,Main} Cp_{He} (T_1 - T_2) = m_{he,IS} Cp_{He} (T_9 - T_8)$$





$$T_2 - T_{10} \geq \Delta T, T_1 - T_8 \geq \Delta T$$

IS



Generating hydrogen through IS process using the HTGR heat.

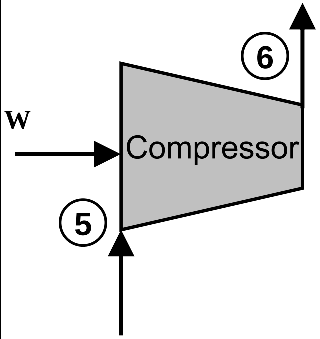
$$P_{Hydrogen} = m_{He,IS} Cp_{He} (T_8 - T_9) \times 0.5 / 286 \times 22.4 \times 10^{-3} \times 3600 (m^3/h)$$

From H. Karasawa , 2005

Basic Thermodynamic Analysis of Component(2)

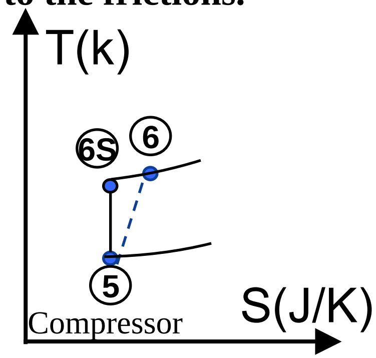
Compressor

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



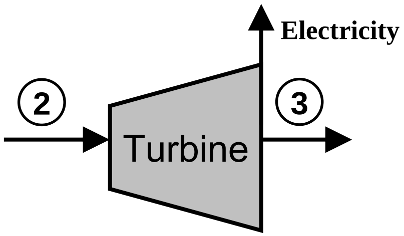
$$E_6 - E_5 = m_{he} Cp_{He} (T_6 - T_5) = W$$

$$\frac{T_{6s}}{T_5} = PR^{\frac{k-1}{k}} \qquad \frac{T_{6s} - T_5}{T_6 - T_5} = \eta_{comp}$$



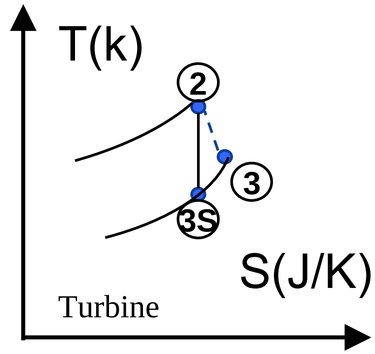
Turbine

The turbine are described as polytrophic processes with the efficiency η_{turb} due to the frictions.



$$\frac{T_{3s}}{T_2} = \left(\frac{1}{PR}\right)^{\frac{k-1}{k}} \qquad \frac{T_2 - T_3}{T_2 - T_{3s}} = \eta_{turb}$$

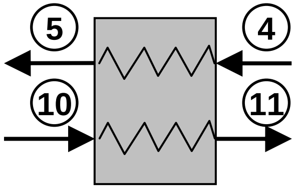
$$E_2 - E_3 = m_{he} Cp_{He} (T_2 - T_3) = Electricity$$



Basic Thermodynamic Analysis of Component(3)

