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Thermodynamic Study of Liquid CO_2 Energy Storage System Integrated to a Conventional PWR

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1. Introduction

The energy production from renewable energy (RE) sources is increasing globally and domestically. Globally, according to the United Nations World Climate Convention, the ratio of RE is expected to increase to reduce greenhouse gas (GHG) emission. In Korea, the energy policy 3020 was announced, which aims to increase the ratio of RE to 20% by 2030 [1]. However, as the proportion of RE increases, major technical challenges also arise.

Solving the intermittency issue of RE is one of the major challenges. Power generation from wind and solar is affected by weather and climate conditions and therefore it cannot always generate power when the demand is high. 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 an NPP. Energy Storage System (ESS) attached to the power cycle can solve this issue. Among the various ESSs, compressed CO_2 energy storage (CCES) is promising ESS due to high round-trip efficiency (RTE) and simple layout.

CCES integrated to a conventional PWR was studied and analyzed thermodynamically previously [2]. From this reference, its maximum RTE was estimated to be around 52%. However, it had quite low energy density, 3.2kWh/m^3 [2]. Liquid air energy storage (LAES) has high energy density due to small mass flow rate and high density of working fluid from liquefaction of air [3]. In order to make CCES more economical, CCES needs to further increase the energy density. This paper proposes to use the liquefaction process for this purpose.

Therefore, in this paper, a thermodynamic modeling and analysis of a liquid CO_2 energy storage (LCES) integrated to a conventional PWR is presented. Compared to CCES, the performance of LCES in terms of round-trip efficiency and power density are presented in this paper.

2. Thermodynamic modeling

2.1 Steam cycle modeling

In order to store energy in CCES, it is necessary to branch steam from the steam cycle of an NPP and determine which section to bypass in the steam cycle before it merges back. Referring to the previous study, a steam turbine that drives a CO_2 compressor in CCES is used to store the mechanical energy. The branched steam passes through the steam turbine. Since the mass flow rate of LP turbine (LPT) inlet and inlet of feedwater heater (FWH) are changed from the nominal mass flowrate, off-design models for the LPT and FWH are applied to evaluate the lost work due to energy storage. Steam turbine off-design model and cycle evaluation are explained in this paper [4]. ε-NTU is used for the off-design model of FWH.

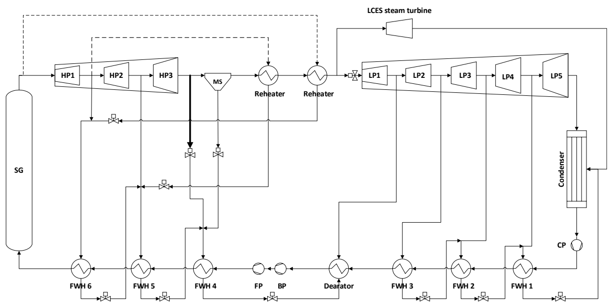


Figure 1. Layout and Steam Cycle integrated with LCES

2.2 Thermodynamic modeling of LCES

Assumptions used for the modeling are as follows:

(1) CO_2 tanks and the TES tanks have the same temperature, pressure, and therefore, thermophysical properties at the inlet and outlet, respectively.
(2) There is no pressure drop in the pipelines.
(3) Turbines and compressor have constant isentropic efficiencies, respectively.
(4) The ratio of charging time to discharging time is unity.
(5) There are no changes in potential and kinetic energies

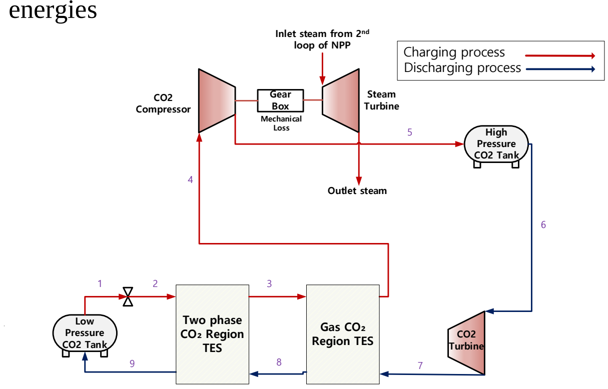


Figure 2. Layout of LCES integrated to PWR steam cycle

As shown in Figure 2, processes 1-5 are the energy storage process (Charing operation) and the rest of processes are the energy recovery process (Discharging operation). In order to achieve high energy density, a liquefaction process is introduced before entering the low-pressure tank. TES for the liquefaction process and a throttling valve for better heat exchange are added. In addition, TES is divided into two sections (Gas CO_2 TES and Two-phase CO_2 TES) due to the two-phase section and pinch problem.

