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Thermodynamic analysis of Carnot Battery energy storage systems based on organic flash cycle

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ABSTRACT

In this work, a Carnot Battery energy storage system based on organic flash cycle is constructed. And the thermodynamic performance of the system with two working fluids (i-Pentane and cyclopentane) is investigated. The results showed that with the increase of flash evaporation temperature, the system round-trip efficiency, thermodynamic efficiency and energy storage density exhibited a trend of first increasing and then decreasing. The performance of system with i-Pentane is better than that of system with cyclopentane. Meanwhile, the proportion of saturated steam decreases. The performance of system is affected significantly when the isentropic efficiency of the compressor and turbine increases.

Keywords: Carnot Battery, flash cycle, round-trip efficiency, thermodynamic performance

NOMENCLATURE

Abbreviations	
COP	Coefficient of Performance
HP	Heat Pump
St	Heat Storage
PTP	Power to Power
in	Inlet
out	Outlet
Symbols	
W	Power(W)
h	Enthalpy(J/kg)
m	Mass Flow Rate(kg/s)
f	Flash
w	Water

1. INTRODUCTION

Due to the excessive use of fossil energy, energy shortage and global warming have become a huge problem. Therefore, increasing the use of new energy such as solar energy and wind energy is an effective means to solve the above problems. However, these renewable energy sources usually have the intrinsic intermittence and fluctuation [1]. Energy storage technology is an effective means to solve this problem.

In recent years, a new type of Carnot Battery energy storage system (also known as Pumped Thermal Electricity Storage, PTES), which has low cost, long life, is not limited by geographical conditions, can achieve the advantages of large-scale power storage, so it has received widespread attention[2]. Smallbone et al. [3] conducted a pilot experimental study on Brayton PTES, and found that for a 2MW/16MWh system, the round-trip efficiency can reach 52%~72%. In order to estimate the effect of irreversibility, Steinmann et al. [4] studied five different PTES models and found that PTES based on Brayton cycle requires the turbine and compressor to reach the isentropic efficiency of 0.9, so that the round-trip efficiency can reach more than 60%. McTigue et al. [5] studied the dynamic behavior of the packed tank of Brayton PTES, and characterized its round-trip efficiency, available power output and energy density, and found that the packed tank may require 10 full charge-discharge cycles to achieve cyclic operation. Mercangöz and Morandin et al. [6, 7] optimized a Carnot battery system, which contains a transcritical CO_2 cycle. Kim et al. [8] studied PTES systems based on transcritical and supercritical CO_2 Rankine cycles, and found that the energy storage at the temperature of 396 K could eventually achieve the round-trip efficiency of 53%. Morandin et al. [9] conducted a thermoeconomic optimization of a Carnot battery system consisting of a transcritical CO_2 Rankine cycle and water, brine, and ice storage, and found that the variables of cycle pressure can affect the optimal configuration of system performance and cost.

The previous reports about PTES is mainly based on the Brayton cycle and the organic Rankine cycle. Organic flash cycle (OFC) is another potential cycle which can effective improve temperature matching and reduce exergy losses during heat addition. However, at present, there are few studies about PTES with OFC. Thus, the PTES system based on the OFC is investigated in the present work. The thermodynamic performance of the system and its potential to replace the organic Rankine cycle are discussed in this paper, which sheds some lights on PTES systems.

2. MODELS AND METHODS

2.1 System description

The Carnot Battery energy storage system based on organic flash cycle is mainly composed of a heat pump cycle system and a flash cycle system, including the charging process and the discharging process. As shown in Figure 1, the heat pump cycle system includes evaporator, compressor, condenser, expansion valve. The flash cycle system includes heat exchanger, flash tank, two expansion valves, expander, mixer, condenser and pump. The system also includes a high temperature storage tank and a low temperature storage tank.

In order to simplify the calculation, the following assumptions are made:

(1) All components work stable.

(2) The pressure drops in the pipes and components are ignored.

(3) The heat losses of each component is ignored.

Since the discharge cycle in this paper is the OFC, the i-Pentane and cyclopentane are selected for their fine performance in the system [10]. Besides, i-Pentane has the characteristics of high condensation specific heat and high steam density, which can reduce the size of condenser and expander, thereby cutting down the investment cost [11].

Here, the sensible heat storage method is employed. And water is chosen as the heat storage fluid due to its low price.

