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Thermodynamic analysis of a novel liquid carbon dioxide energy storage system with low pressure storage and cold recuperator

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ABSTRACT

It is an effective way to expand the scale of renewable energy utilization by combining energy storage technology with renewable energy. In this paper, a novel energy storage technology based on liquid carbon dioxide storage, low pressure storage and latent cold energy storage is proposed. The main work of this paper is to establish the thermodynamic model of the system, and investigate the influence of key parameters on the performance of the system through parameter analysis. The analysis results show that in a certain range, there are optimal R_{4419}, R_{129}, R_{2118} and R_{3836} respectively to make round trip efficiency reach the maximum value. Increasing R_{129} and R_{2118} can improve the energy density of the system.

Keywords: carbon dioxide energy storage; low pressure storage; latent cold energy storage; thermodynamic study

NONMENCLATURE

Abbreviations	
CGES	Compressed gas energy storage
CCES	Compressed carbon dioxide energy storage
LCES	Liquid carbon dioxide energy storage
LCS	Latent cold energy storage
Symbols	
h	Specific enthalpy (J/kg)
m	Mass flow rate (kg/s)
W	Power (W)
Q	Heat transfer rate (W)
t	Time
RTE	Round trip efficiency
ρ_E	Energy density
R_{4419}	The ratio of mass flow rate between stream 44 and stream 19
R_{129}	The ratio of mass flow rate between stream 12 and stream 9
R_{2118}	The ratio of mass flow rate between stream 21 and stream 18
R_{3836}	The ratio of mass flow rate between stream 38 and stream 36

1. INTRODUCTION

Compressed gas energy storage (CGES) technology is one of the effective methods to conquer the fluctuation of renewable energy and maintain the co-ordination of power supply and demand [1]. Due to the excellent thermophysical properties of carbon dioxide (CO_2), such as low critical temperature and high density, the use of CO_2 as the working medium of CGES system has attracted a lot of attention [2].

Some researches based on compressed carbon dioxide energy storage (CCES) have been carried out. Liu et al presented a novel CCES system with two-reservoir [3]. By comparing the performance of the system under supercritical and transcritical conditions, it can be concluded that the transcritical CCES system has better system performance. Hao et al proposed a transcritical CCES system with thermal energy storage and a heat pump to overcome the dependence of the system on fossil fuels [4].

In transcritical and supercritical CCES systems, the dependence on geographical conditions is one of the main obstacles limiting the application of technology. Liquid carbon dioxide energy storage (LCES) [5]， which uses liquid storage to store CO_2, is a new development direction without geographical restrictions. In order to obtain better thermal and economic performance, Liu et al presented a LCES system which can utilize waste heat [6]. Xu et al used solar energy to increase the temperature of CO_2 in the turbine inlet of the LCES system and thus increase the power outlet of the system [7]. For solving the problem of CO_2 condensation in discharge progress, Liu et al proposed a new LCES system integrated with ejector condensing cycle [8].

A novel LCES system with low pressure storage and cold recuperator is presented in this paper. The storage of CO_2 as a low-pressure liquid can reduce the material requirements for storage devices. The LCS can store latent cold energy to liquefy CO_2 from the expander outlet and greatly reduce the required cold storage volume. In order to improve the heat storage capacity, high pressure water is used to store compression heat. The performance of the system is studied by establishing the thermodynamic model and analyzing the parameters of the system.

2. SYSTEM DESCRIPTION

The schematic diagram of the proposed system is shown in Fig. 1. The working process of the system is divided into charge process and discharge process. During charge process, the CO_2 from LST1 is throttled in the valve and then cold energy is stored in the LCS. Further, the gas CO_2 mixed with the separator outlet stream 16 adsorbs heat in HE1 and is then compressed by two compressors. At this time, the compression heat is absorbed by water in LCL and HCL and stored in HWV. Next, the compressed CO_2 dissipates heat in the radiator, and then further cools down through HE1 and HE2. Finally, the expanded CO_2 in CryoT is separated by separator and stored in LST2. During discharge process, the liquid CO_2 from LST2 is pressurized in CryoP and then absorbs heat in HE3 and HE4. Afterwards, the CO_2 before entering the turbine is further heated by hot water stored in the HWV, the heated CO_2 expands in two turbines and outputs power. The expanded CO_2 dissipates heat in the radiator, and then further cools down in HE4. Finally, the expanded CO_2 in the expander absorbs the cold energy in the LCS and is liquefied, and then is stored in the LST1. In this system, methanol and water are used to store sensible heat energy and latent cold energy storage is used to store latent cold energy.

