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Thermodynamic analysis of a Conventional PWR Integrated with Compressed CO_2 Energy Storage System

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1. Introduction

Recently, the ratio of renewable energy in the grid has increased globally to curb climate change caused by greenhouse gas emissions. In Korea, renewable energy will account for 20% of the nation's power generation by 2030, according to the 'Renewable Energy 3020' plan [1]. However, renewable energies have unexpectable intermittency for power generation. This issue can be alleviated by load-following operation of a nuclear power plant (NPP). However, it is not economical to control power output of the reactor in NPP. Energy Storage System (ESS) can be an alternative to solve this issue. Various ESS types (e.g., Thermal Energy Storage (TES), Li battery) can be considered.

Among them, the compressed air energy storage (CAES) system seems feasible due to having high efficiency, good technical feasibility, great power rating and capacity [2]. However, compressed air has very high pressure that the storage for compressed air cannot be constructed economically with pressure vessel. Thus, it can be constructed when underground cavern areas where large amount of high pressure air can be stored safely are available. As a resolution to this issue, a supercritical compressed CO_2 energy storage (CCES) system concept was suggested to improve power density of CAES [3].

In this paper, the proposed CCES integrated with a NPP utilizes branched steam from the steam cycle to store energy. In addition, thermal storage using TES and mechanical storage using a steam turbine driven compressor can store energy simultaneously, and the branched steam returns back to the steam cycle after delivering heat and mechanical work to CCES. However, it will be difficult to maintain the steam generator (SG) inlet temperature at 232℃ nominal value. If the SG inlet temperature is not maintained, it will affect the primary side power through feedback in pressurized water reactor type NPP. Therefore, in this paper, how the SG inlet temperature is maintained and a thermodynamic analysis when CCES is integrated to a conventional PWR are first studied.

2. Thermodynamic modeling

In order to store energy in CCES, it is necessary to branch steam in the steam cycle and determine which section to bypass in the steam cycle before it merges back. In the layout shown in Figure 1, the bypass steam is branched off from the LP turbine entrance (No. 11) since it should be steam that has high pressure and temperature enough to transfer energy to CCES and far from the steam generator to minimize any safety concerns by affecting the primary side system.

CCES has two storage methods. First, there is thermal energy storage (TES). The next is mechanical storage using a steam turbine that drives a CO_2 compressor in CCES. Part (No. 69) of the branched steam passes through a heat exchanger, and the rest (No. 71) of it passes through the steam turbine. The diverted steam to CCES has a large pressure difference with the main stream, so it is difficult to merge back to the main stream directly. Therefore, the steam passing through the heat exchanger is merging to the branch steam (No. 73) of the HP turbine outlet, and the steam passing through the steam turbine is merging to the condenser inlet (No. 20), separately. Since the mass flow rate of LP turbine inlet was changed from the nominal mass flowrate, an off-design model for the LPT is applied to evaluate the lost work due to energy storage.

When branching the flow rate and applying the off-design model, the temperatures and pressures change, so the SG inlet temperature will be different from the design point. Then, it will affect the primary side of NPP. Thus, to maintain this, a butterfly valve will be installed to control the branch flow at the HP turbine outlet.

