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Thermodynamic analysis of a compressed carbon dioxide energy storage system with a big flexible holder

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ABSTRACT

The utilization of energy storage technology is beneficial to improve renewable energy penetration. A novel compressed carbon dioxide energy storage system is proposed in this paper. A flexible gas holder is applied to store low pressure carbon dioxide in gaseous state. Detailed mathematic model of the novel compressed carbon dioxide energy storage system is established. To investigate the influence of key parameters on system performance, the parametric analysis is conducted. Results indicate that higher energy storage pressure has a positive effect on increasing system round trip efficiency within certain ranges. Higher isentropic compressor efficiency and turbine efficiency are beneficial to improve the system round trip efficiency. Lower energy storage pressure and higher isentropic efficiency of compressors are effective to reduce input power.

Keywords: compressed carbon dioxide energy storage; gas holder; thermodynamic analysis

NONMENCLATURE

Abbreviations	
CO_2	Carbon dioxide
CAES	Compressed air energy storage
CCES	Compressed carbon dioxide energy storage
LCES	Liquid carbon dioxide energy storage
Symbols	
h	Specific enthalpy (J/kg)
m	Mass flow rate (kg/s)
Q	Heat transfer rate (W)
t	Time
W	Power (W)
RTE	Round trip efficiency (%)
η	Isentropic efficiency (%)

1. INTRODUCTION

Compressed air energy storage (CAES) technology plays an important role in improving renewable energy penetration [1]. As an important development direction of CAES, compressed carbon dioxide (CO2) energy storage (CCES) is proposed in recent years. Compared with air, carbon dioxide has superior physical properties. CO2 has excellent density and heat capacity under supercritical state. Thus, the turbomachinery and heat transfer units applied in CCES system are more compactable in comparison with CAES system [2].

Based on CCES technology, Energy Dome of Italy has constructed a demonstration project with capacity of 2.5MW/4MWh in Sardinia island. Scholars have also conducted many theoretical work according to the advantages of CCES. Xu et al. [3] proposed a supercritical CCES system based on Brayton cycle. They employed flexible underwater energy bags in order to maintain isobaric storage. Zhang et al. [4] proposed a novel liquid carbon dioxide energy storage (LCES) system. They utilized low-temperature thermal energy storage to improve utilization efficiency of compression waste heat. Hao et al. [5] put forward a new transcritical CCES system. They employed a heat pump system to recover waste heat sufficiently.

Scholars also applied different research methods to explore the performance of CCES system. Alami et al. [6] represented experimental research on a CCES system. They set up three cylinders to drive an air turbine to generate power. Liu et al. [7] conducted a comprehensive study on a transcritical CCES system using conventional and advanced exergy analyses. Fu et al. [8] also proposed a comparative research between supercritical CCES system and transcritical CCES system which both coupled with solar heat storage.

Inspired by the techniques of liquid carbon dioxide storage and gaseous carbon dioxide storage, according to abovementioned studies. In this paper, an innovative compressed carbon dioxide energy storage system with a huge flexible holder is proposed. The flexible holder is employed to store CO2 in the gaseous state. Ambient water is applied to recycle compression heat and condensate working medium after the high pressure cooler. To understand the effect of main operation parameters on system performance, thermodynamic analysis of the proposed system is conducted.

2. SYSTEM DESCRIPTION

The schematic diagram of the proposed CCES system is shown in Fig. 1. The system is composed of compressors, turbines, heat exchangers, a gas holder, a liquid CO_2 storage tank and water vessels. During energy storage stage, gaseous CO_2 is released from the gas holder and then undergoes a three-stage compression process to become supercritical state. The compression heat produced by the compression process is absorbed through coolers and then stored in the Heater storage. Next, the supercritical CO_2 is condensed into liquid state in the Condenser. Finally, the condensed liquid CO_2 is stored in the CO_2 liquid storage. During energy release stage, the liquid CO_2 from the CO_2 liquid storage is first throttled to constant pressure through the Valve. Then, the CO_2 is heated in the Evaporator and converted into gas state. The gas CO_2 is then heated to a supercritical state by high temperature water in the high-pressure heater. The supercritical CO_2 undergoes a three-stage expansion process to generate electricity. Finally, the expanded gas CO_2 is cooled to ambient temperature and stored in the Gas holder for the next cycle.