Precooler

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

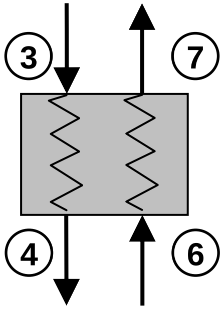


$$m_{water}(h_{11}-h_{10})=m_{he,Main}Cp_{He}(T_4-T_5)$$

$$T_4-T_{10}\geq\Delta T$$

Recuperator

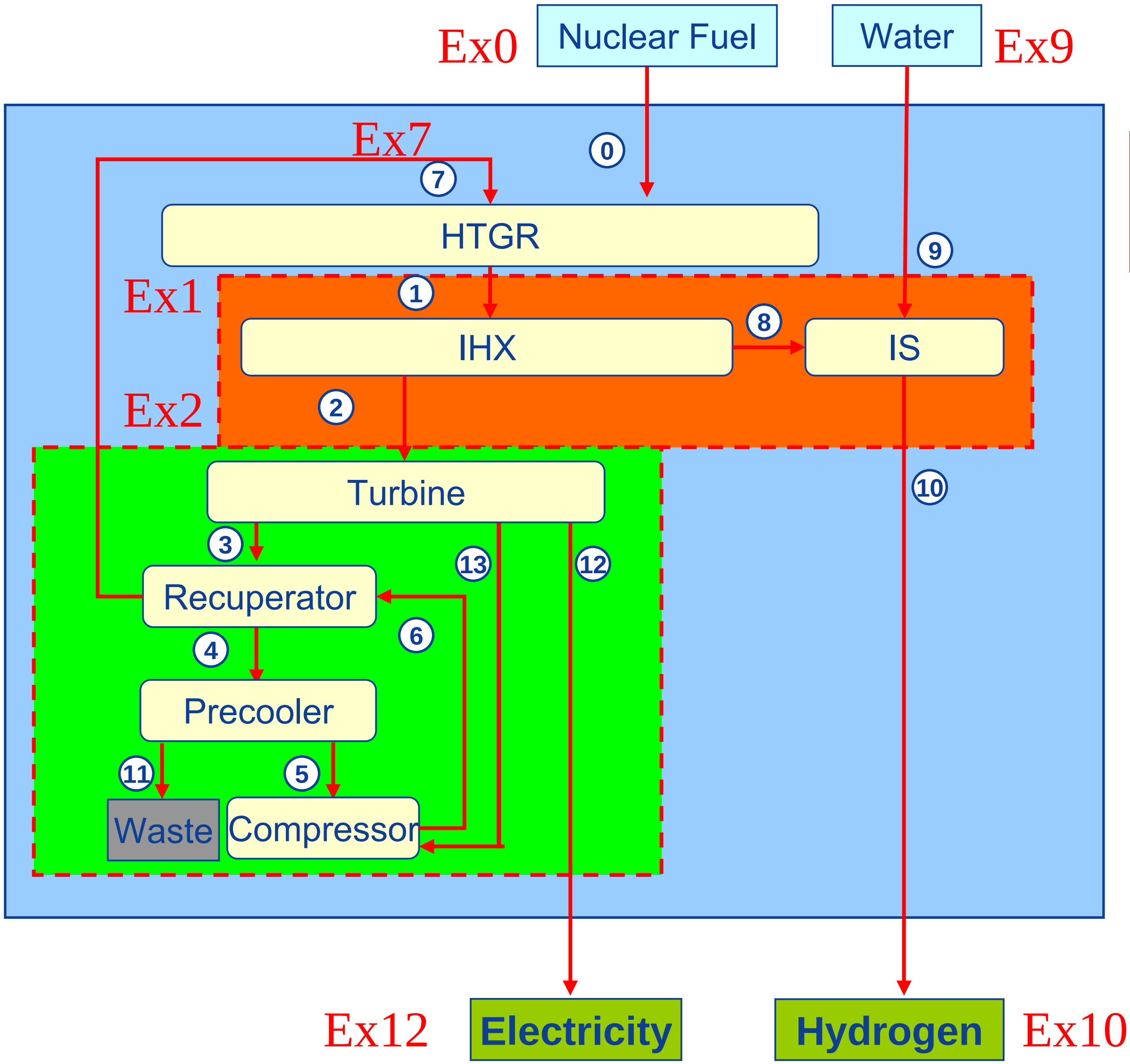
The thermodynamic analysis of the recuperator is similar with the IHX