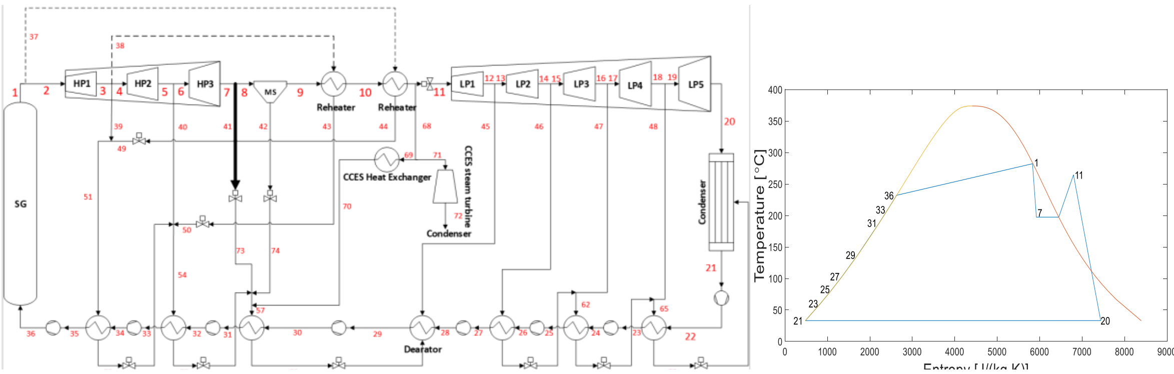

Figure 1. Layout and T-s diagram of Steam Cycle integrated with CCES

2.1 Off-design Steam Turbine

There are various off-design steam turbine models. Among them, the below equation is applied as the off-design steam turbine model.

$$Q = c_d A \sqrt{\frac{2\gamma R T_1}{\gamma - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{\gamma}} - \left(\frac{p_2}{p_1}\right)^{\frac{\gamma+1}{\gamma}}\right]} \text{ [4]}$$

In the above equation, Q is volumetric flow rate, c_d is Flow rate coefficient, A is area, γ is specific heat ratio, R is ideal gas constant, T is temperature, P is pressure, 1 and 2 are inlet and outlet of steam turbine, respectively. From this, if the volumetric flow rate is constant even if the mass flow rate is changed, the pressure ratio will remain constant. Thus, if LP turbine inlet pressure, which keeps volumetric flow rate constant, changes, the pressure ratios of the first to the one stage before the last stage can remain nominal values.

However, the outlet pressure of the last stage in LP turbine is fixed to the condenser pressure, so the isentropic efficiency of the last stage changes. Thus, the off-design isentropic efficiency is obtained from the below equation.

$$\eta = \eta^* - \alpha\left(\frac{N/\sqrt{\Delta h_s}}{N^*/\sqrt{\Delta h_s^*}} - 1\right)^2 \text{ [5]}$$

η is off-design isentropic efficiency, η^* is on-design isentropic efficiency, α is a positive constant, N is off-design rotational speed, N^* is on-design rotational speed, Δh_s^* is on-design enthalpy difference between inlet and outlet and Δh_s is off-design enthalpy difference between inlet and outlet. In this study, α is 2 and on and off-design rotational speed is same.

2.2 Cycle condition and Parameters

Table1. Design parameters of cycle

Parameters	Value	Unit
SG thermal energy (Q_{in})	3985	MW
Pressure of SG outlet	6.6327	MPa
Temperature of SG outlet	282.205	℃
Total steam mass flow rate	2250.6	kg/s
Steam mass flow rate of on-design LPT inlet ($M_{11,on}$)	1463.7	kg/s
Temperature of Condenser	33.1407	℃
Pressure drop in HX	1.0	%
Temperature of TES cold tank	150	℃

Table2. Variables of cycle

Parameters	Range of Variation	Unit
Total steam bypass fraction to CCES ($\frac{M_{69}}{M_{11,on}}$)	0 - 50	%
Steam bypass fraction to HX of CCES ($\frac{M_{70}}{M_{69}}$)	0.1 – 0.9	
TES mass flow rate	1000 - 9000	kg/sec

The design parameters are shown in Table1 and the variables and ranges of variation are shown in Table2.

Among them, total steam bypass fraction to CCES means how much steam is branched off to CCES from the steam cycle. Then, there are two methods to store the energy from the bypass steam: Thermal storage using TES and Mechanical storage using steam turbine that drives the CO_2 compressor. Thus, steam bypass fraction to HX of CCES means the ratio of mass flow rate of HX for the TES and steam turbine. Finally, depending on the TES side mass flowrate, the enthalpy of the steam outlet can vary in the HX for the TES. Therefore, this variable is evaluated as well.

