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Influence of the component efficiency on the performance of a compressed CO2 energy storage

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ABSTRACT

Compressed CO_2 energy storage has received a lot of attention as a favorable solution on solving the intermittency of renewable energy sources. A novel compressed CO_2 energy storage system with a flexible gas holder is proposed in this paper. Mathematic models are established and parametric analyses are conducted to evaluate the thermodynamic and economic performance of the proposed system. Results demonstrate that there exists an optimum turbine efficiency of 86% to achieve the lowest levelized cost of electricity. Higher isentropic efficiency of compressors produces higher round-trip efficiency and higher levelized cost of electricity. Higher round trip efficiency and lower levelized cost of electricity are operated with lower pressure loss and pinch temperature difference of heat exchangers. Meanwhile, system performance such as round trip efficiency and levelized cost of electricity are more sensitive to heater1.

Keywords: Compressed CO_2 energy storage system, pinch temperature difference, pressure loss

NONMENCLATURE

Abbreviations	
	Carbon dioxide
CO2	*Compressed carbon dioxide energy storage*
CCES	
LCES	*Liquid carbon dioxide energy storage*
Symbols	
W	*Power (W)*
$\dot{m}$	*Mass flow rate (kg/s)*
h	*Specific enthalpy (J/kg)*
Q	*Heat transfer rate (W)*
η	*Isentropic efficiency (%)*
RTE	*Round trip efficiency (%)*
LCOS	*Levelized Cost of Storage ($/kWh)*

1. INTRODUCTION

Climate change is a global issue that could lead to serious environmental problems and dramatic changes in people's productive lives [1]. The excessive use of fossil fuels and overexploitation of geological resources are considered to be major factors [2]. The fact remains that the world's electricity generation is overly determined by fossil fuels. Meanwhile, renewable energy sources suffer from intermittency in the production of electricity, which leads to instability in energy storage [3].

Energy storage systems are of strategic importance in energy security and guarantee, energy transition, carbon emission reduction, and power system optimization [4]. Compared to conventional long-term energy storage technologies, CCES technology has caught some eye for high efficiency, environmental friendliness, and sustainability.

CCES technology has caught many researchers' eyes. Wang et al. [5] proposed a basis liquid carbon dioxide energy storage (LCES) system and two improved LCES systems. The results indicated the combination of single-stage turbomachinery was the best system configuration for these three options. Liu et al. [6] presented a new LCES system with a cold recuperator and low-pressure stores. They found that the efficiency of the system was more sensitive to the cooling temperature of the high-pressure cooler. Meng et. al. [7] presented an integrated LCES and Power to Methane system to increase the potential of system processes in a flexible and continuous manner. Xu et al. [8] proposed a combined heating and power system based on compressed CCES systems for carbon. They found that the improvement of low storage pressure has a positive effect on the system output. Yang et al. [9] systematically explored the effects of insufficient charging and discharging on compressed carbon dioxide energy storage systems in three typical scenarios. Zhao et al. [10] designed a CCES system with a

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flexible gas holder as a low-pressure store. The results indicated an optimal cooling temperature existed in the cooler to increase system efficiency and reduce the levelized cost of storage.

This article proposes a unique system layout and analyzes key component parameters such as heat exchanger pressure loss and turbomachinery isentropic efficiency for the system performance in a compressed CO2 energy storage system. Especially, a gas holder is used to keep CO_2 under ambient pressure as a low-pressure store. To evaluate the impact of the key component parameters on the performance, a thermodynamic and economic analysis of the system is carried out.

2. SYSTEM DESCRIPTION

The system is specifically provided with all specific details in Fig. 1. The whole system consists of compressors, heat exchangers, a liquid storage tank for CO_2, throttle valves, turbines, a gas holder for CO_2 under ambient pressure, water tanks for heat storage, and pumps. The entire process consists of a water cycle and a carbon dioxide cycle, both of which are closed.

