Preliminary Study of Compressed CO_2 Energy Storage System Integrated to a Conventional PWR

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1. Introduction

Recently, the ratio of renewable energy in the grid has increased globally due to climate change caused by carbon dioxide 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] But renewable energy has unexpectable intermittency during 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 solve this issue. Various ESS types (e.g., Thermal Energy Storage (TES), Li battery) can be considered and they are shown in Figure 1.

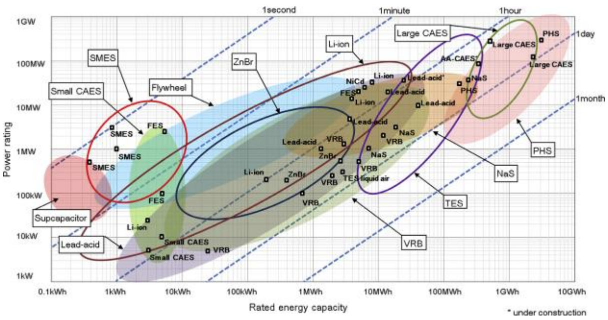

Figure 1. Comparison of power rating and rated energy capacity with discharge time duration at power rating [2]

Among them, the compressed air energy storage (CAES) system has high efficiency, technical feasibility, great power rating and capacity. However, compressed air has very high pressure that it cannot be constructed except in underground rocky areas where large amount of high pressure air can be stored safely. In China, supercritical compressed CO_2 energy storage (CCES) system is developed because it can be the material of CAES at lower pressure [3]. Therefore, in this paper, a preliminary analysis of a supercritical compressed CO_2 energy storage (CCES) integrated to a conventional PWR are studied.

2. Thermodynamic modeling of CCES

Some assumptions about this modeling are as follows:

1) The CO_2 tanks and the TES tanks have the same temperature, pressure, and properties at the inlet and outlet, respectively.
2) There is no pressure drop in the pipes, cooler and heat exchangers.
3) The temperatures of inlet/outlet steam from the secondary side of NPP are constant.
4) The turbines and compressor have constant isentropic efficiencies, respectively.
5) Two turbines have the same pressure ratio.
6) The ratio of charging time to discharging time is 3.

These following assumptions make the modeling of CCES simple to analyze.

2.1. Layout and modeling of component

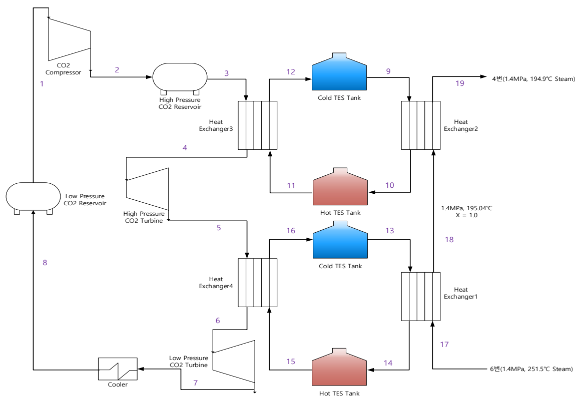

Figure 2. Schematic of CCES

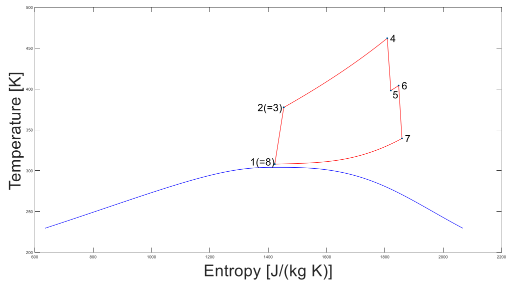

Figure 3. T-s diagram of supercritical-CCES

The schematic and T-s diagram are shown in Figures 2 and 3. Processes 1-2, 9-10 and 13-14 are the energy storage process and the rest of processes are the energy recovery process. 20% of the steam mass flow rate from the secondary side is partially used for bypass and the remaining fraction is used for supplying the compressor work.