2.3 Thermodynamic evaluation of steam cycle

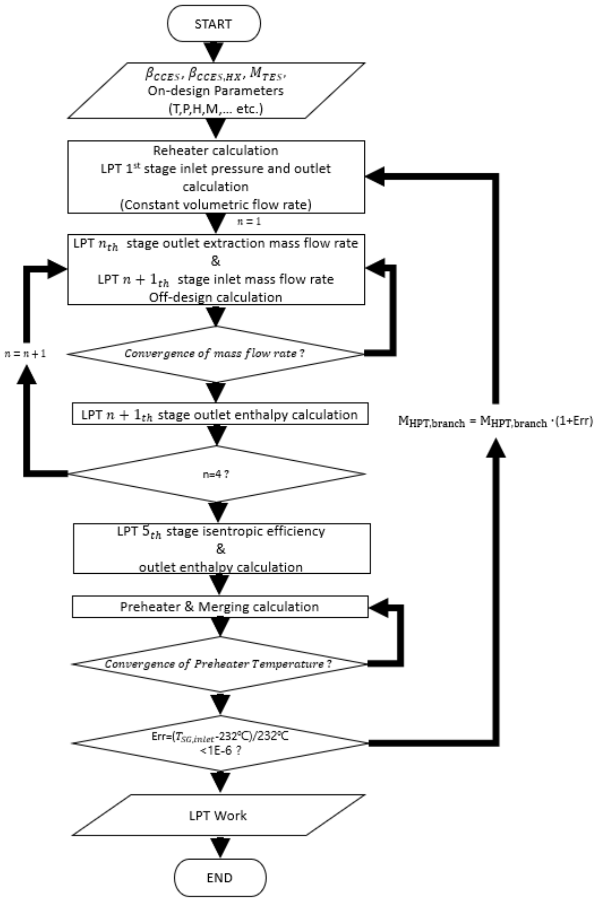

Figure 2. The overall steam cycle flow chart

As mentioned in the introduction, when branching and merging steam, the inlet temperature of the steam generator must be maintained at the design point (i.e. nominal value). Considering the steam turbine's integrity and SG inlet temperature control, branch steam (No. 41) at the outlet of the HP turbine is used to maintain the SG inlet temperature. In Figure 1, it is shown in bold line.

The overall cycle calculation algorithm is shown in Figure 2. As mentioned above, off-design pressure ratio and the final stage isentropic efficiency of LP turbine are obtained from two off-design steam turbine model equations. There are three convergence criteria: off-design steam turbine mass flowrate, overall temperature, and constant SG inlet temperature. LP turbine work loss and HP turbine outlet branch fraction from the calculation.

KAIST CCD code developed by KAIST research team is used for the calculation.

3. Results

As shown in Figure 3, the SG inlet temperature can be maintained at the design point by controlling HPT outlet branch mass flowrate. Then, in Figure 4, it can be seen that the quality (vapor fraction) of LP turbine increases as the total steam bypass fraction to CCES increases. Thus, there will be no effect to the primary side of NPP and LP turbine.

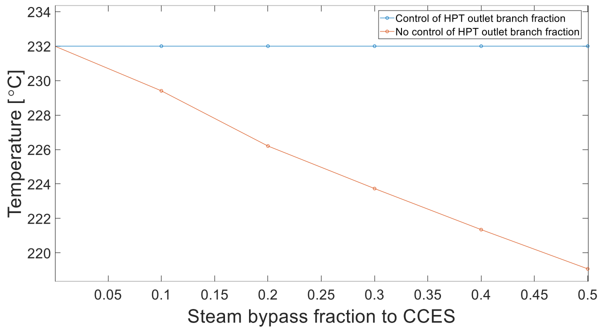

Figure 3. SG inlet temperature vs Total steam bypass fraction to CCES

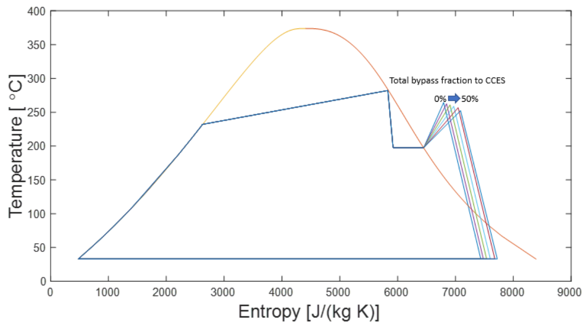

Figure 4. T-s diagram of steam cycle with CCES (Total bypass fraction: 0~50%)

As shown in Figure 5, the LPT work loss increases as the total steam bypass fraction to CCES increases. In the small total steam fraction such as 10% and 20%, when the TES mass flow rate is above a certain level, there is no change in LPT work loss. Since the heat which is transferred from the steam through HX of CCES has limits, the work loss does not change even as the TES mass flow rate increases. In Figure 6, the work loss is constant even if TES mass flow rate increases.

