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Study of Compressed CO_2 Energy System with low-temperature storage tank

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1. Introduction

Recently, as the demand for electricity increases, the share of renewable energy is also increasing. However, renewable energy has unpredictable intermittency in power generation. This problem can be solved by the application of Energy Storage System (ESS). ESS can store not only existing base load energy, but also renewable energy. There are many types of ESS and Thermal Energy Storage (TES), Compressed Air Energy Storage (CAES), Liquid Air Energy Storage (LAES) etc. are mainly used for large scale ESS. CAES is popular due to its high RTE and technical feasibility, and currently commercialized CAES has 42-54% of RTE and 2-6Wh/L of power density [1]. However, it has geographic limitation of air storage, because it is possible only in a large underground cavern reservoir [2]. To overcome this limitation, the concept of compressed CO_2 energy storage (CCES) was proposed that uses carbon dioxide as a working fluid, which has higher density than air, and stores in a pressure tank [3].

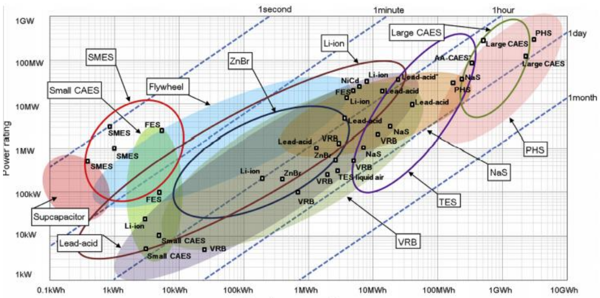


Figure 1. Comparison of power rating and rated energy capacity with discharge time duration at power rating [2]

LAES has high power density 60-120Wh/L [4], because it is an open cycle, so there is no need to store air after discharge, and it has high compression ratio over 100 or more. On the other hand, since CCES is a closed cycle, there are two or more storage tanks, and temperature of stored CO_2 in a low pressure tank (LPT) is relatively high, and the compression ratio is also low. As a result, CCES has low power density.

Therefore, in this paper, to compensate for low power density of CCES, results from a study on compressing CO_2 at low pressure near the triple point, and storing saturated liquid in LPT are presented.

2. System description

Assumptions 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.
3) The turbine and compressors have constant isentropic efficiencies, respectively.
4) The ratio of mass flow rate of charging and discharging is unity.
5) There are no changes in potential and kinetic energies.

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

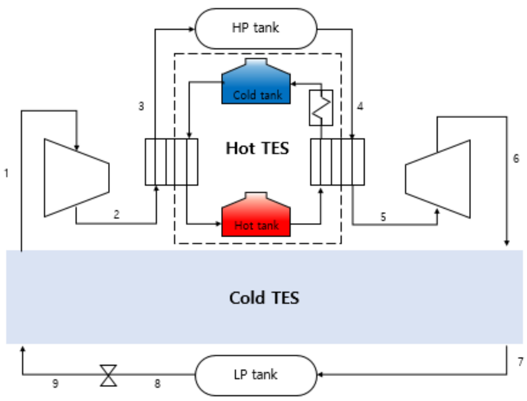


Figure 2. Schematic of CCES

CCES is a closed cycle and has components such as compressor, turbine, high pressure tank (HPT), low pressure tank (LPT), cooler and heat exchanger etc. The schematic is shown in Figure 2. Processes 1-2, 2-3, 8-9 and 9-1 are the energy charging process and the rest of processes are the energy discharging process. In HPT, CO_2 is stored in a supercritical state, and in LPT, it is stored in a saturated liquid state.

3. Thermodynamic model of CCES

3.1. Heat exchanger

Generally, the effectiveness, ε is defined :

$$\varepsilon = \frac{q}{q_{max}}$$

In a counterflow heat exchanger, one of the fluids would experience the maximum possible temperature difference, $T_{hot,inlet} - T_{cold,inlet}$. Therefore, q_{max} is determined to have the minimum heat capacity between cold flow and hot flow to achieve larger temperature difference.

$$q_{max} = C_{min}(T_{hot,inlet} - T_{cold,inlet})$$

All heat exchangers in this CCES system have constant pressure drop, and pinch point in heat exchangers should be larger than 5K. If it has pinch problem, effectiveness is decreased until satisfying this condition.

3.2. Hot TES

Therminol vp-1 is used for the material of hot TES. In the TES, the used specific heat capacity (c_p) is the average value of cold and hot tanks' temperatures. The specific heat capacity of therminol vp-1 at 1bar is the following.