2.1.1. Heat exchanger

All heat exchangers in this system have isobaric process. For given temperature and pressure of inlet/outlet of hot side and inlet of cold side, the mass flow rate and temperature of cold side can be obtained from using heat exchanger effectiveness and following equations.

$$Q_{actual} = \dot{m_{hot}}(h_{hot,out} - h_{hot,in})$$
$$\dot{m_{cold}} = f(Q_{actual}, \eta_{HX}, T_{cold,in})$$

For only one heat exchanger with high effectiveness, it will have a pinch problem due to phase change of steam. Thus, it should be switched to two heat exchangers. 'Heat exchanger2', the heat exchanger from process 9-10 and 18-19, has the phase change process from steam to water, and 'Heat exchanger1', the heat exchanger from process 13-14 and 17-18 is where the heat exchange process between steam and HITEC takes place.

2.1.2. TES

HITEC is used for the material of Thermal Heat Storage (TES). This melting temperature is 142.35℃ and specific heat is constant at the molten state. Thus, its enthalpy is proportional to its temperature like the below relation.

$$h_{HITEC} = 1.555 * 10^3(T_{HITEC} - 422.039) + 2.56 * 10^5$$

2.1.3. Compressor

The outlet pressure and temperature of a compressor can be obtained from the equation and given compressor work, mass flow rate, isentropic efficiency, inlet temperature and pressure.

$$\eta_c = \frac{h_{out,s} - h_{in}}{h_{out} - h_{in}}$$
$$P_{out}, T_{out} = g(\eta_c, T_{in}, P_{in}, W_{comp}, \dot{m})$$

2.1.4. Turbine

This system has two turbines with the same pressure ratios. The pressure ratios of the turbines are determined by the inlet/outlet pressure of the compressor. Then, the outlet pressure and temperature of turbine are obtained from the below equation.

$$\eta_t = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}}$$
$$P_{out}, T_{out} = g(\eta_t, T_{in}, P_{in}, PR)$$

2.2. Modeling of parameters

Table1. Design parameters of CCES

Parameters	Value	Unit
Temperature of low-pressure reservoir	308	K
Temperature of inlet steam of HX1	524.65	K
Temperature of steam between HX1 and HX2	468.19	K
Quality of steam between HX1 and HX2	1.0	
Temperature of outlet steam of HX2	468.05	K
Pressure of steam	1.40	MPa
Pressure of TES tank	2.0	MPa
Mass flow rate of steam from secondary side	2227.05	kg/s
Isentropic efficiency of turbines	0.9	
Isentropic efficiency of compressor	0.8	
Effectiveness of heat exchangers	0.95	
Ratio of charging time to discharging time	3	
Thermal efficiency of NPP (η_{NPP})	0.3515	

The design parameters are shown in Table1 and the variables and ranges of variation are shown in Table2. For the supercritical compressed CO_2 energy storage system, the temperature and pressure range of a low-pressure reservoir are set above the critical point of CO_2 (7.39 MPa, 304.25 K). If the bypass fraction of steam is less than 9%, the inlet temperature of cold side is over than the outlet temperature of hot side in 'Heat exchanger3' due to large compression work. Cold TES tank temperature is also set from the melting temperature to the temperature not higher than the outlet of hot side in the heat exchanger.

Table2. Variables of CCES

Parameters	Range of Variation	Unit
Bypass fraction of steam	9-15	%
Cold TES tank temperature(process9)	415.5-444.5	K
Pressure of low-pressure reservoir	7.9-8.9	MPa

3. Optimization & Results

A round-trip efficiency is the ratio of discharge work to charging work in the energy storage system. This is the criteria for cycle optimization. The round-trip efficiency in this system can be calculated using,

$$\eta_{RT} = \frac{W_t}{W_c + Q_{in} * \eta_{NPP}}$$

KAIST CCD code developed by KAIST research team is used for cycle optimization of round-trip efficiency calculation and the optimization condition can be obtained.