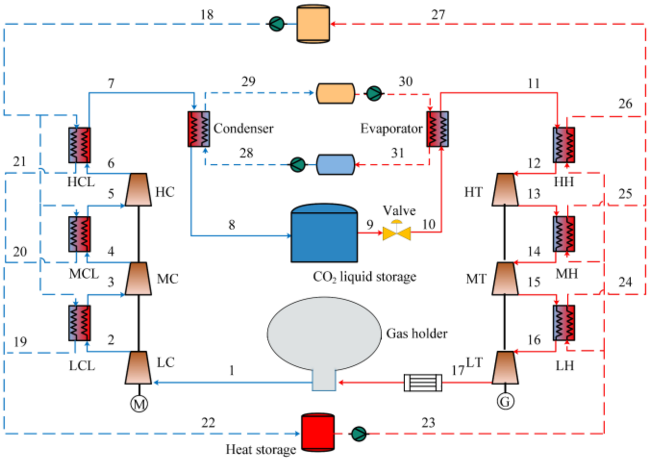

Fig. 1 Schematic diagram of the proposed CCES system

3. MATHEMATIC MODEL

In this section, thermodynamic model is established to evaluate system performance based on the first law of thermodynamics.

The power consumption of compressors is shown as:

$$W_{LC} = m_{CO_2}(h_2 - h_1) \tag{1}$$

$$W_{MC} = m_{CO_2}(h_4 - h_3) \tag{2}$$

$$W_{HC} = m_{CO_2}(h_6 - h_5) \tag{3}$$

The power generation of turbines can be expressed as:

$$W_{HT} = m_{CO_2}(h_{12} - h_{13}) \tag{4}$$

$$W_{MT} = m_{CO_2}(h_{14} - h_{15}) \tag{5}$$

$$W_{LT} = m_{CO_2}(h_{16} - h_{17}) \tag{6}$$

The isentropic efficiency of compressors and turbines can be shown separately as:

$$\eta_C = \frac{h_{out,is} - h_{in}}{h_{out} - h_{in}} \tag{7}$$

$$\eta_T = \frac{h_{in} - h_{out}}{h_{in} - h_{out,is}} \tag{8}$$

The heat energy balance equations of coolers and heaters are shown as:

$$Q_{LCL} = m_{CO_2}(h_2 - h_3) = m_{water,19}(h_{19} - h_{18}) \tag{9}$$

$$Q_{MCL} = m_{CO_2}(h_4 - h_5) = m_{water,20}(h_{20} - h_{18}) \tag{10}$$

$$Q_{HCL} = m_{CO_2}(h_6 - h_7) = m_{water,21}(h_{21} - h_{18}) \tag{11}$$

$$Q_{LH} = m_{CO_2}(h_{16} - h_{15}) = m_{water,24}(h_{23} - h_{24}) \tag{12}$$

$$Q_{MH} = m_{CO_2}(h_{14} - h_{13}) = m_{water,25}(h_{23} - h_{25}) \tag{13}$$

$$Q_{HH} = m_{CO_2}(h_{12} - h_{11}) = m_{water,26}(h_{23} - h_{26}) \tag{14}$$

The heat exchanged in the evaporator and the condenser can be illustrated as:

$$Q_{Cond} = m_{CO_2}(h_7 - h_8) = m_{water,28}(h_{29} - h_{28}) \tag{15}$$

$$Q_{Evap} = m_{CO_2}(h_{11} - h_{10}) = m_{water,30}(h_{30} - h_{31}) \tag{16}$$

The power consumption during the charge process is expressed as:

$$W_{input} = W_{LC} + W_{MC} + W_{HC} \tag{17}$$

The power generation during the discharge process is expressed as:

$$W_{output} = W_{LT} + W_{MT} + W_{HT} \tag{18}$$

The round trip efficiency (RTE) of the proposed system is expressed as:

$$RTE = \frac{W_{output} t_{dis}}{W_{input} t_{ch}} \times 100\% \tag{19}$$

4. RESULTS AND DISCUSSION

In this section, thermodynamic analysis of the proposed CCES system is represented. The detailed operation conditions are listed in Table 1.