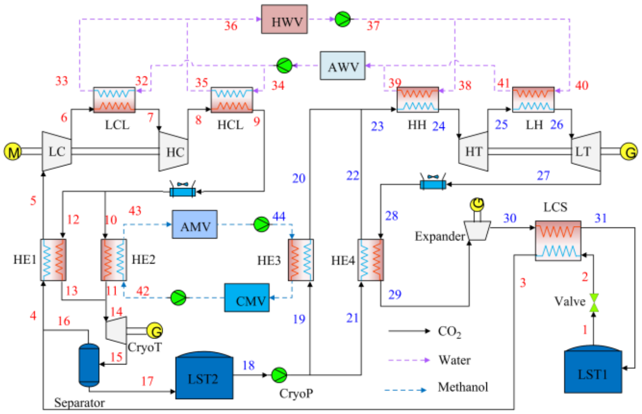

Fig. 1. Schematic diagram of the proposed system

3. THERMODYNAMIC MODEL

In this paper, the thermodynamic model of the system is established to evaluate the performance of the system. The model is based on the law of conservation of mass and law of conservation of energy. Some assumptions about the system model are as follows:

(1) The condition of the system is steady-state.
(2) The operation time of the charge process and the discharge process are equal.
(3) The heat transfer between system components and the environment is negligible.
(4) The efficiency of generators and motors is 100%.
(5) The temperature of AWV and AMV is equal to the ambient temperature.

The power consumed by compressor and pump are [9]:

$$W_C = m_{CO_2,ch}(h_{C,out} - h_{C,in}) \tag{1}$$

$$W_{CryoP} = m_{19}h_{19} + m_{21}h_{21} - m_{18}h_{18} \tag{2}$$

The power generated by CryoT, turbine and expander are:

$$W_{CryoT} = m_{CO_2,ch}(h_{14} - h_{15}) \tag{3}$$

$$W_T = m_{CO_2,dis}(h_{T,in} - h_{T,out}) \tag{4}$$

$$W_E = m_{CO_2,dis}(h_{29} - h_{30}) \tag{5}$$

The heat exchanged in HE1, HE2, HE3 and HE4 are respectively:

$$Q_{HE1} = m_{CO_2,12}(h_{12} - h_{13}) = m_{CO_2,ch}(h_5 - h_4) \tag{6}$$

$$Q_{HE2} = m_{CO_2,10}(h_{10} - h_{11}) = m_{methanol,42}(h_{43} - h_{42}) \tag{7}$$

$$Q_{HE3} = m_{methanol}(h_{44} - h_{42}) = m_{CO_2}(h_{20} - h_{19}) \tag{8}$$

$$Q_{HE4} = m_{CO_2,dis}(h_{28} - h_{29}) = m_{CO_2,21}(h_{22} - h_{21}) \tag{9}$$

For LCL, HCL, HH and LH, the heat exchanged are:

$$Q_{LCL} = m_{CO_2,ch}(h_6 - h_7) = m_{water,32}(h_{33} - h_{32}) \tag{10}$$

$$Q_{HCL} = m_{CO_2,ch}(h_8 - h_9) = m_{water,34}(h_{35} - h_{34}) \tag{11}$$

$$Q_{HH} = m_{water,38}(h_{38} - h_{39}) = m_{CO_2,dis}(h_{24} - h_{23}) \tag{12}$$

$$Q_{LH} = m_{water,40}(h_{40} - h_{41}) = m_{CO_2,dis}(h_{26} - h_{25}) \tag{13}$$