2.2.1 Heat exchanger

All heat exchangers in this LCES system are assumed to have constant pressure drop rate. For given temperature and pressure of inlet of hot side and cold side, the outlets of hot side and cold side can be obtained from using heat exchanger effectiveness and the following equations.

$$Q_{max} = \min(\dot{m_{hot}}(h_{hot,in} - h_{hot,out,i}), \dot{m_{cold}}(h_{cold,out,i} - h_{cold,in}))$$

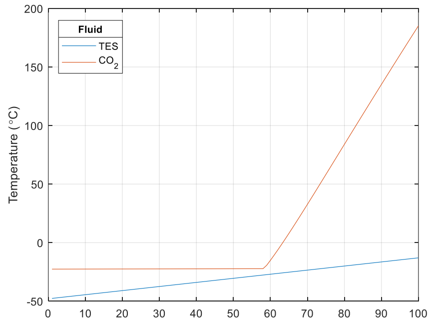
$$\varepsilon_{HX} = \frac{Q_{act}}{Q_{max}}$$

$$Q_{act} = \dot{m_{hot}}(h_{hot,in} - h_{hot,out})$$

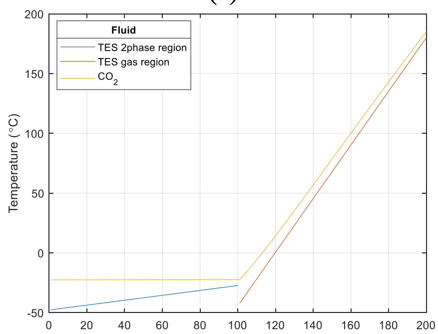
In this paper, pinch in heat exchangers is set to be larger than 5K. If it has a pinch problem, heat exchanger effectiveness is decreased until satisfying this condition.

2.2.2 TES

It has two TES due to two-phase heat exchange and pinch problem: Gas region CO_2 TES and two-phase region CO_2 TES. The temperature range of gas region CO_2 TES and two-phase region CO_2 TES are -20~180℃ and -50~-20℃ respectively. Therefore, LT therminol oil is used as the heat transfer fluid (HTF) for gas region and two-phase region.



(a)



(b)

Figure 3. Temperature profile in one TES (a) and two TESs (b) of

As shown in Figure 3, when it uses only one TES for liquefaction of CO_2, the maximum temperature loss of CO_2 is quite high due to pinch problem in the heat exchanger. Hence, the turbine work may be too small because of the low turbine inlet temperature (TIT). On the other hand, when it uses two TESs, the maximum temperature loss problem can be avoided.

2.2.3 Compressor

The compressor is driven by the steam turbine. It is called steam turbine driven compressor (STDC). Thus, it doesn't need motor and electricity to run the compressor. The outlet pressure, temperature and mass flow rate of a compressor can be obtained from the following equation and the prescribed compressor work, isentropic efficiency, inlet temperature and pressure ratio.

$$\eta_c = \frac{h_{out,s} - h_{in}}{h_{out} - h_{in}}$$

$$\dot{m}, T_{out} = f(\eta_c, T_{in}, P_{in}, P_{out}, W_{comp})$$

2.2.4 Turbine

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.

$$\eta_t = \frac{h_{in} - h_{out}}{h_{in} - h_{out,s}}$$

$$P_{out}, T_{out} = g(\eta_t, T_{in}, P_{in}, PR)$$

2.2.5 Pipe sizing

Since the flow rate can be quite large under certain design conditions, the pipe size issue must be addressed. The maximum diameter was referred from the ASME standard [5], and the diameter of each point for S- CO_2 is obtained from an empirical formula suggested by Ronald W. Capps [6].

$$D = 2\sqrt{\frac{\dot{m}}{\pi f_{pv} \rho^{0.7}}}$$

where D represents diameter of a pipe, f_{pv} represents pipe velocity factor and its optimal value is 29.

2.3 Modeling of parameters

Table1. Design parameters of LCES

Parameters	Value	Unit
Total steam bypass fraction to LCES	20	%
Ratio of charging time to discharging time	1	
Inlet temperature of CO_2 compressor	308.15	K
Isentropic efficiency of turbines	0.9	
Isentropic efficiency of compressor	0.85	
Effectiveness of heat exchangers	0.9	
ΔT between two tanks in 2-phase region TES	20	K
Pressure drop in HX	1	%
Mechanical loss of gear box	5	%

Table2. Variables of LCES

Parameters	Range of Variation	Unit
Pressure of low-pressure reservoir	0.6-3.4	MPa
Pressure of high-pressure reservoir	20-30	MPa

The design parameters are shown in Table 1 and the variables and ranges of variation are shown in Table 2. For the liquid CO_2 energy storage system, the minimum pressure range of CO_2 is set below the critical point of CO_2 (7.39MPa, 31°C). Similar to the previous study, total steam to bypass from steam cycle is fixed at 20% of nominal LPT mass flow rate.

