# Thermodynamic Analysis of Hydrogen Power Generation Integrated Pressurized Water Reactor

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## 1. Introduction

Hydrogen is recognized as the most suitable next-generation energy source for the new climate system since only water remains as a byproduct after being used as energy. Naturally, interest in the production of zero-carbon hydrogen is increasing. In the recent years the scope of the IAEA (International Atomic Energy Agency) program on non-electric applications of nuclear energy has been widened to include hydrogen production using nuclear energy. Also, KEEI (Korea Energy Economics Institute) and INL (Idaho National Laboratory) presented the potential for hydrogen production in conventional PWR (pressurized water reactor) [1, 2].

Following theses global energy industry trends, the layout of hydrogen production integrated PWR was suggested and the off-design operation of the PWR secondary side due to hydrogen production were also analyzed previously [3]. Since hydrogen production results in PWR work loss, there can be a power generation technology that can compensate for PWR work loss by utilizing the produced hydrogen. Thus, in this study, the layout of hydrogen power generation integrated PWR is suggested and thermodynamically analyzed thermodynamically. The sectors focused in this study among the various energy sectors are show in Fig. 1.

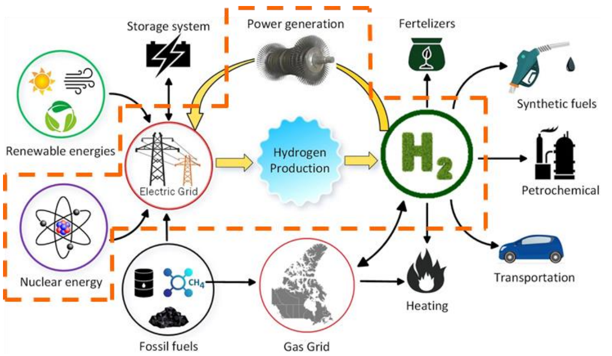


Fig. 1. Importance of hydrogen in integrating different energy sectors [4]

## 2. Hydrogen power generation integrated PWR

Typical examples of using hydrogen as a power source are fuel cell and hydrogen combustion. In this study, the fuel cell is excluded since this study focuses on the hydrogen power generation technology that utilizes the existing PWR infrastructure. Most of the existing hydrogen combustion turbines are mixed with fuel and air, so there is a problem such as NOx emission, which is one of the main causes of fine dust. This technology is not suitable for the new climate system. Thus, this study suggests a system that operates turbine after combustion with hydrogen and oxygen under steam condition, which are products of high temperature steam electrolysis. The steam is extracted from the PWR secondary side. This technology is called hydrogen oxy-combustion (HOC). When this technology is applied, the generation of NOx can be fundamentally blocked and additional power can be generated without any carbon emission. When the power generation of renewable energy suddenly decreases, it is possible to rapidly increase the power for the stability of the grid through HOC power generation in a nuclear power plant.

### *2.1 Extraction point for hydrogen power generation*

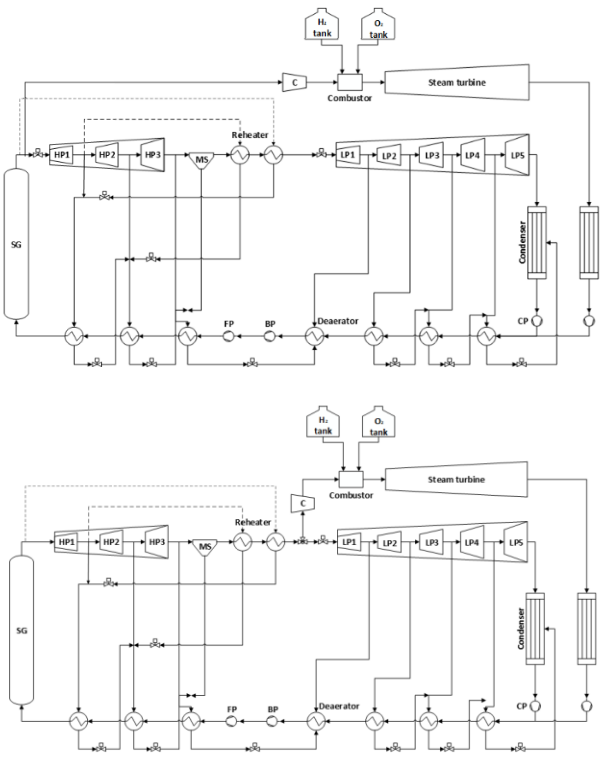


Fig. 2. Hydrogen power generation integrated steam system layout (top) HPT inlet (bottom) LPT inlet

Table I: HPT and LPT inlet conditions of typical PWR

| | Temperature [°C] | Pressure [MPa] |
|---|---|---|
| HPT | 282.21 | 6.63 |
| LPT | 263.36 | 1.44 |

The extraction point for HOC power generation can be the high-pressure turbine (HPT) inlet or the low-pressure turbine (LPT) inlet (Fig. 2), just like the hydrogen production extraction point suggested in the previous work [3]. If the steam is extracted at HPT inlet, the PWR work loss is occurred from the HPT, so the work loss is bigger than that of the extraction of LPT inlet (Fig. 3).