$$m_{he,Main}Cp_{He}(T_3-T_4)=m_{he,Main}Cp_{He}(T_7-T_6)$$

$$T_3-T_7\geq\Delta T, T_4-T_6\geq\Delta T$$

Exergy and Exergy Costing Analyses for the HTGR System



Exergy Analysis for whole system

$$\varepsilon_{whole} = \frac{Ex10 + Ex12}{Ex0 + Ex9} 100\%$$

- 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

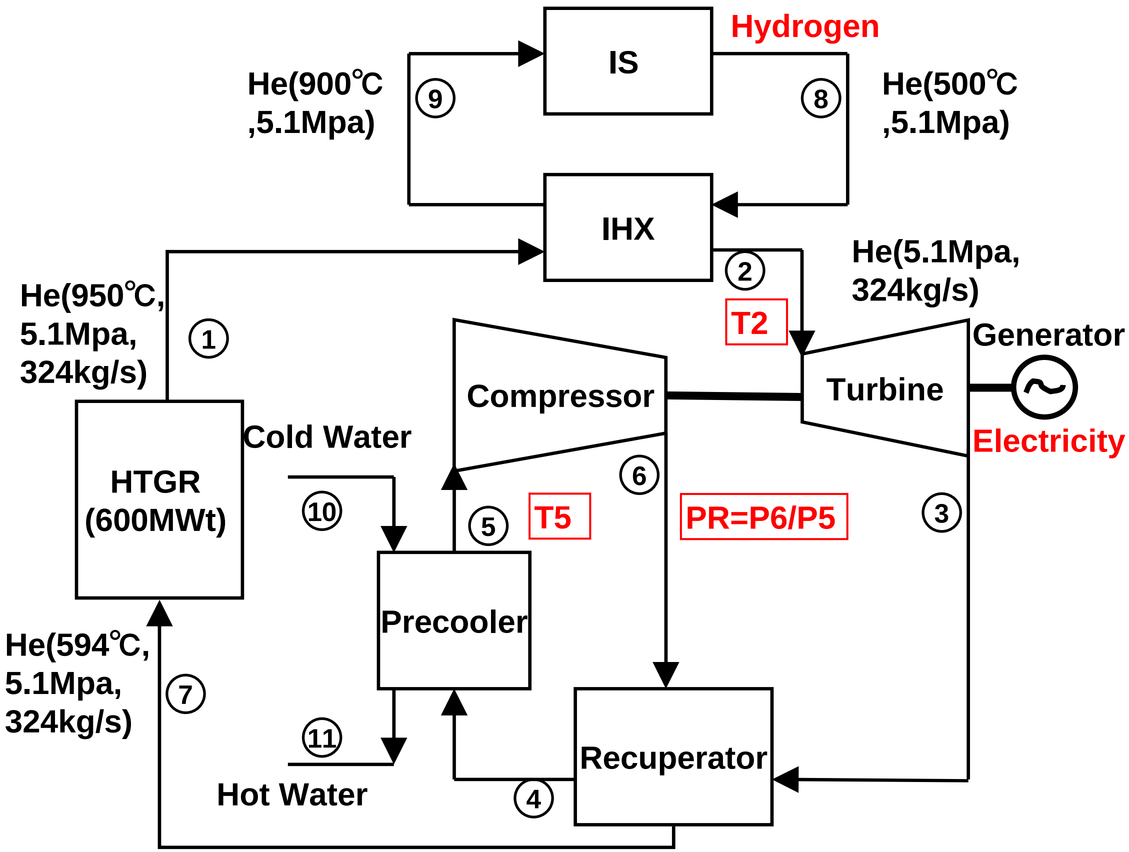
T2, T5 and PR