2.2 Mathematical model

Table 1 Basic parameter settings of the system

Item	Unit	Value
Flash temperature	℃	55~95
Mass flow rate of heat source	Kg/s	50
Ambient temperature	℃	20
Ambient pressure	kPa	101.325
Compressor efficiency	—	0.74~0.9
Turbine efficiency	—	0.74~0.9
Pump efficiency	—	0.75
Pinch point temperature difference	℃	5
Superheat degree in evaporator	℃	2
Condensing temperature in flash cycle	℃	30
Storage duration	h	6

The basic parameters of the system in this paper are shown in Table 1. For the turbine, the output power is

$$W_{\mathrm{tur}} = m_{\mathrm{fv}}(h_{\mathrm{t\_out}} - h_{\mathrm{t\_in}}) \tag{1}$$

where m_{fv} is mass flow of saturated steam in the flash cycle. $h_{\mathrm{t\_out}}$ is turbine outlet specific enthalpy. $h_{\mathrm{t\_in}}$ is turbine inlet specific enthalpy.

The isentropic efficiency of the turbine is

$$\eta_{\mathrm{tur}} = \frac{h_{\mathrm{t\_in}} - h_{\mathrm{t\_out(a)}}}{h_{\mathrm{t\_in}} - h_{\mathrm{t\_out}}} \tag{2}$$

where $h_{\mathrm{t\_out(a)}}$ is the outlet specific enthalpy of the actual process of the turbine.

For the pump, the consumed power is

$$W_{\mathrm{pump}} = m_{\mathrm{f}}(h_{\mathrm{p\_out}} - h_{\mathrm{p\_in}}) \tag{3}$$

where m_{f} is mass flow in the flash cycle. $h_{\mathrm{p\_out}}$ is pump outlet specific enthalpy. $h_{\mathrm{p\_in}}$ is turbine inlet specific enthalpy.

The isentropic efficiency of the pump is

$$\eta_{\mathrm{pump}} = \frac{h_{\mathrm{p\_out}} - h_{\mathrm{p\_in}}}{h_{\mathrm{p\_out(a)}} - h_{\mathrm{p\_in}}} \tag{4}$$

where $h_{\mathrm{p\_out(a)}}$ is the outlet specific enthalpy of the actual process of the pump.

For the compressor, the consumed power is

$$W_{\mathrm{com}} = m_{\mathrm{HP}}(h_{\mathrm{c\_out}} - h_{\mathrm{c\_in}}) \tag{5}$$

where m_{HP} is mass flow of heat pump cycle. $h_{\mathrm{c_out}}$is compressor outlet specific enthalpy. $h_{\mathrm{c\_in}}$ is compressor inlet specific enthalpy.

The isentropic efficiency of the compressor is

$$\eta_{\mathrm{com}} = \frac{h_{\mathrm{c\_out}} - h_{\mathrm{c\_in}}}{h_{\mathrm{c\_out(a)}} - h_{\mathrm{c\_in}}} \tag{6}$$

where $h_{\mathrm{c\_out(a)}}$ is the outlet specific enthalpy of the actual process of the compressor.

The round-trip efficiency (η_{PTP}) is an important indicator to measure the performance of the PTES system, which can be calculated by

$$\eta_{\mathrm{PTP}} = \eta_{\mathrm{f}}.COP \tag{7}$$

where η_{f} thermal efficiency of the flash cycle. COP is Coefficient of Performance of Heat Pump.

The thermal efficiency of the flash cycle can be calculated by

$$\eta_{\mathrm{f}} = \frac{W_{\mathrm{tur}}}{Q_{\mathrm{st}}}$$

where Q_{st} is the heat stored in the system.

