A Sensitivity Study of Compressed CO_2 Energy Storage with High Temperature TES

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1. Introduction

In recent years, as the demand for electricity increases, the share of renewable energy is also increasing. However, renewable energy has an intermittency problem in the power generation process. Energy storage systems (ESS) can alleviate this problem. ESS can store not only energy from thermal power plants and nuclear power plants, which are previously responsible for the base load, but also extra renewable energy. Among various types of ESS, Compressed Air Energy Storage (CAES) is gaining popularity due to its high round-tip efficiency and technical feasibility. However, it has a geographical limitation, because air storage is possible only in large underground cavern reservoir [1]. To overcome this limitation, Compressed CO_2 Energy Storage (CCES) concept was proposed that uses carbon dioxide as a working fluid, which has higher density than air, and stores it in a pressure tank [3].

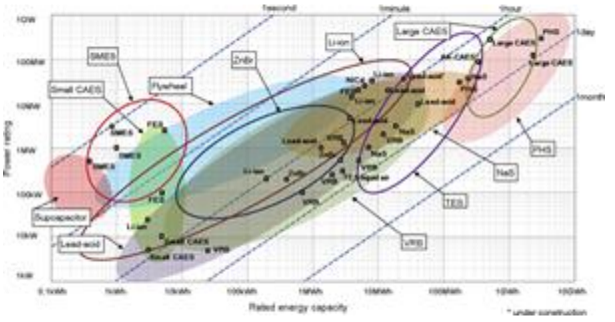


Figure 1. Comparison of power rating and rated energy capacity with discharge time duration at power rating [1]

Using Thermal Energy Storage (TES) in CCES enables CO_2 to be stored lower temperature (i.e. high density) in a pressure tank. Since the density of CO_2 increases as the temperature decreases. Therefore, the size of pressure tank can be reduced as stored CO_2 has lower temperature, which can reduce the overall size of CCES. In this paper, results of a parametric study obtained when adopting high temperature TES at CCES are presented.

2. System description

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 turbine and compressors have constant isentropic efficiencies, respectively.

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

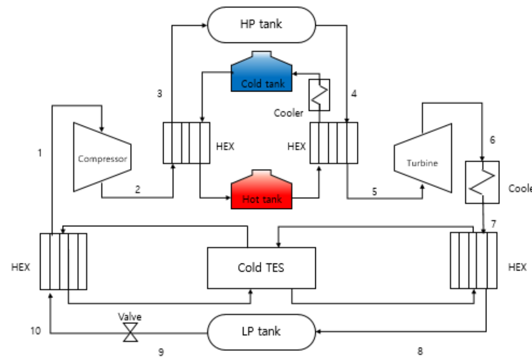


Figure 2. Schematic of CCES

CCES is a closed cycle and has components such as compressor, turbine, high pressure tank (HPT), low pressure tank (LPT), cooler and heat exchanger (HEX) etc. The schematic is shown in Figure 2. Processes 1-2, 2-3, 9-10 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. 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 6s denotes the outlet state of the turbine for the isentropic state. The outlet enthalpy and temperature of a turbine can be obtained from the equation. Also, compression work, W_c can be obtained by charging mass flow rate, and enthalpy difference.

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

3.2. 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 2s denotes the outlet state of the compressor for the isentropic state. Expansion work, W_t is defined:

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

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

3.3 TES

Therminol 66 is used for the material of TES and it is a high performance highly stable synthetic heat transfer fluid at temperatures up to 345°C. [2] In the TES, the pressures of the cold tank and hot tank are all at 1bar, and the specific heat capacity (c_p) changes depending on the temperature. The used c_p is the average value of cold and hot tanks' temperatures. The specific heat capacity of therminol 66 at 1bar is as follow.

$$c_p = 0.003313 * (T - 273.15) + 0.0000008970785 * (T - 273.15)^2 + 1.496005\ [kJ/kg \cdot K][2]$$

3.4. Cold TES

Cold TES stores the heat of CO_2 before it is stored in the LPT and transfers the heat before being compressed in the compressor.

3.5. Heat exchanger

Generally, the effectiveness, ε is defined :

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

In 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 get larger temperature difference.

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

3.6. Cooler

It is used to set the temperature after CO_2 exits the turbine and TES fluid flow from the hot tank into the cold tank. The temperature of CO_2 can drop to 25℃ and TES fluid temperature can drop to cold tank temperature.

4. Results and Discussion

By varying mass flow ratio of TES and CO_2, and the temperature of TES cold tank, the Round-Trip Efficiency (RTE) and the power density can be calculated. The calculations are 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.

$$\text{RTE} = \frac{\text{Expansion work}}{\text{Compression work}}$$

$$\text{Power density} = \frac{\text{Expansion or Compression work}}{\text{Volumes of HPT and LPT}}$$

Table 1. Main parameters of CCES

Parameters	Value
Compressor isentropic efficiency (%)	80
Turbine isentropic efficiency (%)	85
Inlet pressure of HPT (MPa)	30
Outlet pressure of LPT (MPa)	3.26
Outlet temperature of LPT (℃)	-2.5
Outlet pressure of turbine (MPa)	5.457
Minimum temperature approach in HEXs (℃)	5
Maximum effectiveness of heat exchanger	0.9
Outlet temperature of cooler (℃)	25
TES mass flow rate (kg/s)	1

Table2. Variables of CCES

Parameters	Range of Variation
CO_2 mass flow rate ratio	0.7 - 1.7
TES cold tank temperature (℃)	75 - 125