$c_p = 0.003703T - 3.0274 \times 10^{-6}T^2 + 2.9324 \times 10^{-9}T^3 + 0.9279$ $[kJ/kg]$ (T: [°C]) [5]

3.3. Cold TES

The triple point temperature of CO_2 is -56.6°C. So, therminol LT is appropriate for cold TES material in its temperature range. It is assumed that the temperature difference between each tank of cold TES is 20K so that CO_2 can sufficiently exchange heat inside the cold TES, and pinch in heat exchangers is also larger than 5K.

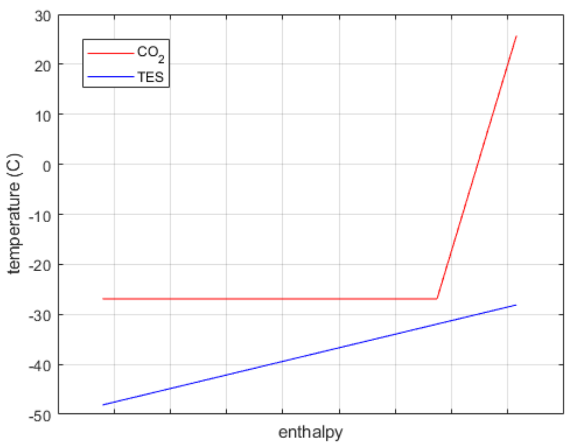


Figure 3. Temperature profile in cold TES when compressor inlet pressure is 0.6 MPa

3.4. Compressor

The isentropic efficiency of compressor, η_c is defined as:

$$\eta_c = \frac{h_{2s} - h_1}{h_3 - h_1}$$

where the subscript 2s denotes the outlet state of the compressor for the isentropic state. The outlet enthalpy and temperature of a compression can be obtained from the equation. Also, compression work, W_c can be obtained by charging mass flow rate, and enthalpy difference.

$$W_c = \dot{m}_{ch}(h_2 - h_1)$$

$\dot{m}_{ch}$ is charging mass flow rate.

3.5. Turbine

The isentropic efficiency of turbine, η_t is defined as:

$$\eta_t = \frac{h_5 - h_6}{h_5 - h_{6s}}$$

where the subscript 6s denotes the outlet state of the turbine for the isentropic state. Turbine outlet pressure is determined by pinch in a heat exchanger for the cold TES. Expansion work, W_t is defined as:

$$W_t = \dot{m}_{dis}(h_2 - h_1)$$

$\dot{m}_{dis}$ is discharging mass flow rate.

4. Results and Discussion

Round-Trip Efficiency (RTE) is the ratio of expansion work to compression work, and the power density is represent by expansion work per unit volume of storage tanks. The calculations were carried out by MATLAB and using the property database of REFPROP. RTE and power density indicate the performance of CCES, and are defined as follows.

$$\text{RTE} = W_t \,/\, W_c$$

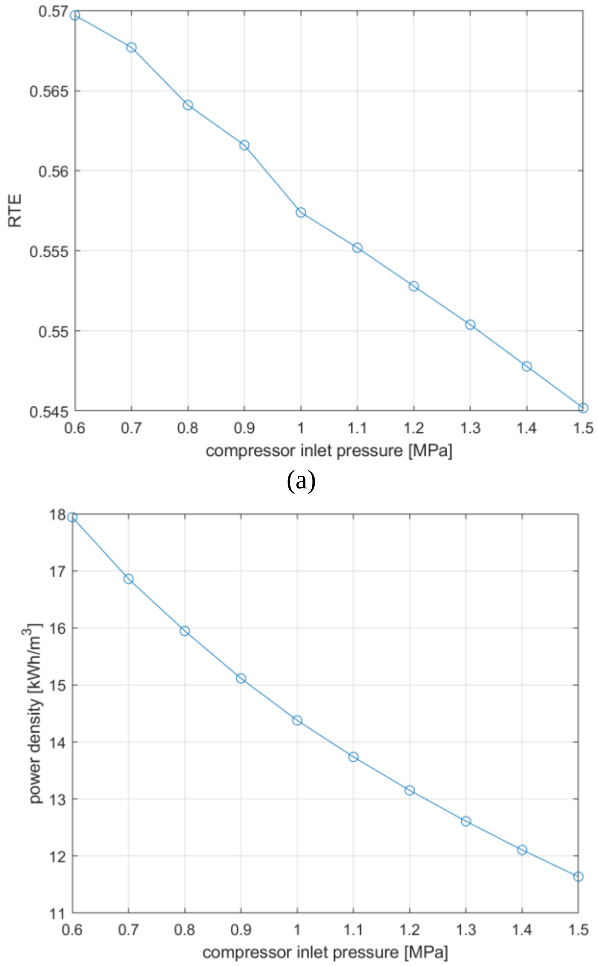
$$\text{Power density} = \frac{W_t}{\dot{m}_{ch}/\rho_{HPT} + \dot{m}_{dis}/\rho_{LPT}}$$