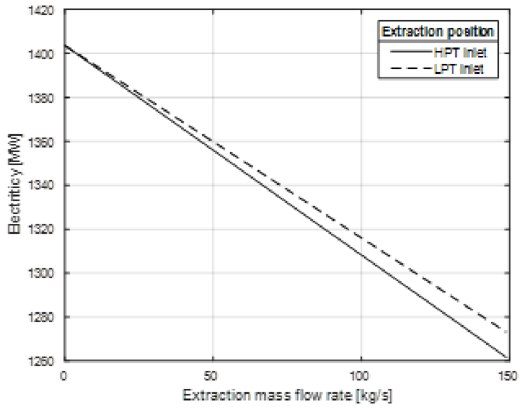


Fig. 3. Electricity according to extraction steam mass flow rate from PWR secondary side

When the inlet temperature of the combustion turbine is assumed to be 800°C, the turbine work at HPT inlet extraction is higher because of higher pressure ratio (Fig. 4). However, required combustion heat at HPT inlet is also higher. Considering the work loss (Fig. 3) and ratio of combustion heat and turbine work (yellow line in Fig. 4), LPT inlet extraction is recommended.

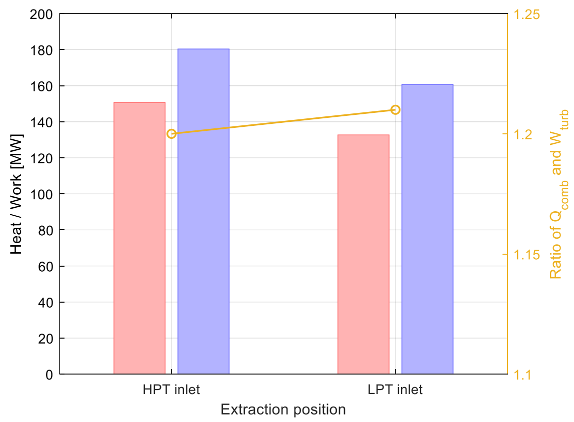


Fig. 4. Combustion heat (red bar) and turbine work (purple bar) according to extraction points

*2.2 Hydrogen oxy-combustion power cycle layouts*

Since extracted steam is split into hydrogen and oxygen via high temperature electrolysis, extracted steam cannot be returned to the secondary system of PWR after hydrogen production process. However, the extracted steam can be returned to the steam system during hydrogen power generation process. The extracted steam return points can be the LPT inlet or condenser outlet. In the case of LPT inlet return, it is called the circulation cycle. When returning to the condenser outlet, simple cycle or reheat cycle are possible since the pressure ratio is large. Thus, circulation cycle, simple cycle or reheat cycle can be candidates of HOC power cycle layout. Table II shows the HOC power cycle conditions.

Table II. HOC power cycle conditions

| | Turbine | Compressor |
|---|---|---|
| Efficiency [%] | 90 | 80 |
| Extraction steam mass flow rate [kg/s] | 110.89 | |
| Inlet temperature [°C] | 800.00 | 263.36 |
| Inlet pressure [MPa] | Variable | 1.44 |