Valid Ranges

740℃ ≤T2 ≤850℃

30℃ ≤T5 ≤160℃

1.5≤PR≤2



Constrains

$$T_3 = (T_2 - \eta_{tur} \times (T_2 - T_2 PR^{\frac{1-k}{k}})) > T_7$$

$$T_4 < T_6$$

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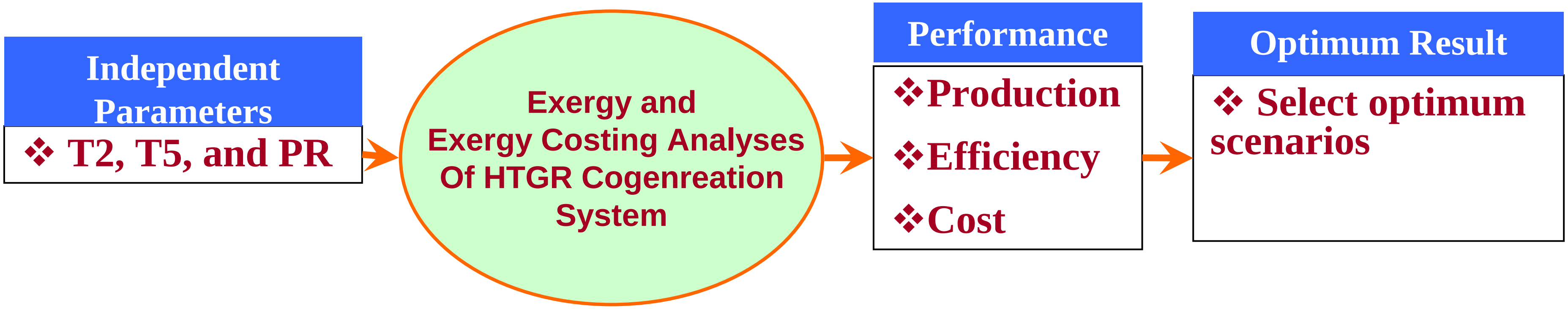
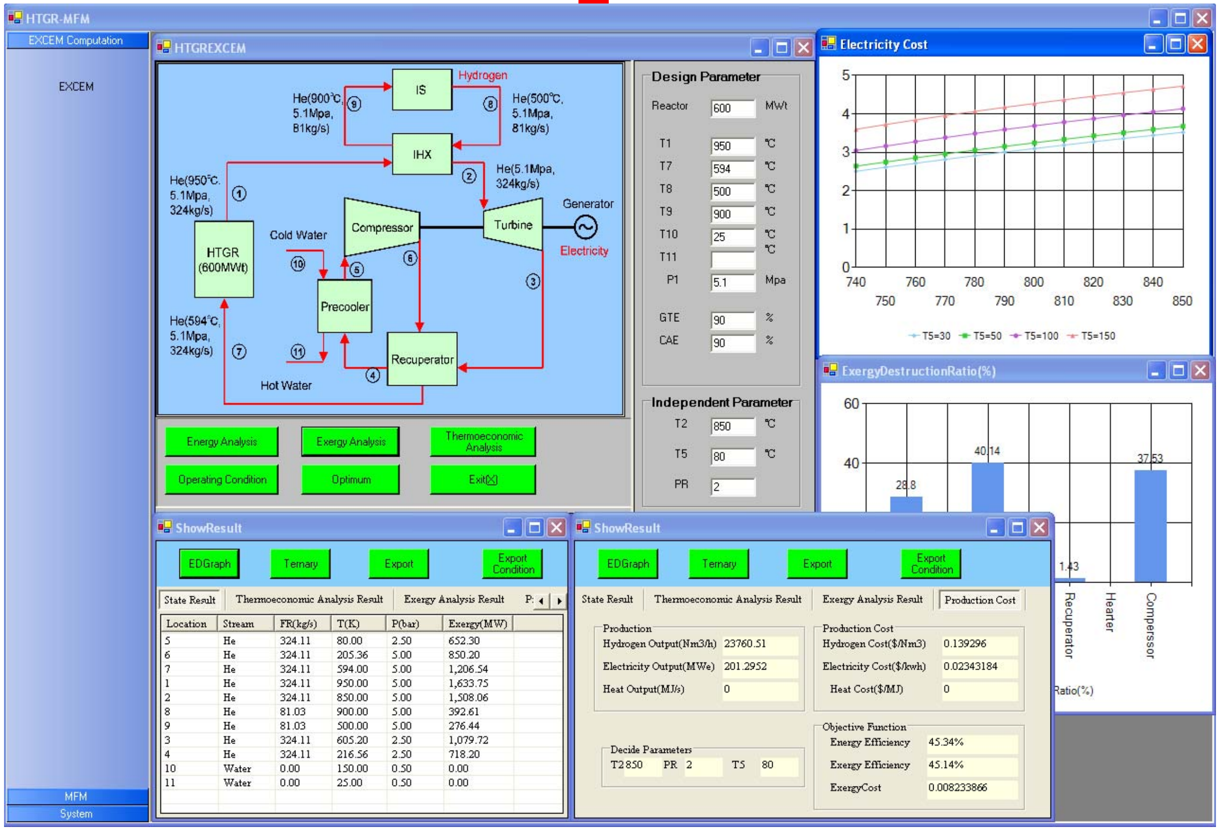
Conducting the Exergy and Exergy Costing Analyses at Various Operating Conditions