Table 1. Main parameters of CCES

Parameters	Value
Compressor isentropic efficiency (%)	80
Turbine isentropic efficiency (%)	85
Pressure of HPT (MPa)	30
Pinch in heat exchangers (℃)	5
Maximum effectiveness of heat exchanger	0.9
Heat exchanger pressure drop (%)	1
TES mass flow rate (kg/s)	1
Quality of CO_2 in LPT	0
Quality of CO_2 in compressor inlet	1
Hot TES cold tank temperature (℃)	100
Temperature difference between cold TES (℃)	20

Table2. Variables of CCES

Parameters	Range of Variation
Compressor inlet pressure (MPa)	0.6 - 1.5



(a)

(b)

Fig. 4. (a) Effect of compressor inlet pressure on RTE
(b) Effect of compressor inlet pressure on power density

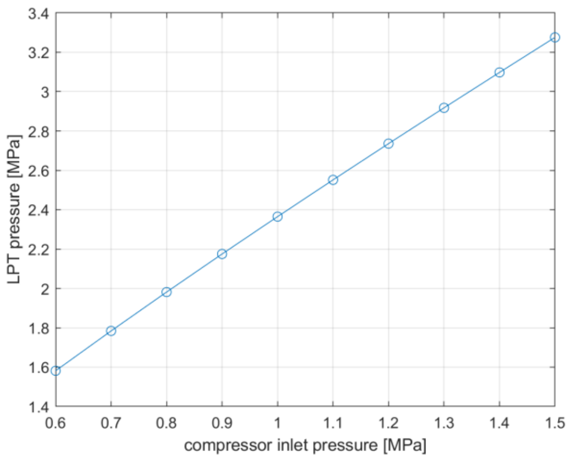


Fig. 5. Effect of compressor inlet pressure on LPT pressure

Both RTE and power density increase as the compressor inlet pressure decreases. Pressure of the LPT determined by the compressor inlet pressure, cold TES temperature difference, and the pinch in the heat exchangers. Fig. 5 shows the relation between compressor inlet pressure and LPT pressure. As the compressor inlet pressure increases, the LPT pressure increases. Accordingly, the temperature of the saturated liquid CO_2 stored in the LPT increases, thus the CO_2 density decreases. When the compressor inlet pressure is 0.6MPa, the temperature of LPT is -27.08℃ and the CO_2 density is 1062.5 kg/m^3. In addition, when the turbine outlet pressure is decreased, the turbine work also decreases. Therefore, the RTE and power density tend to decrease together.

5. Summary and Future works

From the result, it is shown that as the compressor inlet pressure decreases, the round-trip efficiency and power density are improved. The maximum RTE is about 57% and the maximum power density is about 17.94 kWh/m^3.

In the future, a tank model to limit the maximum pressure will be added, and cold TES optimization will be proceeded to further improve the system's performance. More detail modeling will be conducted soon regarding the optimization of CCES RTE and power density by adding off-design model.

Acknowledgement

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REFERENCES

[1] Chen, Haisheng, et al. "Progress in electrical energy storage system: A critical review." Progress in natural science 19.3 (2009): 291-312.
[2] Luo Xing, Jihong Wang, et al. "Overview of current development in electrical energy storage technologies and the application potential in power system operation". Applied energy 137 (2015): 511-536.
[3] Yuan Zhang, Ke Yang, et al. "Thermodynamic Analysis of a Novel Energy System with Carbon Dioxide as Working Fluid". Renewable Energy 99 (2016): 682-697.
[4] Ding, Yulong, et al. "Liquid air energy storage." Storing Energy. Elsevier, 2016. 167-181.
[5] Ronald W. Capps, Fluid Handling, textbook of the Gulf Coast Consulting Group, 2013.