Table 1

Detailed operation conditions of the proposed system

Parameter	Unit	Value
Ambient temperature	K	298.15
Ambient pressure	MPa	0.1
Energy storage pressure	MPa	9

Pinch temperature difference in the condenser and the evaporator	K	3
Pinch temperature difference in the coolers and the heaters	K	5
Evaporation temperature	°C	22
Isentropic efficiency of compressors	-	0.85
Isentropic efficiency of turbines	-	0.88

4.1 Effect of energy storage pressure

Fig. 2 illustrates the effect of energy storage pressure on the system performance. It is obviously that the variation of energy storage pressure has opposite effects on W_{output} and m_{ch}. Meanwhile, the W_{input} increases as the increase of energy storage pressure. The RTE increases first and then decreases gradually. It can be seen that the RTE reaches the peak value of 69.77% when the energy storage pressure is equal to 9 MPa.

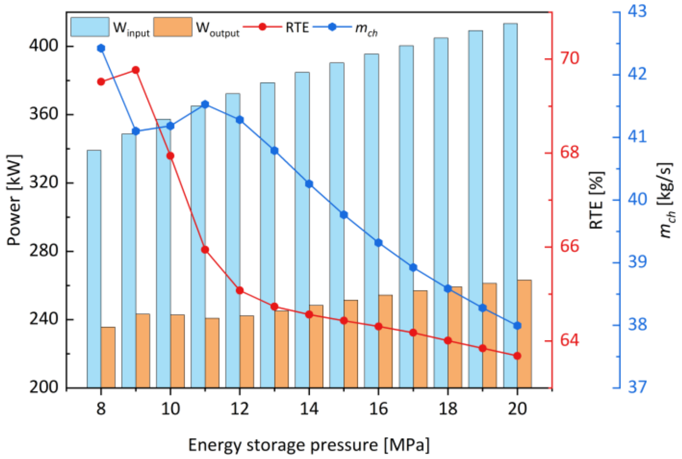

Fig. 2 Effect of energy storage pressure on the system performance

4.2 Effect of the η_C

Fig. 3 expresses the effect of compressor isentropic efficiency on system performance. The W_{input} and the W_{output} both decrease with the increase of the η_C. And the changing trend of the former is higher than that of the later. The RTE and the m_{ch} both increase gradually as the η_C increases. With the changing of η_C from 0.7 to 0.9, the RTE and m_{ch} of the proposed system rise by 11.31% and 3.29 kg/s respectively.