In the initial phase of the cyclic process, CO_2 is compressed to a supercritical state by compressors. The cooler after each section is arranged to recover the compression heat. Specifically, due to the pseudo-critical point of CO_2, an additional condenser is required to liquefy the CO_2. Finally, the liquid CO_2 is transported and stored in a tank. Meanwhile, the recovered compression heat in coolers is transported by water to hot tank#1.
And then, liquid CO_2 in the tank is transported to throttle valves for maintaining continuous pressure. The liquid CO_2 is heated in an evaporator to achieve its vaporization. In particular, the CO_2 absorbs compression heat in heaters to achieve preheating and then enters the turbine to realize power output to drive the generator. Eventually, CO_2 enters the gas holder for storage through the radiator to release the excess heat to the ambience.

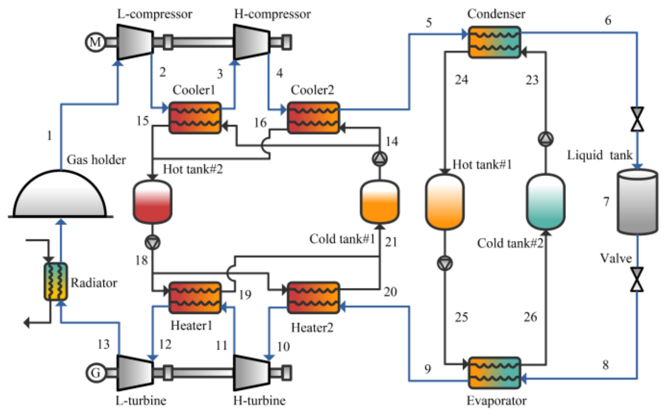

Fig. 1 Specific details of the proposed CCES

3. MATERIAL AND METHODS

This section describes the workflow and modeling process of the system in terms of thermodynamic and economic performance.

3.1 Thermodynamic modeling

CO_2 as a circulating medium undergoes thermodynamic processes.

Compressor:

The power of compressors is expressed as：

$$\dot{W}_{LC} = \dot{m}_1(h_2 - h_1) \quad (1)$$

$$\dot{W}_{HC} = \dot{m}_3(h_4 - h_3) \quad (2)$$

Isentropic efficiency (η_C) is defined as：

$$\eta_C = \frac{h_{out,is} - h_{in}}{h_{out} - h_{in}} \quad (3)$$

Turbine:

The power generated by the turbine is expressed as:

$$\dot{W}_{LT} = \dot{m}_{12}(h_{12} - h_{13}) \quad (4)$$

$$\dot{W}_{HT} = \dot{m}_{10}(h_{10} - h_{11}) \quad (5)$$

Isentropic efficiency (η_T) is expressed as:

$$\eta_T = \frac{h_{in} - h_{out}}{h_{in} - h_{out,is}} \quad (6)$$

Heat exchanger:

The energy balance equation is expressed as:

$$\dot{Q} = \sum_{i=1}^{N} \dot{Q}_i \quad (7)$$

$$\dot{Q} = \dot{m}_{CO_2}(h_{CO_2,i+1} - h_{CO_2,i}) = \dot{m}_{water}(h_{water,i+1} - h_{water,i}) \quad (8)$$

The round trip efficiency (RTE) is one of the indicators used to measure the performance of a system. It is defined as:

$$RTE = \frac{\int_0^{t_{dis}} \dot{W}_{dis} dt}{\int_0^{t_{ch}} \dot{W}_{ch} dt} \quad (9)$$

with

$$\dot{W}_{ch} = \dot{W}_{LH} + \dot{W}_{HH} \quad (10)$$

$$\dot{W}_{dis} = \dot{W}_{LT} + \dot{W}_{HT} \quad (11)$$

3.2 Economic modeling

The approach of Levelized Cost of Storage (*LCOS*) is widely referred to in energy storage systems and then is expressed as:

$$LCOS = \frac{\sum_{y=1}^{life} \frac{Z_{OM} + Z_{ch}}{(1+dr)^y} + Z_{PC} + Z_{IC}}{\sum_{y=1}^{life} \frac{cycle W_{dis} t_{dis}}{(1+d_r)^y}} \quad (12)$$

Where Z_{OM} is operation and maintenance cost; Z_{IC} represents the installation cost; Z_{PC} represents purchased cost; Z_{ch} is the electricity purchase cost.