When the total steam bypass mass flow rate to HX of CCES is large and TES mass flow rate is small, the outlet enthalpy (No. 70) of steam through HX of CCES is too high and then No. 31 steam enthalpy increases too much in a feedwater Heater between No. 71 and No. 30. Thus, even with the control of HPT outlet branch steam mass flowrate, the SG inlet temperature cannot be maintained at the design point. This can be resolved with larger TES side mass flowrate.

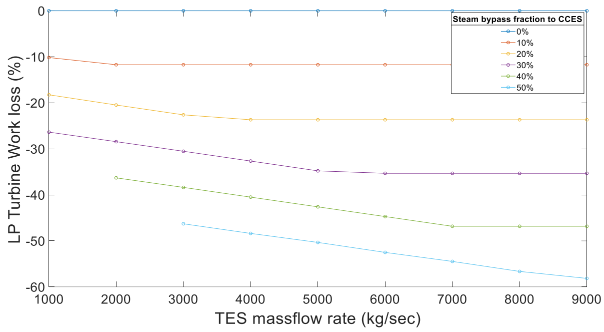

Figure 5. LPT work loss vs TES mass flow rate (Steam bypass fraction to HX of CCES: 0.4)

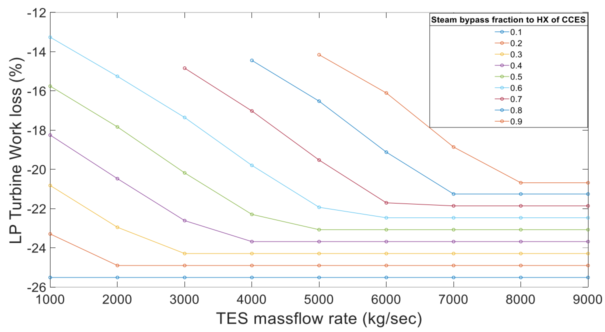

Figure 6. LPT work loss vs TES mass flow rate (Total steam bypass fraction to CCES: 20%)

As shown in Figures 7and 8, as the total steam bypass fraction to CCES increases, LPT work loss increases. As the steam bypass fraction to HX of CCES increases, work loss decreases. In other words, the steam through HX loses less energy than the steam through CCES steam turbine. It means that CCES can store more energy if steam bypass fraction to the CCES steam turbine increases.

In addition, the regions where the slope changes rapidly are shown. When steam bypass fraction to HX of CCES is larger than a certain value, the slope of work loss changes rapidly. If a large amount of steam exchanges heat with TES, the steam cannot transfer enough heat. Thus, the outlet enthalpy of steam (No. 70) becomes higher. Before the point that slope changes rapidly, the outlet enthalpy of steam is constant. It is obvious that the HPT work does not change in Figure 8 since there was no change in the HPT operating conditions.

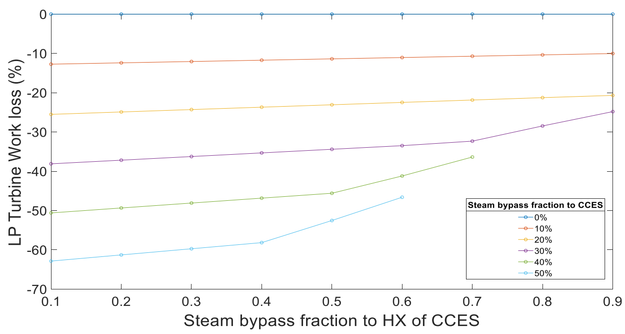

Figure 7. LPT work loss vs Steam bypass fraction to HX of CCES (TES mass flow rate: 9000kg/sec)