EXCEM Studio for Conducting the Exergy and Exergy Costing Analyses at Various Operating Conditions

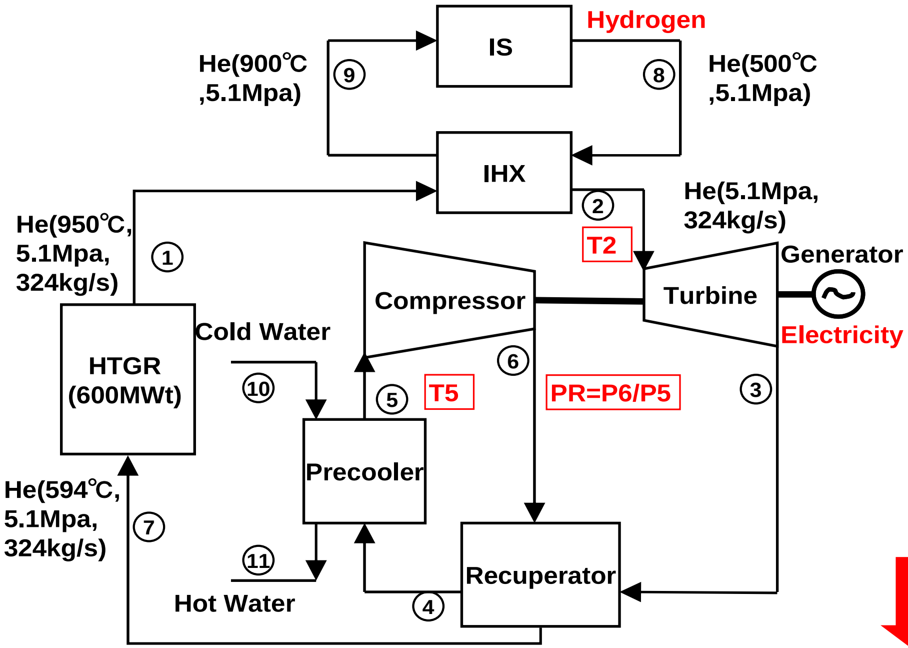
Exergy and Exergy Costing analyses of HTGR Cogenreation system