4. RESULTS AND DISCUSSION

The specific design parameters of the system can be found in Table 1.

Table 1

Preliminary design parameters.

Parameter	Unit	Value
Ambient temperature	°C	25
Ambient pressure	MPa	0.1
Compressors' isentropic efficiency	%	85
Turbines' isentropic efficiency	%	85
Heaters' pressure losses	MPa	0.02
The pinch temperature difference in coolers	°C	5
Charge duration	h	8
Discharge duration	h	8
Valley electricity price	$/kWh	0.052

4.1. The influence of isentropic efficiency on compressors

The influences of isentropic efficiency on compressors are illustrated in Fig. 2. *RTE* and *LCOS* both increase monotonically as compressor efficiency increases. The curves and histogram reveal that they are more sensitive to variation in the combination of the compressor in comparison with each compressor.

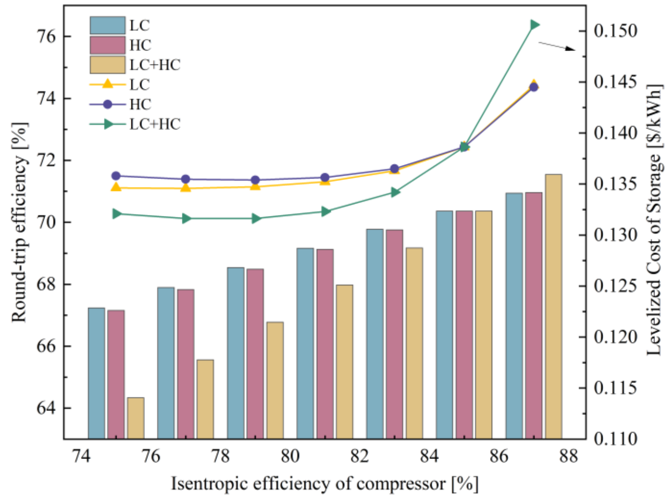

Fig. 2 The influence of isentropic efficiency on compressors

4.2. The influence of isentropic efficiency on turbines

The variations of *RTE* and *LCOS* under different turbine isentropic efficiencies are expressed in Fig. 3. Only the *RTE* varies monotonically with the turbine isentropic efficiency varying. Raising turbine isentropic efficiency promotes the increase of *RTE*. The curves of *LCOS* illustrate analogous variation tendency. It reaches the lowest value when the turbine's isentropic efficiency is 86%.

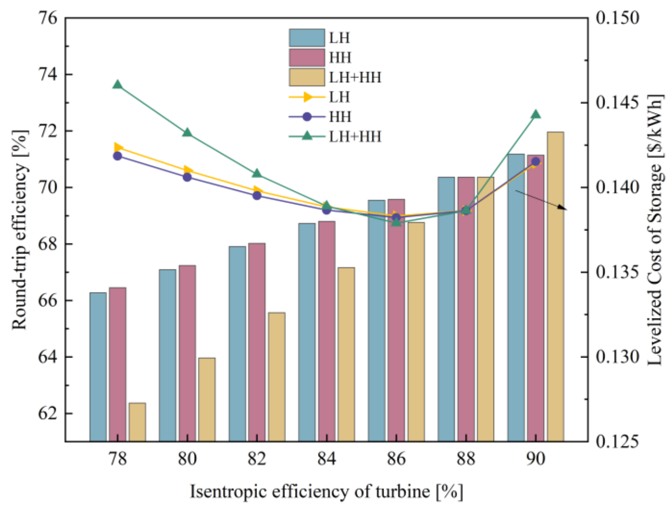

Fig. 3 The influence of isentropic efficiency on turbines

4.3. The influence of pinch temperature difference on coolers

The influences of the pinch temperature difference on coolers are represented in Fig. 4. As can be seen that the decrease in *RTE* is caused by the increasing pinch temperature difference of coolers. The *LCOS* arrives at the optimum values at the pinch temperature difference of 6 °C for cooler1 and 4 °C for cooler2.