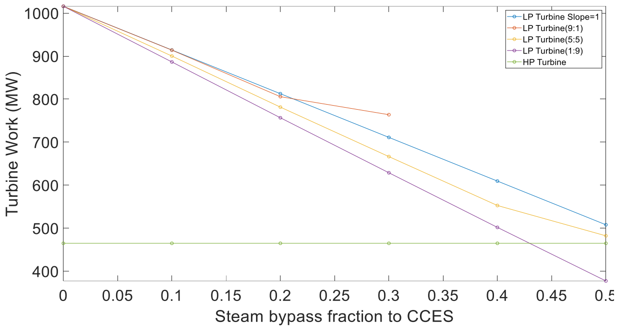

Figure 8. Turbine work vs Total steam bypass fraction (TES mass flow rate: 9000kg/sec)

As shown in Figure 9, it can be also seen that the slope of mass flow rate (No. 41) changes rapidly. As mentioned earlier, the reason is that the outlet of steam through HX of CCES has much higher enthalpy. As mass flow rate of HPT outlet branch increases, the temperature of SG inlet decreases. However, when the SG inlet temperature becomes too high, it cannot be brought back to the nominal value by controlling only the HPT outlet branch ratio.

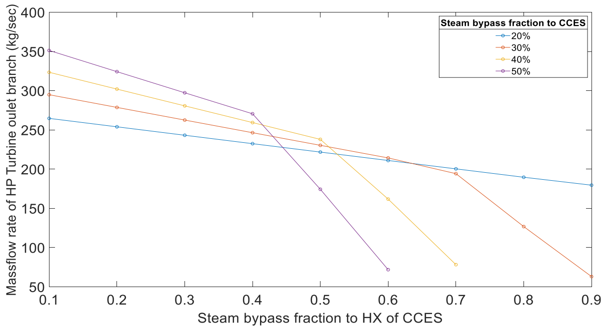

Figure 9. Mass flow rate of HPT outlet branch vs Steam bypass fraction to HX of CCES (TES mass flow rate: 9000kg/sec)

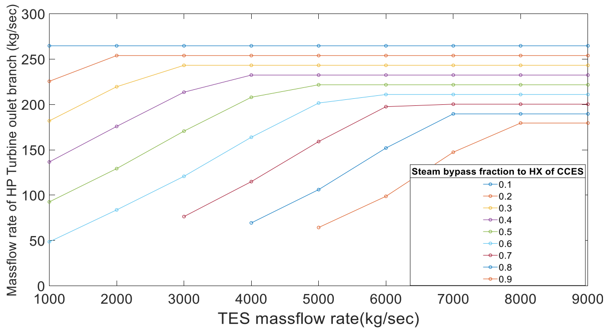

Figure 10. Mass flow rate of HPT outlet branch vs TES mass flow rate (Total steam bypass fraction to CCES: 20%)

4. Summary and Future Works

In this study, a thermodynamic model of PWR steam cycle integrated with CCES was constructed and the work loss due to the steam bypass fraction to CCES, was first evaluated. The proposed CCES can store both thermal energy via heat transfer occurring in a heat exchanger and mechanical energy via steam driven CO_2 compressor. As the total steam bypass fraction to CCES increases and TES mass flow rate decreases, LPT work loss increases and when TES mass flow rate is larger than a certain value, work loss doesn’t change anymore. As the steam bypass fraction to HX increases, LPT work loss decreases.

It could be observed that the SG inlet temperature can maintain constant by controlling the HPT outlet branch mass flowrate. When the SG inlet temperature is higher than the design point, the temperature can be lowered by increasing the HPT outlet branch mass flowrate. However, if the SG inlet temperature rises too high due to the energy storage with CCES, it cannot be resolved with only the HPT outlet flow branch ratio.

From this paper, the PWR work loss is first estimated. The performance of the CCES to generate power when it is needed will be evaluated next (i.e. discharge mode). Therefore, further investigation will commence soon regarding the performance and the round-trip efficiency of a CCES integrated PWR.

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