(CO_2 mass flow rate ratio) = $\dot{m}_{co2}$ / $\dot{m}_{tes}$

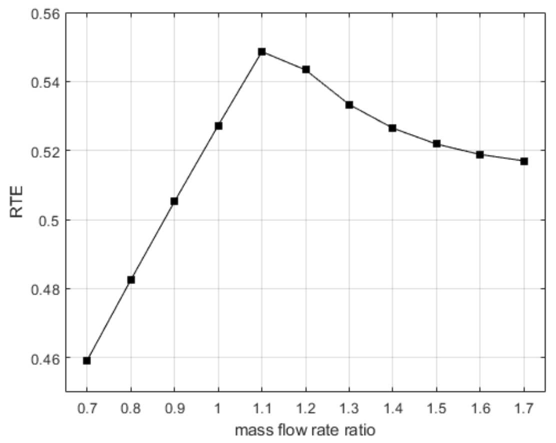


Figure 3. Effect of mass ratio on RTE at 100℃ of cold tank temperature

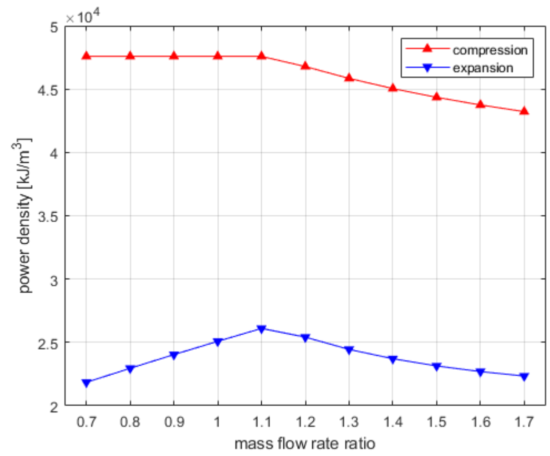


Figure 4. Effect of mass ratio on power density at 100℃ of cold tank temperature

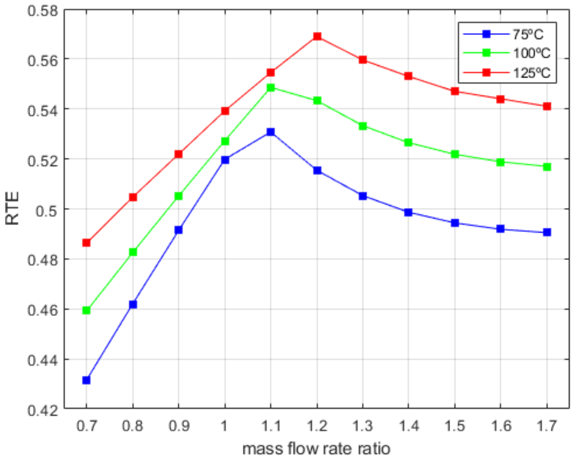
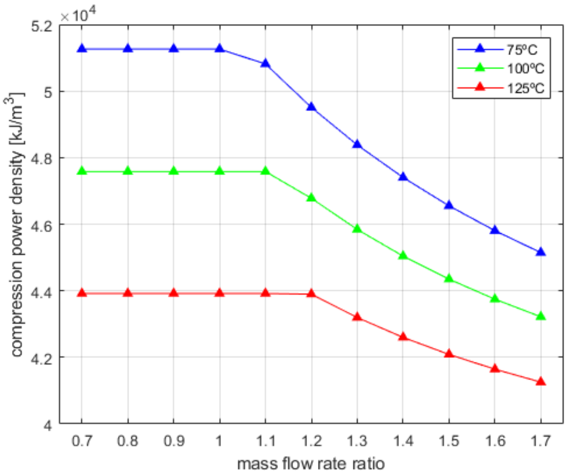
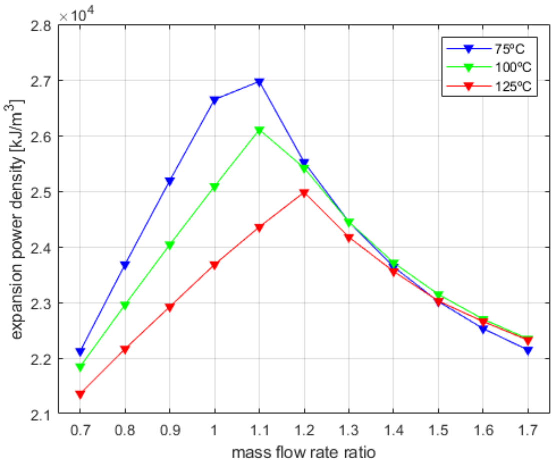


Figure 5. Effect of cold tank temperature on RTE



(a)



(b)

Figure 6. (a) Effect of cold tank temperature on compression power density (b) Effect of cold tank temperature on expansion power density

Figures 3 and 4 show the trend of RTE and power density, when mass flow rate ratio changes. In both cases, they have a maximum value at a specific mass flow rate ratio. Figures 5 and 6 show the RTE and power density change with respect to the cold tank temperature. The higher the temperature of the cold tank is, the higher the maximum value of RTE is, but the lower the maximum value of power density will be. The reason is that the lower the temperature of the cold tank, the lower the temperature of CO_2 stored in the HPT and the volume of CO_2 decreases. However, as the temperature of the cold tank decreases, the temperature of the hot tank also decreases. Therefore, the turbine inlet temperature and expansion work decrease.

5. Summary and future works

In this study, the performances of CCES with high temperature TES were discussed. Both RTE and power density have maximum values at specific mass flow rate ratio. The higher the temperature of the cold tank is, the higher the RTE but the lower the power density will be. For the future study, it is necessary to clarify the pressure tank modeling. If the maximum pressure of pressure tank is determined through modeling, CCES cycles can be optimized.

Acknowledgement

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