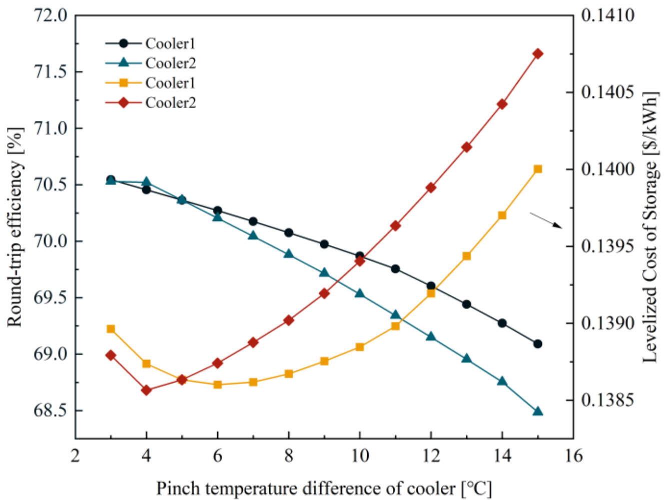

Fig. 4 The influence of pinch temperature difference on coolers

4.4. The influence of pressure loss on heaters

The variations of *RTE* and *LCOS* under different pressure losses of heaters are illustrated in Fig.5. As depicted, system performance is more sensitive to heater1. *RTE* decreases from 70.72% to 69.65% for heater 1 and 70.40% to 70.28% for heater 2. Meanwhile, lower *LCOS* can be promoted by the decrease in pressure losses in heaters. As pressure loss in heaters varies from 0 to 0.06 MPa, *LCOS* increases from 0.1380 $/kWh to 0.1399 $/kWh for heater1 and 0.1386 $/kWh to 0.1388 $/kWh for heater2.

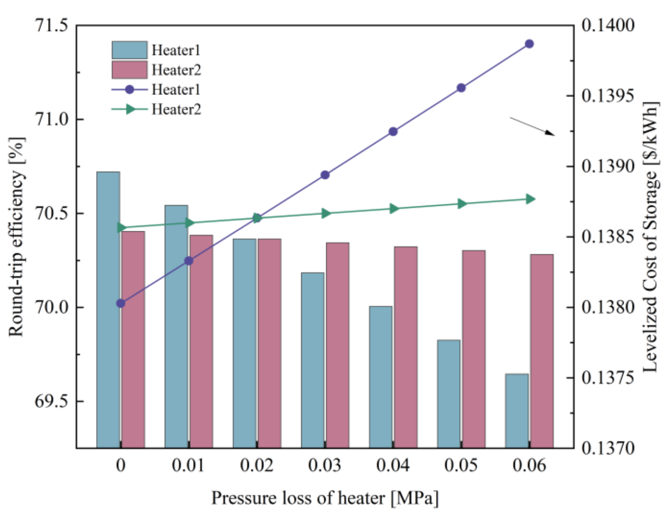

Fig. 5 The influence of pressure loss on heaters

5. CONCLUSIONS

Thermodynamic and economic modeling of the proposed system is carried out to assess influence of main parameters on components. Results demonstrate that there exists an optimum expander efficiency of 86% to achieve the lowest *LCOS*. When the isentropic efficiency of the turbomachinery changes in parallel, the performance of the system behaves more sensitively than individual turbomachinery changes. The system performance is more sensitive to the pressure losses of heater1 than heater2.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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