The heat exchange process in LCS is:

$$Q_{LCS} = m_{CO_2,dis}(h_{30} - h_{31}) = m_{CO_2,2}(h_3 - h_2) \tag{14}$$

The model of separator is:

$$m_{CO_2,15}h_{15} = m_{CO_2,16}h_{16} + m_{CO_2,17}h_{17} \tag{15}$$

The throttling process of the throttle valve is:

$$h_{CO_2,1} = h_{CO_2,2} \tag{16}$$

The power consumed in the charge process is:

$$W_{in} = W_{LC} + W_{HC} - W_{CryoT} \tag{17}$$

The power generated in the discharge process is:

$$W_{out} = W_{HT} + W_{LT} + W_E - W_P \tag{18}$$

The round trip efficiency (RTE) and energy density (ρ_E) of the system are:

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

$$\rho_E = \frac{W_{out} \cdot t_{dis}}{V_{LST1} + V_{LST2}} \tag{20}$$

4. RESULTS AND DISCUSSION

Table 1 shows the basic operating parameters of the system.

Table 1

Basic operating parameters of the system

Parameter	Unit	Value
P_0	Mpa	0.1
T_0	K	298.15
P_5	Mpa	0.6
P_c	Mpa	15
P_d	Mpa	15
W_{out}	kW	1000
T_7 and T_9	K	313.15
η_C	%	85
η_T	%	88
η_E	%	80
η_{cryoT}	%	80
η_{cryoP}	%	80
$T_{pinch,CL}$	K	5
$T_{pinch,H}$	K	5
$T_{pinch,HE}$	K	5
$T_{pinch,LCS}$	K	6
R_{4419}	-	0.9
R_{129}	-	0.4
R_{2118}	-	0.4
R_{3836}	-	0.7

4.1 *Effect of* the R_{4419}

The variation trend of RTE, energy density and net input power of the system with the ratio of mass flow rate of stream 44 and stream 19 (R_{4419}) is shown in Fig. 2. With the increase of R_{4419}, the net input power of the system decreases slightly and then increases. Since the net output power of the system is set at a constant value, the RTE first increases, reaches the maximum value of 54.86% at R_{4419} of 0.87 and then decreases. It can also be found that the energy density remains unchanged.

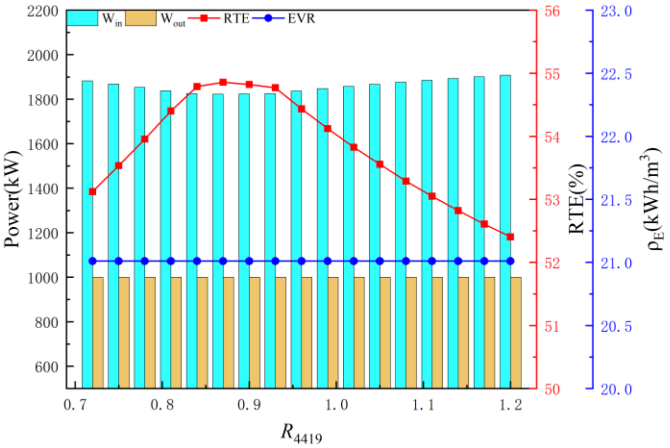

Fig. 2. Effect of the R_{4419} on the system performance

4.2 *Effect of the* R_{129}

Figure. 3 reflects the effect of R_{129} on system performance. When R_{129} increases, the net input power first decreases and then increases. The variation of net input power is related to the change that the RTE increases to the maximum value firstly and then decreases in Figure. 3. The energy density first shows an upward trend and then tends to a stable value.