*2.2.1 Circulation cycle*

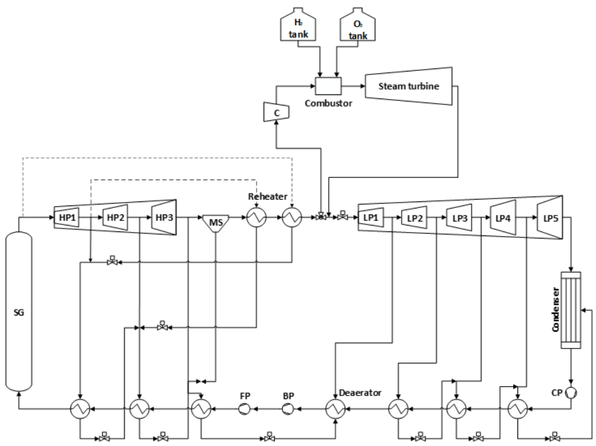


Fig. 5. HOC power cycle: circulation cycle

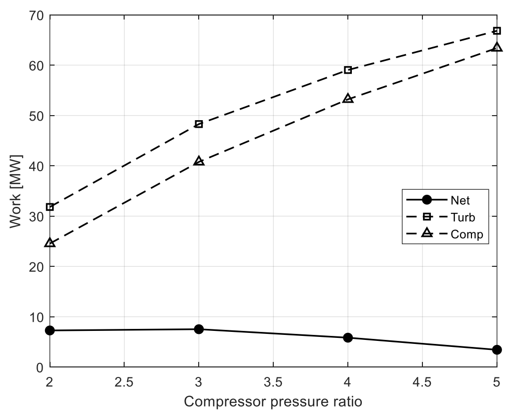


Fig. 6. Circulation cycle turbomachinery work

Fig. 5 shows the circulation cycle layout. In the case of a circulation cycle, a compressor must be required for turbine power generation since compressor inlet pressure and turbine outlet pressure are the same. A feature of this layout is that the LPT maintains steady state power after combustion turbine produces work. Fig. 6 shows the turbomachinery work according to the pressure ratio. As the pressure ratio increases, the compressor work increases more than the turbine work, so the net work decreases. The difference between compressor and turbine work is not large, so the amount of additional power generation is small.

### *2.2.2 Simple cycle & Reheat cycle*

Fig. 7 shows the simple cycle layout and reheat cycle layout. Unlike the circulation cycle, in these two layouts, the reduced steam flow to the LPT. The LPT operates under off-design operating conditions resulting in work loss. The simple cycle result (Fig. 8) shows the same tendency as the circulation cycle result. However, net work is much higher than that of the circulation cycle since turbine pressure ratio is much higher. Compressor pressure ratio of 1 means there is no compressor. It is

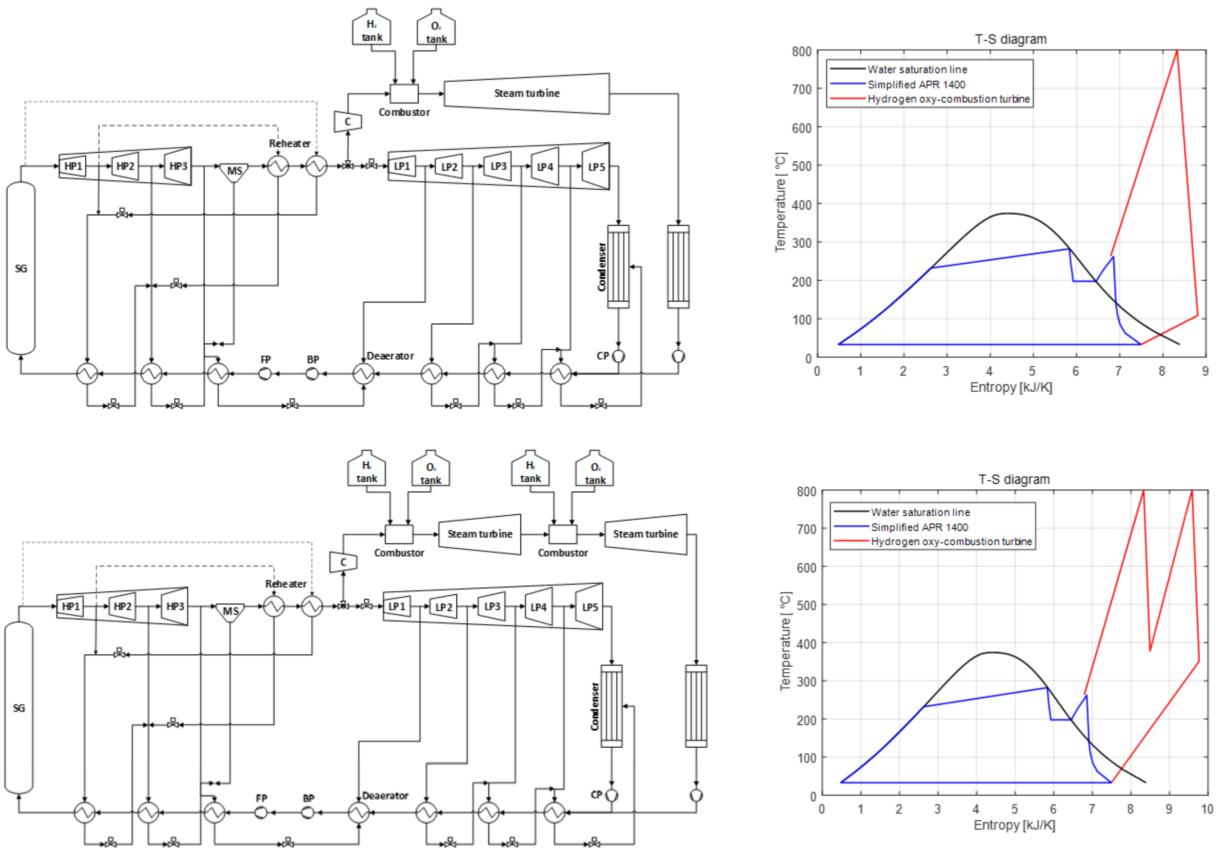


Fig. 7. HOC power cycle and T-s diagram: (top) simple cycle (bottom) reheat cycle