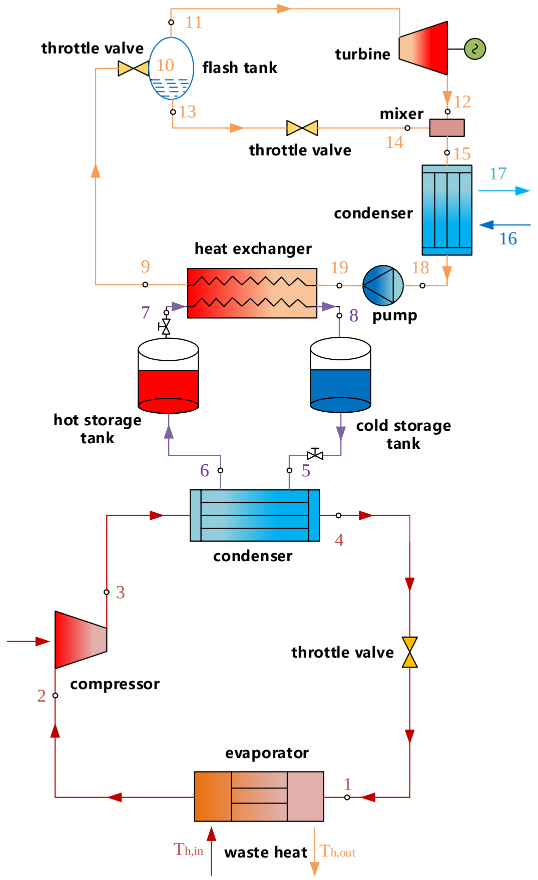

Fig. 1 Schematic diagram of Carnot Battery energy storage system based on flash cycle.

The coefficient of performance of the heat pump can be calculated by

$$COP = \frac{Q_{\mathrm{st}}}{W_{\mathrm{com}}} \tag{9}$$

In addition, the energy storage density of the system is calculated by

$$D_{\mathrm{e}} = c_{\mathrm{p,w}} \rho_{\mathrm{w}} \eta_{\mathrm{s}} \eta_{\mathrm{f}} \left(T_{\mathrm{s,h}} - T_{\mathrm{s,c}} \right) \tag{10}$$

where $C_{\mathrm{p,w}}$ and ρ_{w} are the heat capacity and the density of the storage medium water. η_{s} is the efficiency of the storage and is assumed as 0.95 [13]. $T_{\mathrm{s,h}}$ and $T_{\mathrm{s,c}}$ are the temperature of the hot storage tank and cold storage tank.

2.3 Mathematical validation

In this section, the study of Lee et al.[14] and Hu et al.[12] is adopted to verify the models of the system. The model validation results of OFC and heat pump cycle systems are listed in Table 2 and Table 3 respectively.

Table 2 Validation results for the OFC cycle.

Table 3 Validation results for the heat pump cycle.

States	*P* (kPa) This work	Ref.[15]	Error (%)	*T* (°C) This work	Ref.[15]	Error (%)	*h* (kJ/kg) This work	Ref.[15]	Error (%)
1	249.41	250	-0.24	40	40	0	252.30	252.57	-0.11
2	1545	1549	-0.26	40.64	40.70	-0.15	253.26	253.82	-0.22
3	1545	1549	-0.26	109.36	109.36	0	354.41	354.80	-0.11
4	789	789	0	80.15	80	0.19	354.41	354.80	-0.11
5	789	789	0	80.15	80	0.19	462.86	461.75	0.24
6	249.71	250	-0.12	49.88	51.18	-2.61	443.74	444.95	-0.27
7	789	789	0	80.15	80	0.19	308.98	309.24	-0.08
8	249.41	250	-0.24	40	40	0	308.98	309.24	-0.08
9	249.41	250	-0.24	40	40	0	348.72	349.78	-0.30

States	*P* (kPa) This work	Ref.[12]	Error (%)	*T* (°C) This work	Ref.[12]	Error (%)	*h* (kJ/kg) This work	Ref.[12]	Error (%)
1	299.47	299.40	0.02	50.70	50.70	0	308.86	308.90	-0.01
2	299.47	299.40	0.02	52.70	53.90	2.22	440.51	441.60	-0.25
3	1154.00	1154.00	0	104.74	106.8	1.92	471.82	474.30	-0.52
4	1154.00	1154.00	0	86.70	86.70	0	308.86	308.90	-0.01

The results show that the maximum relative error between the simulated value and the literature value is --2.61%, the data in this paper is basically consistent with the literature data.

3. RESULTS AND DISCUSSION

The discharge process of this system is the OFC, so the effects of the flash temperature on the thermal efficiency, system round-trip efficiency and energy storage density are discussed. Compressors and turbines are important components in the system, so the effect of compressor and turbine efficiency on system performance was also studied.

As is shown in Fig. 2, with the increase of flash temperature, the round-trip efficiency of the system and the thermal efficiency of the flash cycle both increase first and then decrease. As described in Eq. (7), the round-trip efficiency of the system is related to the thermal efficiency η_{f} and the *COP*. Since *COP* remains constant, so the variation tendency of the round-trip efficiency of the system is consistent with η_{f}. According to Eq. (8), the η_{f} is closely related to the output work of the turbine W_{tur}, and the reason is that W_{tur} first increases and then decreases. η_{f} and η_{PTP} of system with i-Pentane are larger than those of system with cyclopentane. The η_{f} and η_{PTP} reach the maximum at the flash temperature of 80 °C. Besides, the system with long molecular chain alkane i-Pentane can achieve better performance than that system of cyclic cyclopentane, which is consistent with previous work[15].