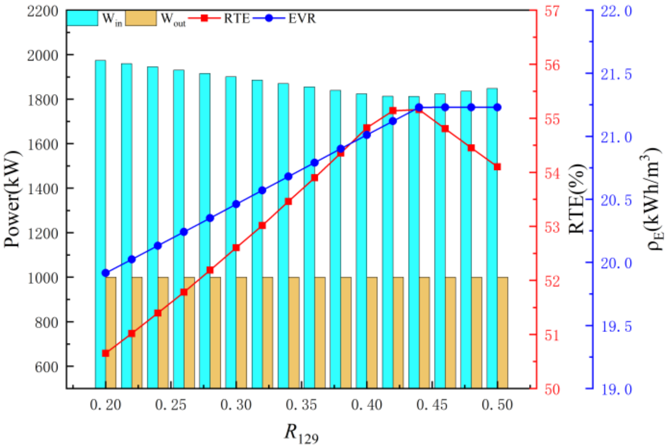

Fig. 3. Effect of the R_{129} on the system performance

4.3 Effect of the R_{2118}

With the increase of R_{2118}, the net input power first decreases and then increases while the RET first increases and then decreases, which can be seen in Fig. 4. The energy density of the system shows an upward trend. When R_{2118} increases from 0.2 to 0.5, the energy density increases from 19.545 kWh/m^3 to 21.513 kWh/m^3.

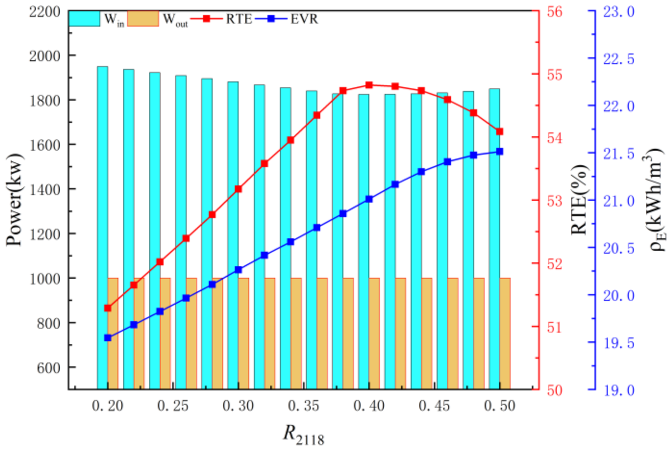

Fig. 4. Effect of the R_{2118} on the system performance

4.4 Effect of the R_{3836}

Fig. 5 indicates that with the increase of R_{3836}, the net input power of the system first shows a downward trend and then an upward trend. The RTE tends to increase first and then decrease. The energy density of the system first increases to the maximum value of 21.0104 kWh/m^3, then tends to be stable, and finally shows a downward trend.

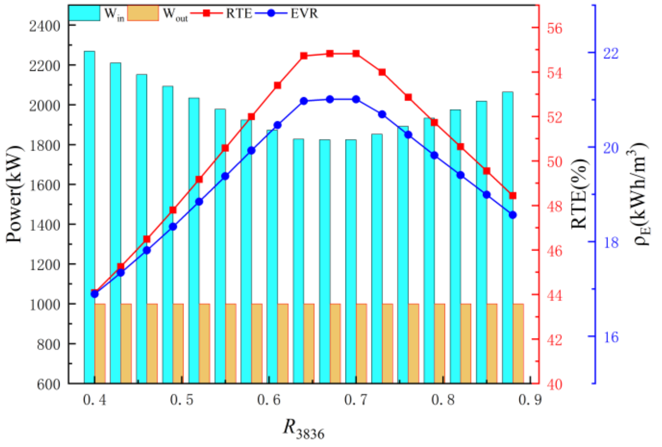

Fig. 5. Effect of the R_{3836} on the system performance

5. CONCLUSIONS

A novel liquid carbon dioxide energy storage system is proposed in this paper. The main conclusions are as follows: within a certain range, increasing the four parameters of R_{4419}, R_{129}, R_{2118} and R_{3836} will make the net input power of the system decrease first and then increase; the RTE first shows an upward trend and then a downward trend with the increase of R_{4419}, R_{129}, R_{2118} as well as R_{3836}; besides, the change of R_{4419} will not affect the energy density, increasing R_{129} and R_{2118} will increase the energy density while the increase of R_{3836} will first increase and then decrease the energy density.

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