3. Thermodynamic evaluation and Results

A round-trip efficiency (RTE) 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,

$$\eta_{RT} = \frac{W_{turb}}{W_{PWR,loss}}$$

where W_{turb} represents the CO_2 turbine work and $W_{PWR,loss}$ represents the difference of work before and after bypass the steam to CCES.

It is necessary to determine the amount of work that can be produced per unit volume of storage capacity. It is called power density or energy density.

$$\rho_{power} = \frac{W_{turb}}{\dot{m}_{charge/}\rho_{LPT} + \dot{m}_{discharge/}\rho_{HPT}}$$

KAIST CCD code developed by KAIST research team is used for cycle evaluation of round-trip efficiency and power density calculation.

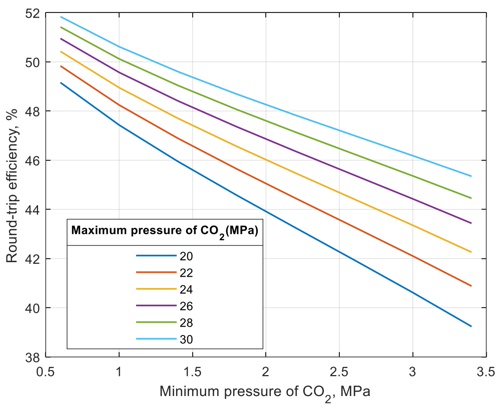


Figure 4. Round-trip efficiency vs Minimum and maximum pressure of system

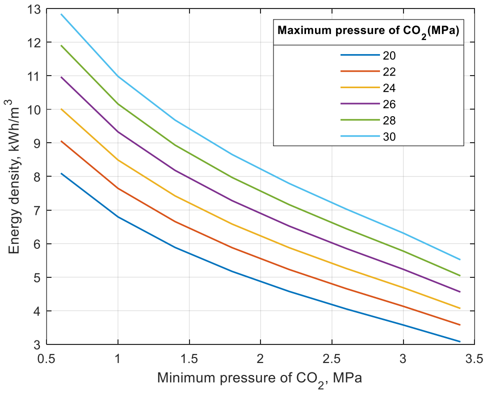


Figure 5. Energy density vs Minimum and maximum pressure of system

As shown in Figure 4 and Figure 5, it has the RTE of 39-52% and the energy density of 3.1-12.8kWh/m^3. As the maximum CO_2 pressure increases and the minimum CO_2 pressure decreases, the energy density and RTE increase. Thus, when the pressure ratio is the largest, it can be seen that it has the highest RTE as well as the highest energy density.

In Tables 3 and 4, the cycle performances under the optimized conditions are summarized. When performing optimization based on the energy density, the maximum and minimum pressures of CO_2 at the optimum point are 30 MPa and 0.6 MPa, respectively. The maximum energy density and RTE are 12.8 kWh/m^3 and 51.8%, respectively. Compared with CCES, LCES has more than 3 times the energy density. The mass flow rate of CO_2 is 529.9kg/sec, which is 1/3 times smaller, and the density of CO_2 stored in the LP tank is 1043.7 kg/m3, which is 3 times larger. However, due to the large compression ratio, the temperature of the CO_2 stored in the HP tank is high, reducing the density by 1/2. In addition, the RTE decreases by 12% due to heat loss using TES.

Table3. Optimization point of LCES

Parameters	Range of Variation	Unit
Pressure of low-pressure reservoir	0.6	MPa
Pressure of high-pressure reservoir	30	MPa

Table4. Optimization result of LCES

Parameters	Value	Unit
Round-trip efficiency	51.8	%
Energy density	12.8	kWh/m^3
CO_2 Turbine work	141.16	MW
CO_2 mass flow rate	529.9	kg/sec
Density of CO_2 in LP tank	1043.7	kg/m^3
Density of CO_2 in HP tank	253.1	kg/m^3

4. Summary and Future works

From the result of the liquid CO_2 energy storage analysis, it is shown that as the maximum pressure increases and the minimum pressure decreases, both the round-trip efficiency and power density increase. The maximum RTE is about 51.8% and maximum power density is about 12.8kWh/m³. Compared with CCES, LCES has almost the same RTE while having more than

3 times the energy density. Thus, it is seen that the energy density of CCES can be made higher by the concept of LCES.

In the future, the liquefaction process of CO_2 before the HP tank will be added to further increase the energy density. Further investigation will commence soon regarding optimization of LCES round-trip efficiency and energy density by adding various liquefaction processes as well.

Acknowledgement

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