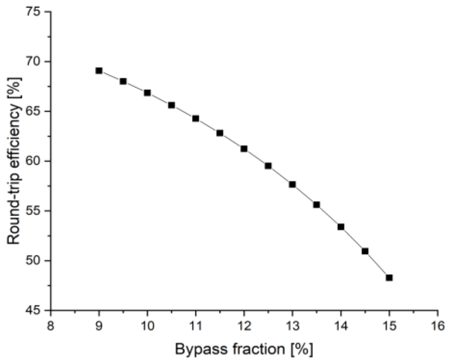

Figure 4. Effect of bypass fraction on round-trip efficiency

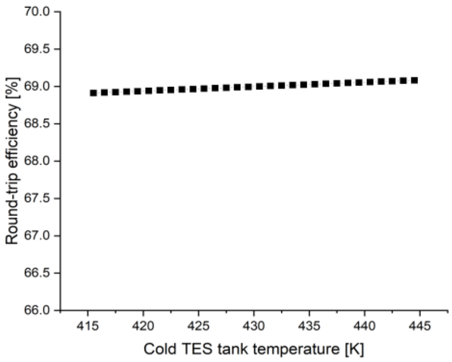

Figure 5. Effect of cold TES tank temperature on round-trip efficiency

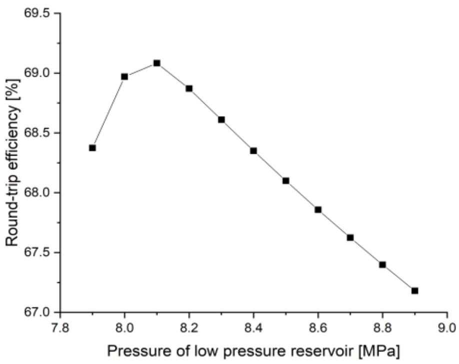

Figure 6. Effect of pressure of low-pressure reservoir on round-trip efficiency

The trends for the effects of the variables are shown in the Figures 4, 5 and 6. In Figure4, as the bypass fraction of steam decreases, the round-trip efficiency increases because of more compress work than the heat from steam. As explained before, the fraction cannot be less than 9%.

As the temperature of cold TES tank decreases, the round-trip efficiency also increases. However, it has little effect of cold TES tank temperature on round-trip efficiency in Figure 5. During the 29K increase, the efficiency doesn't increase more than 0.5%.

In Figure 6, the trends for the effect of the pressure of low-pressure reservoir has maximum. Therefore, the optimization condition of this system is 9%, 444.5K and 8.1MPa and the round-trip efficiency is expected to be 69.02%. The most effective factor is the bypass fraction of steam because compression work has more change than change of bypass fraction.

The thermodynamic data at the optimization condition is seen in the Table3 and T-s diagram is shown in Figure3.

Table3. Thermodynamic data at the optimization condition

Process	T(K)	p(MPa)	h(kJ/kg)	s(kJ/kg·K)
1(=8)	308.00	8.10	330.33	1.42
2(=3)	377.46	38.64	388.10	1.45
4	462.13	38.64	536.12	1.81
5	398.17	17.69	491.91	1.82
6	404.24	17.69	502.68	1.85
7	339.46	8.10	468.41	1.86

3. Conclusions

For optimization of the compressed supercritical CO_2 energy storage, the bypass fraction of steam is the most effective parameter. If the inlet/outlet temperature of steam increases, an effective heat exchanger between steam and TES can be made. The cold TES tank temperature has little effect on this. Thus, it will be fixed in the next study. The effect of the pressure of low-reservoir has maximum performance at 8.1MPa.

Further investigation will commence soon regarding optimization of exergy efficiency on this system and new layout of CCES that has different variables like expansion ratio instead of TES tank temperature will be suggested. Then, the process in the CO_2 reservoirs will be designed.

Acknowledgement

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