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Thermodynamic analysis of an underwater compressed air energy storage system

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ABSTRACT

Compressed air energy storage technology is considered as an effective way to solve the intermittency and instability of renewable energy. In this paper, an underwater compressed air energy storage system is investigated. The thermodynamic model of the system is established to explore the system performance. The parameter analysis is carried out to study the effect of heat exchange efficiency, compressor efficiency, gas velocity in header pipe and offshore distance on system performance. The analysis results show that the increase of heat exchanger efficiency and compressor efficiency is beneficial for increasing system efficiency. Lower gas velocity in header pipe and lower offshore distance could make the system reach higher energy density.

Keywords: renewable energy; underwater compressed air energy storage; thermodynamic model; parameter analysis

NONMENCLATURE

Abbreviations	
CAES	Compressed air energy storage
UWCAES	Underwater compressed air energy storage
Symbols	
h	Specific enthalpy (J/kg)
m	Mass flow rate (kg/s)
W	Power (W)
Q	Heat transfer rate (W)
t	Time (h)
p	Pressure (MPa)
T	Temperature (K)

1. INTRODUCTION

Compressed air energy storage (CAES) technology could be used for conquering the fluctuation of renewable energy and addressing the need of the electricity market [1]. Compared with traditional CAES, underwater compressed air energy storage (UWCAES) can keep the constant pressure of stored air. The compressor and expander always work near the rated working condition. Their expansion and compression processes have higher efficiency [2]. Therefore, it has been a research hotpot of scholars in recent years.

Some research based on UWCAES technology has been carried out. Wang et al. [3] designed a new UWCAES system. They found that the number of compressor stages had a significant impact on the performance of the system. Cheung et al. [4] conducted thermodynamic analysis of a UWCAES system. The results indicated that the exergy destruction of compressor and turbine was more significant than that of other components. Wang et al. [5] proposed a multi-level UWCAES system. Their analysis results indicated that the maximum efficiency of the proposed system is 81%. Pimm et al. [6] established a new UWCAES system with energy storage bag. Their analysis showed that the use of the energy storage bag could reduce the economic cost of the system and improve economic benefit. Liu et al. [7] analyzed a novel trigeneration system based on UWCAES. The results showed that the increase of ambient temperature had a positive effect on heating energy but a negative effect on cooling energy.

According to previous research, there are lack of in-depth parametric analysis based on UWCAES system. In this paper, an underwater compressed air energy storage system is analyzed. In order to explore the performance of the system, the thermodynamic model is established. The parameter analysis is carried out to investigate the impact of heat exchanger efficiency, compressor efficiency, gas velocity in header pipe and offshore distance on system performance.

2. SYSTEM DESCRIPTION

The schematic diagram of the proposed system is shown in Fig. 1. The operation process of the system is mainly divided into energy storage process and energy release process. During the process of energy storage, the external air first undergoes a 2-stage compression process and is compressed into high pressure state. The 2-stage compressors consist of low-pressure compressor (LPC) and high-pressure compressor (HPC). At the same time, the compression heat generated by the compression process is absorbed by the cold oil in 2 coolers and stored in the HHV. The high-pressure air is then sent into the underwater accumulator and stored for the energy release process. During the process of energy release, the high-pressure air from the underwater Accumulator is first heated in the HPH by high-temperature oil. Next, the heated air undergoes a 2-stage expansion process to output electric energy. Finally, the turbine exhaust is discharged into the environment and the energy release process is complete.

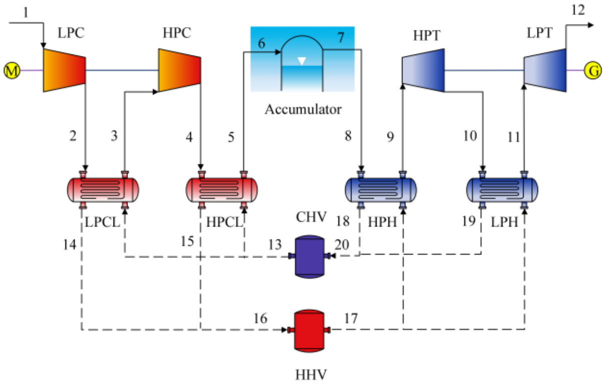

Fig. 1 Schematic diagram of the proposed system

3. THERMODYNAMIC MODEL

In order to explore the performance of the system, The thermodynamic model of the system is established. The model is based on the law of conservation of mass and the law of conservation of energy.