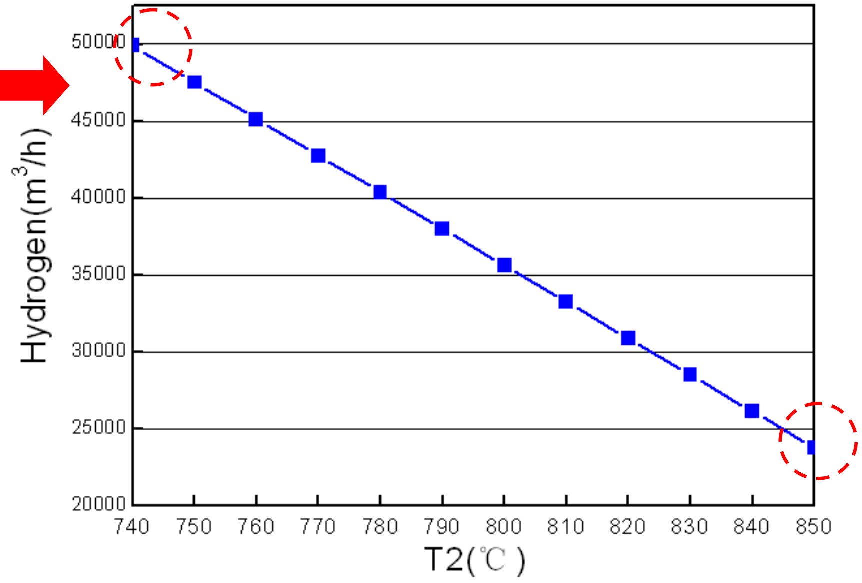
EXCEM Studio

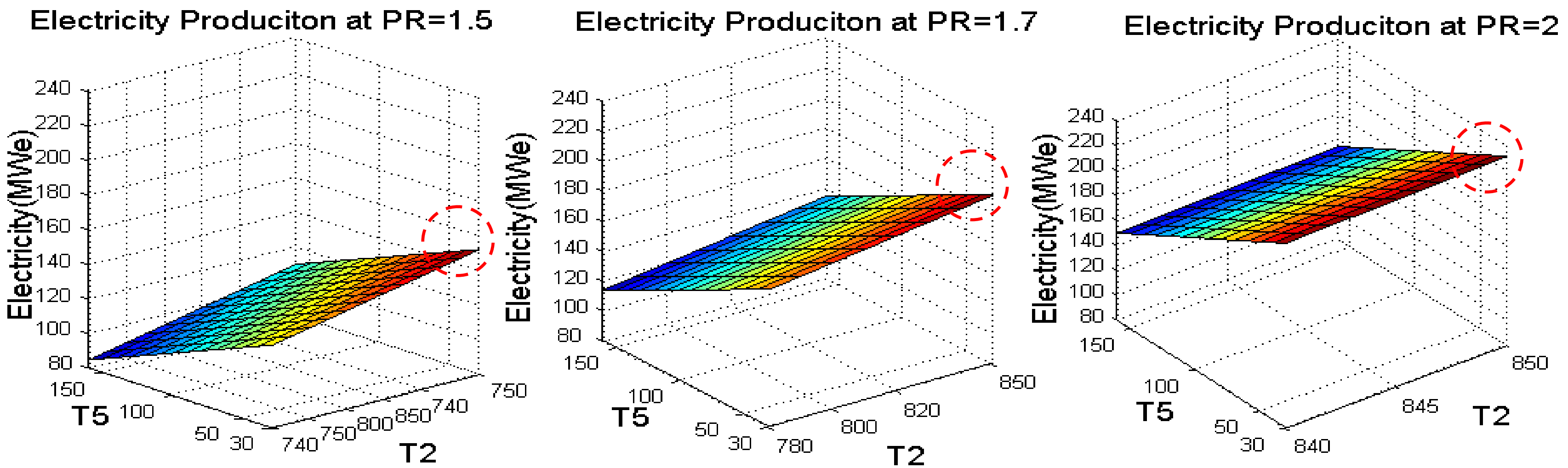


Results of Exergy and Exergy Costing Analyses

Productions of Hydrogen and Electricity at Various Operating Conditions

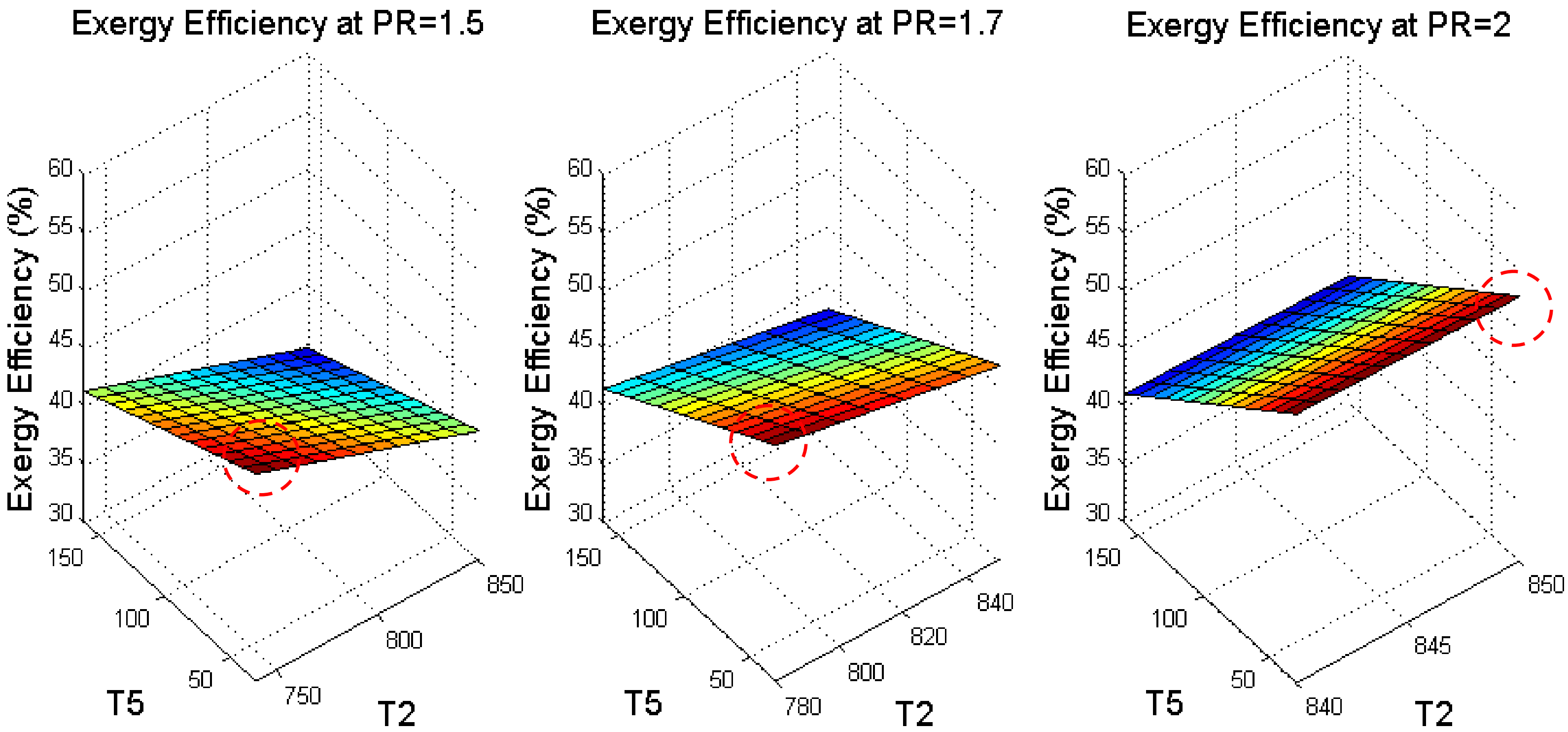