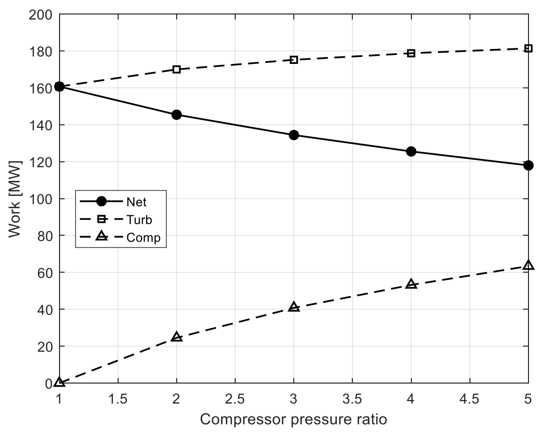


Fig. 8. Simple cycle turbomachinery work

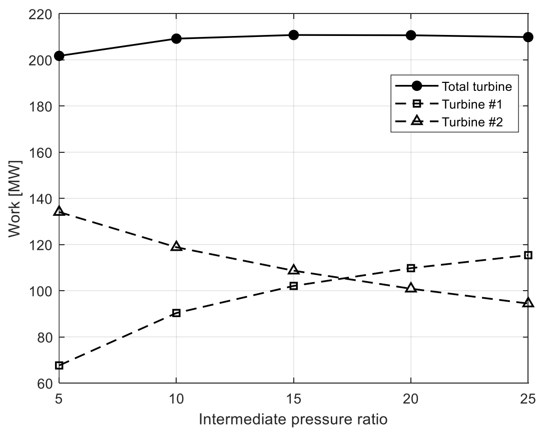


Fig. 9. Reheat cycle turbomachinery work

better to operate the HOC turbine without a compressor. The T-s diagram of a HOC turbine generation without a compressor is shown in Fig. 7.

For the reheat cycle, there are two combustors and two turbines, so there should be the intermediate pressure for reheat. Based on the results of the previous two cycle layouts, the reheat cycle was analyzed only for the intermediate pressure without a compressor. The result is shown in Fig. 9. Intermediate pressure ratio is the first turbine pressure ratio. The second turbine pressure ratio is determined from the ratio of intermediate pressure and the condenser pressure. As the intermediate pressure ratio increases, the first turbine work increases and the second turbine work decreases. The total turbine work is highest when the intermediate pressure ratio is 15 (total pressure ratio is almost 284). The T-s diagram of reheat cycle is shown in Fig. 7.

Fig. 10 shows the comparison of simple cycle and reheat cycle results. The reheat process increases the turbine work, but the required combustion heat increases significantly. Thus, the simple cycle is more efficient since the turbine work compared to the combustion heat (purple line) is less when it is the reheat cycle. LPT work loss according to the extraction steam mass flow rate in Tale II is 100MW, so the additional work through HOC power cycle is about 60MW (simple cycle case).

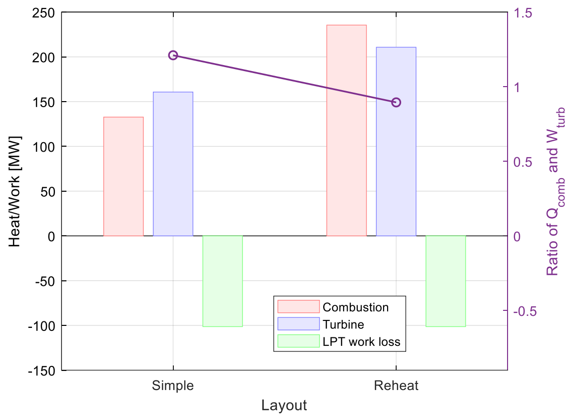


Fig. 10. Comparison of combustion heat and turbine work between simple cycle and reheat cycle

## 3. Conclusions

In this study, the layout of hydrogen power generation integrated PWR using HOC is proposed. HOC power generation solves the problems of conventional hydrogen combustion power generation such as NOx emission and can generate additional power without carbon emission. Circulation, simple and reheat cycles can be candidates for HOC cycle layout, and thermodynamic analysis revealed that simple cycle without compression process is most preferred design choice.

The system proposed in this study is a system that can be implemented to the operating PWR. It is a system capable of adding large capacity to the operating PWR as well as flexibility without carbon emission. If HOC is used as a backup for renewable energy instead of LNG fired power generation, it can greatly contribute to the reduction of greenhouse gas emissions in the energy sector.

## Acknowledgement

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