The power consumed by compressors is:

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

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

The output power process of expanders is as follows:

$$\dot{W}_{HPT} = \dot{m}_9(h_9 - h_{10}) \tag{3}$$

$$\dot{W}_{LPT} = \dot{m}_{11}(h_{11} - h_{12}) \tag{4}$$

The thermodynamic process of heat exchangers is as follows:

$$Q_{LPCL} = \dot{m}_2(h_2 - h_3) = \dot{m}_{14}(h_{14} - h_{13}) \tag{5}$$

$$Q_{HPCL} = \dot{m}_4(h_4 - h_5) = \dot{m}_{15}(h_{15} - h_{13}) \tag{6}$$

$$Q_{HPH} = \dot{m}_{18}(h_{17} - h_{18}) = \dot{m}_8(h_9 - h_8) \tag{7}$$

$$Q_{LPH} = \dot{m}_{19}(h_{17} - h_{19}) = \dot{m}_{10}(h_{11} - h_{10}) \tag{8}$$

The power consumed during the charging process is:

$$W_{\text{in}} = W_{LC} + W_{HC} \tag{9}$$

The output power during the discharging process is:

$$W_{out} = W_{HT} + W_{LT} \tag{10}$$

The round-trip efficiency represents the ratio of the output power during the discharging process to the power consumed during the charging process. The energy density is defined as the ratio of the output power to the volume of the underwater accumulator. Their calculation formulas are as follows:

$$RTE = \frac{W_{out} t_{dis}}{W_{in} t_{ch}} \times 100\% \tag{11}$$

$$\rho_E = \frac{W_{out} \cdot t_{dis}}{V_{ACC}} \tag{12}$$

4. RESULTS AND DISCUSSION

The thermodynamic model of the system is calculated by the program developed in MATLAB. The physical properties of air and oil are obtained using the REFPROP database. The basic design parameters of the system are listed in Table 1.

Table 1

Basic design parameters of the system

Parameter	Unit	Value
Ambient pressure	Mpa	0.1
Ambient temperature	K	298.15
Depth	m	100
Isentropic efficiency of compressors	%	84
Isentropic efficiency of turbines	%	88
Output power	kW	1000
Charge time	h	8
Discharge time	h	8

4.1 Effect of heat exchanger efficiency on system performance

Fig. 2 shows the effect of the heat exchanger efficiency on the system performance. It can be clearly seen from the figure that the system RTE increases from 53.04% to 63.90% with the increase of heat exchanger efficiency. The improvement of heat exchanger efficiency by 20% can increase the energy density of the system by 0.036 kWh/m^3. Moreover, the increase of heat exchanger efficiency drives the decrease of input power. The output power keeps constant value of 1000 kW.

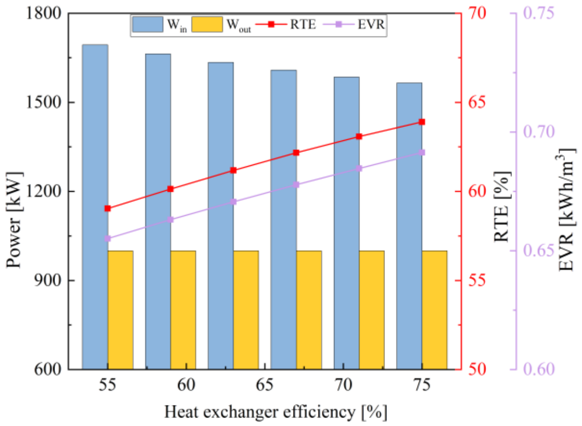

Fig. 2 Effect of efficiency of heat exchanger on system performance

4.2 Effect of compressor efficiency on system performance

Fig. 3 indicates the effect of the compressor efficiency on the system performance of the proposed underwater compressed air energy storage system. As can be seen from the figure, RTE and EVR show opposite trend with the increase of compressor efficiency. The system RTE can reach the maximum value of 67.15% when the compressor efficiency is equal to 88%. Besides, the net input power presents a monotonic downward trend with the increase of compressor efficiency.