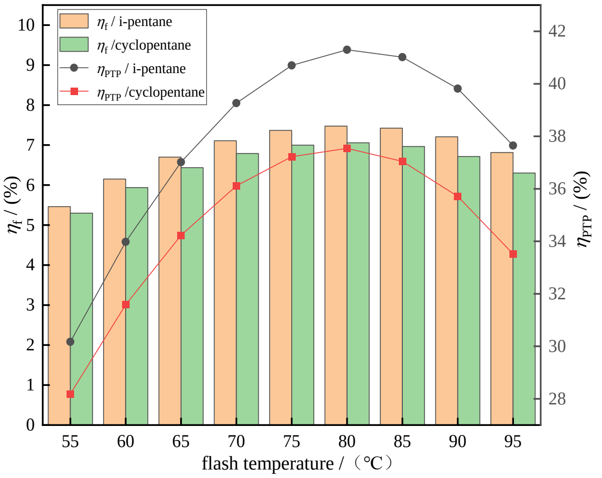

Fig. 2 Variations of η_f and η_{PTP} with flash temperature.

Fig. 3 shows the proportion of saturated steam Q_{fv} and the mass flow of saturated steam m_{fv} in the flash process with the change of the flash temperature. As the flash temperature increases, Q_{fv} and m_{fv} decrease. This is because m_{fv} and Q_{fv} are positively correlated. For the system using i-Pentane, its Q_{fv} and m_{fv} are higher than the system using cyclopentane. It denotes that the use of i-Pentane can produce more saturated steam and mass flow to produce more output work.

As is shown in Fig. 4, when the isentropic efficiency of the compressor increases, both η_{PTP} and *COP* of the system increase. When the system using i-Pentane, η_{PTP} increases from 38.76% to 45.53%, and the *COP* increases from 5.18 to 6.09. While η_{PTP} increases from 35.25% to 41.35%, and *COP* increases from 5.00 to 5.86 of the system using cyclopentane. As is described in Eq. (7), since η_f of the system keeps constant, η_{PTP} of the system increases with the increase of *COP*. Therefore, it indicated that the increase of isentropic efficiency of compressor has a positive effect on η_{PTP} and *COP*.

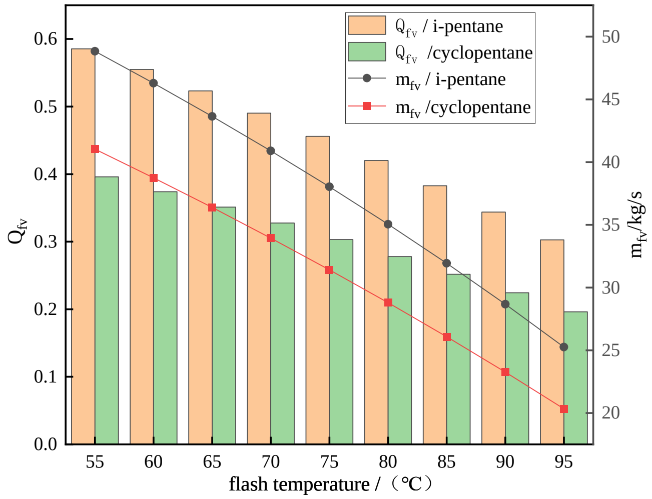

Fig. 3 Variations of Q_{fv} and m_{fv} with flash temperature.

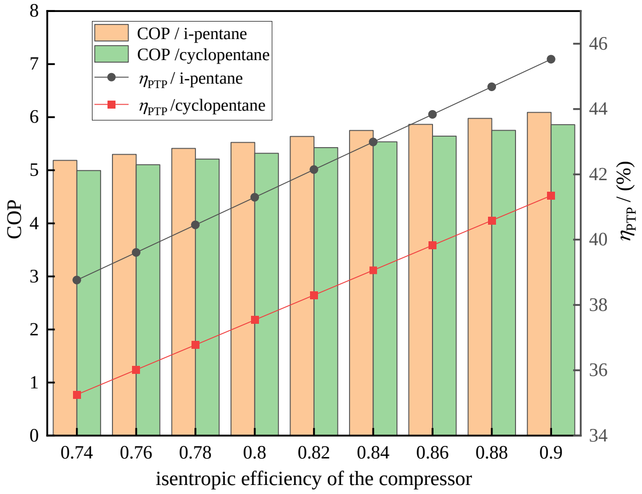

Fig. 4 Variations of COP and η_{PTP} with isentropic efficiency of the compressor.