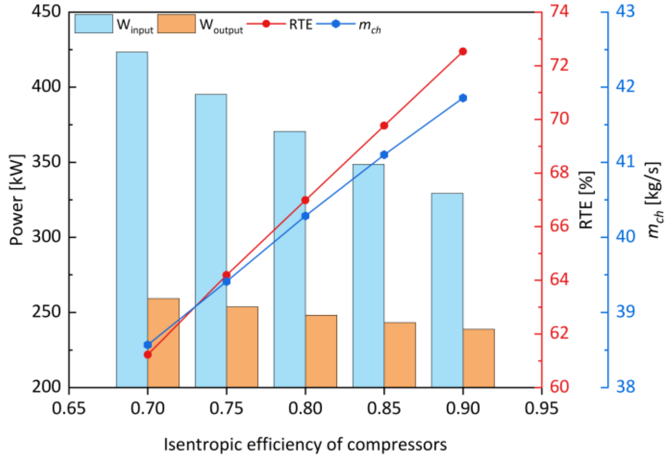

Fig. 3 Effect of the η_C on the system performance

4.3 Effect of the η_T

In this section, the effect of turbine isentropic efficiency on system performance is revealed in Fig. 4. It is obviously that the variation of η_T has no influence on the W_{input}. With the improvement of η_T, the W_{output} and the RTE both show an increasing trend. The W_{output} and the RTE enhanced by 54.95 kW and 15.76% respectively as the η_T varies from 0.7 to 0.9. It can also be seen from the figure that the m_{ch} decrease monotonously. The m_{ch} reduced 11.39 kg/s when the η_T is enhanced by 0.2.

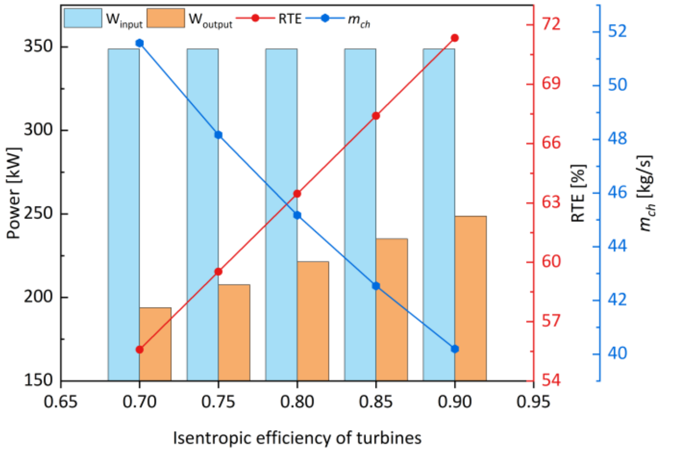

Fig. 4 Effect of the η_T on the system performance

4.4 Effect of the T_{11}

Furthermore, the effect of T_{11} on system performance is depicted in Fig. 5. It is obviously that the variation of the T_{11} has slightly effect on the W_{output}. Moreover, the W_{input} keeps constant value of 348.75 kW as reflected in the Figure. Besides, the system RTE and m_{ch} show opposite changing trend with the increase of the T_{11}.

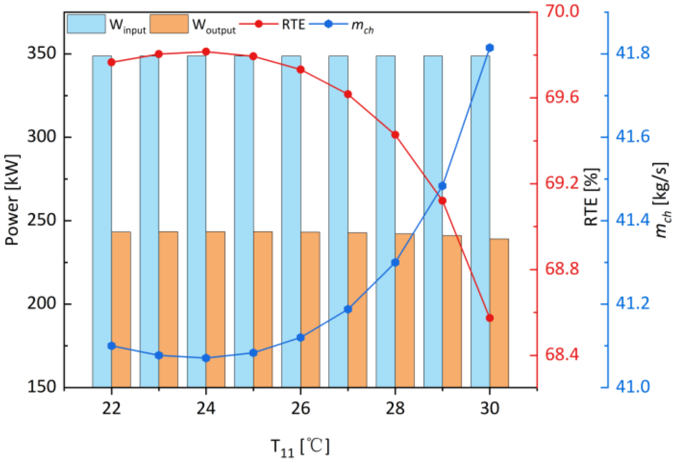

Fig. 5 Effect of the T_{11} on the system performance

5. CONCLUSIONS

In this paper, a new compressed carbon dioxide energy storage system using a flexible gas holder as the discharge storage is proposed. The significant conclusions are as follows: higher energy storage pressure and T_{11} have a positive effect on increasing system RTE within certain ranges, higher η_C and η_T are beneficial to improve the system RTE; lower energy storage pressure and higher η_C are effective to reduce W_{input}; lower η_C and higher η_T are favor to improve power generation of turbines; higher energy storage pressure, lower T11, higher η_C and η_T contribute to smaller m_{ch}.

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NONE

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