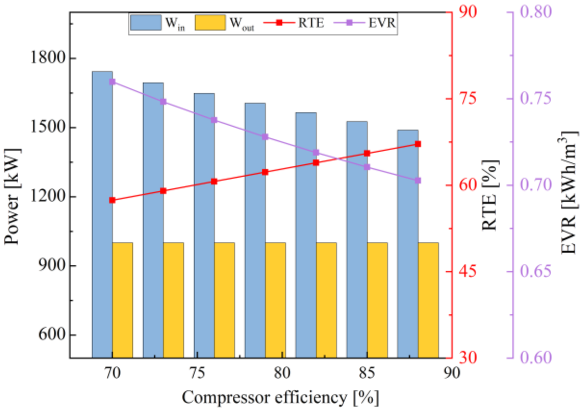

Fig. 3 Effect of compressor efficiency on system performance

4.3 Effect of gas velocity in header pipe on system performance

The effect of gas velocity in header pipe on the system performance is shown in Fig. 4. With the increase of the gas velocity in header pipe, the input power increases gradually. Within the scope of the study, the energy density and system efficiency of the system show an downward trend. When the gas velocity in header pipe increases from 0.5 m/s to 8 m/s, the system efficiency decreases from 71.45% to 69.24%.

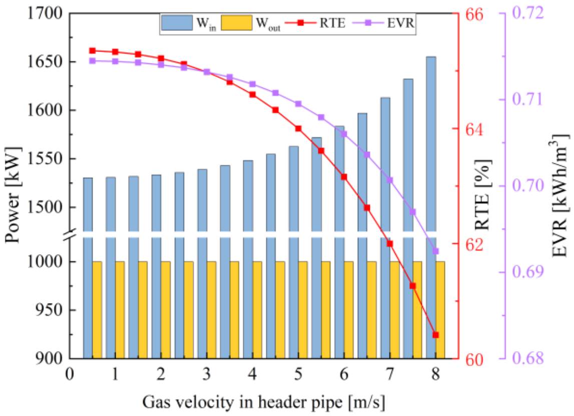

Fig. 4 Effect of gas velocity in header pipe on system performance

4.4 Effect of offshore distance on system performance

Fig. 5 expresses the effect of the offshore distance on the system performance. It can be observed from the figure that the net input power increases with the increase of offshore distance. Both the RTE and EVR show downward trend. When the distance is set to 2.5km, the system can reach the maximum RTE of 65.16% and EVR of 0.714kWh/m^3.

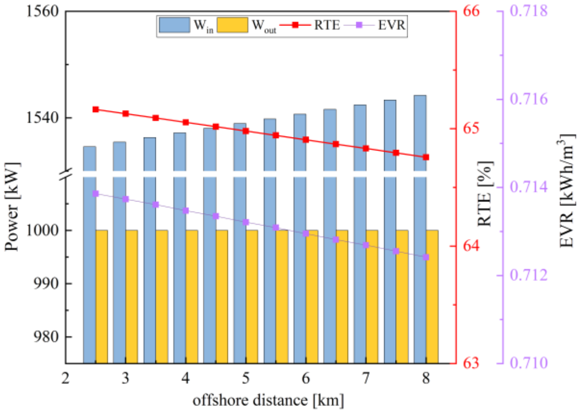

Fig 5. Effect of offshore distance on system performance

5. Conclusions

The thermodynamic performance of an UWCAES system is explored in this paper. The main conclusions are as follows: increasing the compressor efficiency and heat exchanger efficiency is beneficial to improve the system efficiency while the increase of gas velocity in header pipe and offshore distance will lead to the decrease of system efficiency; the increase of the gas velocity in header pipe, compressor efficiency and offshore distance will make the energy density decrease.

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NONE

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