Fig. 5 reveals the effect of the isentropic efficiency of turbine on system performance. When the isentropic efficiency of the turbine increases, both η_{PTP} and η_f of the system increase. When the system using i-Pentane, η_{PTP} increased from 39.63% to 48.21%, and η_f increased from 6.51% to 7.91%. While η_{PTP} increases from 36.00% to 43.78%, and η_f increases from 6.14% to 7.47% of the system using cyclopentane. According to Eq. (7), since *COP* of the system keeps constant, η_{PTP} of the system increases with the increase of η_f. Thus, the increase of isentropic efficiency of turbine has a positive effect on η_{PTP} and η_f.

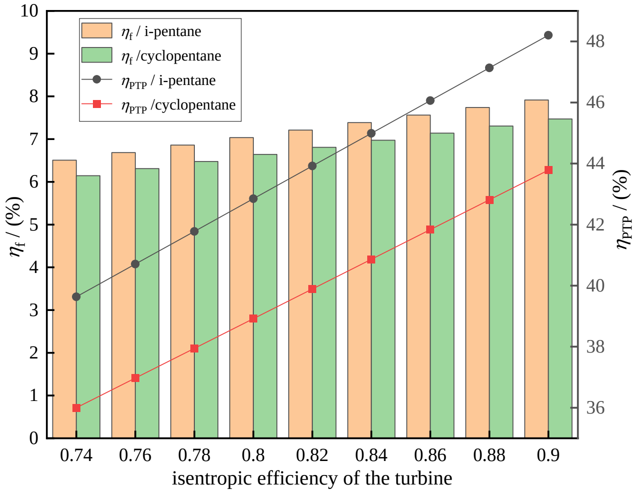

Fig. 5 Variations of η_f and η_{PTP} with isentropic efficiency of the turbine.

The energy storage density can clearly reflect the storage capacity of the system. The greater the energy storage density, the smaller the volume requirement of the energy storage tank, the lower investment cost and the footprint of system. As is shown in Fig. 6, D_e of the system increases first and then decreases with the increase of the flash temperature. As is described in Eq.

(10), D_{e} is closely related to η_{f} of the system, so the variation tendency of D_{e} is similar to that of η_{f}.When flash temperature is 80 °C, D_{e} reaches the maximum value. Meanwhile, when using i-Pentane as working medium, D_{e} of the system is significantly higher and the performance is better.

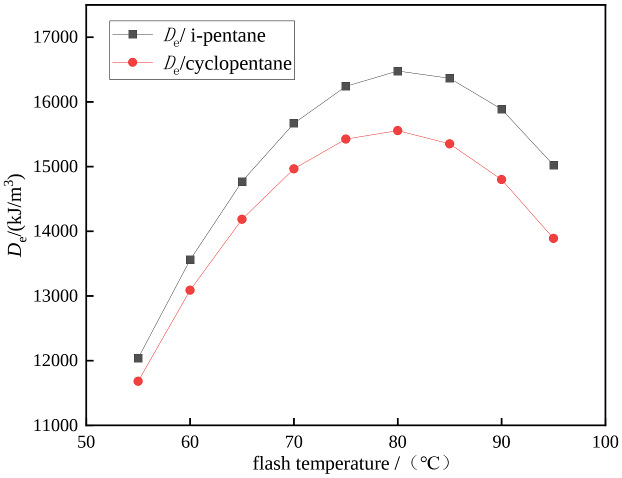

Fig. 6 Variations of D_{e} *with flash temperature.*

4. CONCLUSIONS

In this paper, a Carnot battery energy storage system with organic flash evaporation cycle as the discharge process is discussed. The main conclusions are as follows

(1) With the increase of flash temperature, η_{PTP} of the system, η_{f} and D_{e} of the studied system all show the trend of first increases and then decreases, and there is a maximum value. Meanwhile, the increase of the flash temperature results in a decrease in the saturated steam ratio and mass flow of the flash cycle. Besides, the system with i-Pentane are performed better than that with cyclopentane.

(2) When the isentropic efficiency of the compressor increases, η_{PTP} and COP value of the system increase. The system with i-Pentane are performed better than that with cyclopentane.

(3) When the isentropic efficiency of the turbine increases, η_{PTP} and η_{f} value of the system increase. And the system with i-Pentane are performed better than that with cyclopentane.

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