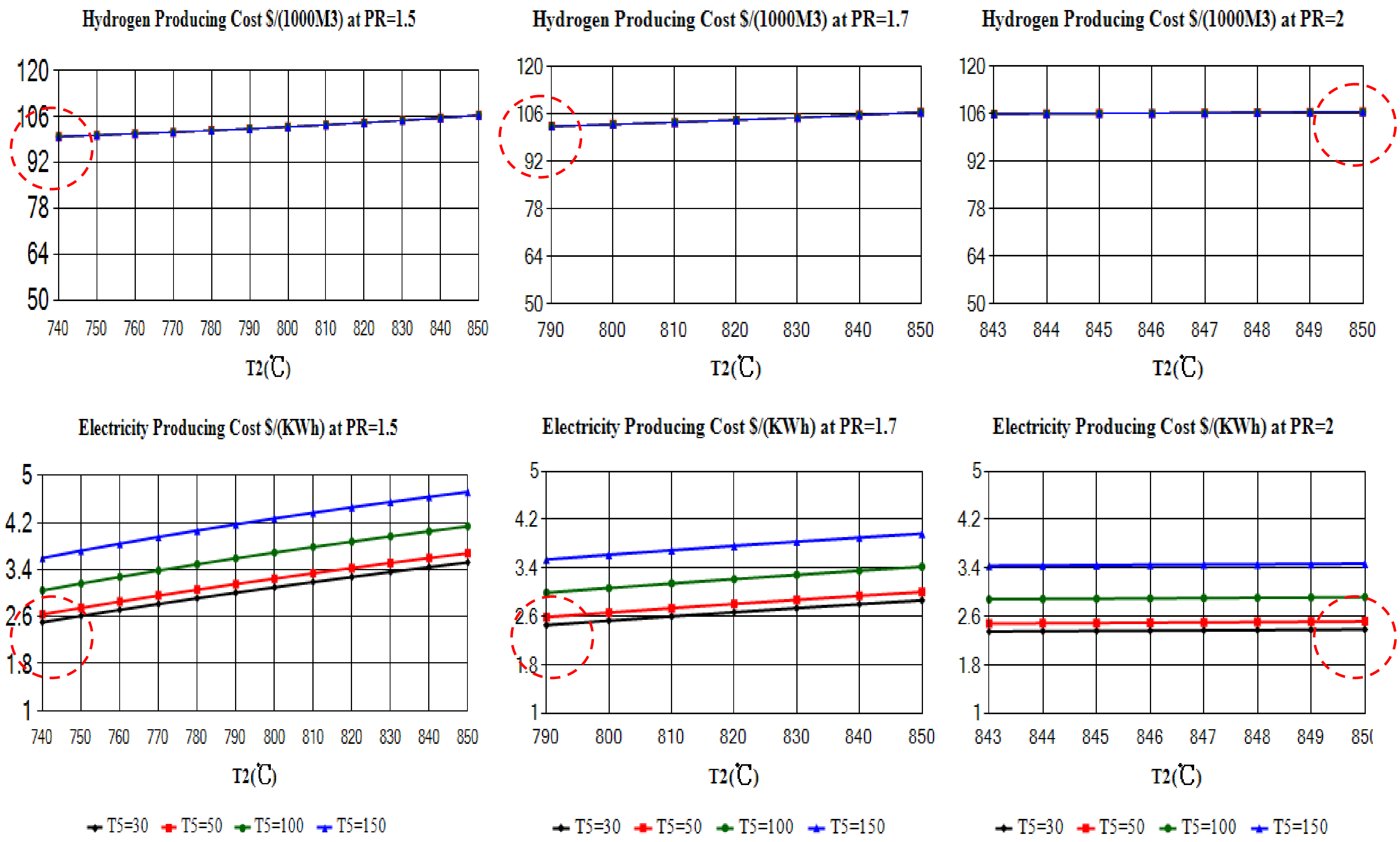


Exergy Efficiency at Various Operating Conditions by Exegy Analysis

Exergy efficiency



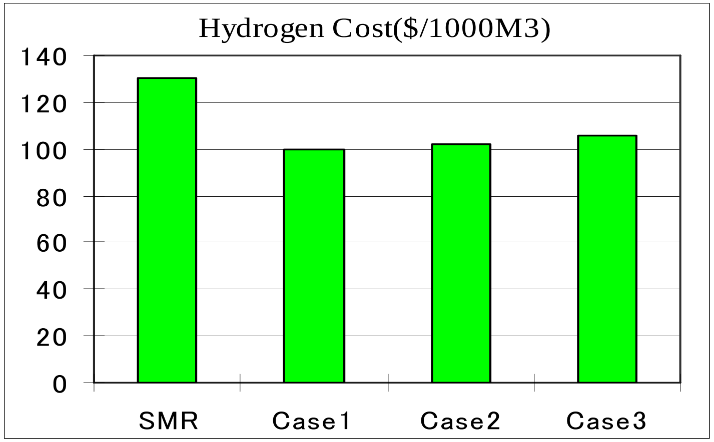
Costs of Hydrogen and Electricity at Various Operating Conditions by Exergy Costing Method

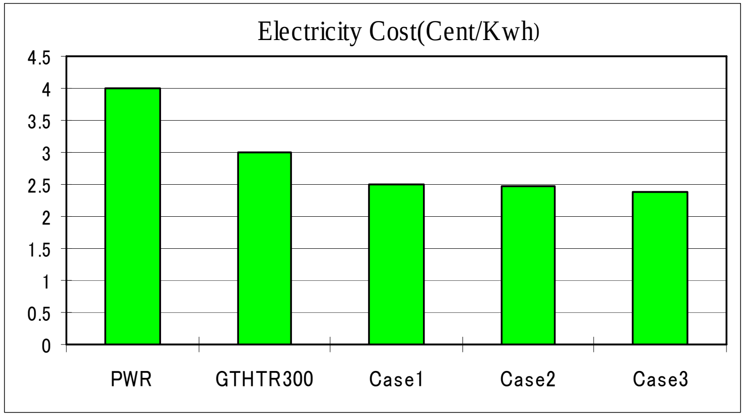


Three Cases

- 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.

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





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;