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Performance comparison of discharge cycles in a cold storage Carnot battery[#]

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ABSTRACT

Cold storage Carnot batteries (CSCBs) have emerged as a promising solution for long-duration energy storage by integrating ice-based cold storage. However, existing architectures are constrained by limited efficiency caused by suboptimal discharge cycles. In this study, two modified discharge cycles, recuperated and regenerative configurations, are investigated within the CSCB system framework. Additionally, two low-GWP working fluids, R1234ze(E) and R1234yf, are evaluated. Results show that the regenerative cycle provides a higher efficiency improvement than the recuperated cycle (7.3% versus 4.2%), and R1234ze(E) outperforms R1234yf across all discharge configurations. Increasing the cold storage temperature can enhance the overall system round-trip efficiency (RTE). With ice/water as a storage medium, the proposed CSCB system achieves an RTE of approximately 78.3%. This study provides insights into modifying the CSCB system to achieve high-efficiency, sustainable, long-duration energy storage.

Keywords: pumped thermal energy storage, ice-cold storage, organic Rankine cycle, low-GWP working fluid, Performance comparison.

NOMENCLATURE

Abbreviations	
CES	Cold energy storage
CSCB	Cold storage Carnot battery
GWP	Global warming potential
LGH	Low-grade heat
PPTD	Pinch point temperature difference
RTE	Round-trip efficiency
VCR	Vapor compression refrigeration
Symbols	
h	Specific enthalpy [J/kg]
m	Mass flow rate [kg/s]
Q	Heat transfer rate [kW]
W	Power [kW]

1. INTRODUCTION

The escalating global drive towards decarbonization has led to the rapid deployment of variable renewable energy, primarily solar and wind. Driven by substantial cost reductions, their installed capacity has been increasing dramatically [1]. However, their stochastic nature challenges the stability and reliability of electrical grids. Therefore, the development of grid-scale, long-duration energy storage is paramount for effectively mitigating the supply-demand imbalance [2].

Carnot batteries emerge as a promising solution for long-duration energy storage. The functionality of a Carnot battery involves a power-to-thermal-to-power process that integrates heat upgrading, thermal energy storage, and power cycle technologies. This architecture enables the decoupling of power and energy capacity, offering lower energy-related costs [3]. Rankine-type Carnot batteries commonly employ high-temperature heat pumps with organic Rankine cycles (ORCs). The crucial advantage lies in their ability to utilize low-grade heat (LGH), thereby enhancing the overall system efficiency. For these Carnot batteries, achieving high system efficiency by modifying the thermodynamic cycle configuration remains a central research objective. Previous works shown that incorporating recuperation [4] or exploring alternative cycles, e.g., the organic flash cycle [5], can effectively enhance the overall system efficiency.

LGH can be incorporated into the discharge cycle, enabling the decoupling of the hot-end temperatures of the two cycles. The resulting cold storage Carnot battery (CSCB) integrates a vapor compression refrigeration (VCR) system and a cold energy storage (CES) unit for charging, while the external LGH and stored cold energy simultaneously power the discharge cycle. This unique integration aims to enhance the system's performance by utilizing diurnal variations in ambient temperature and relatively low-cost ice-based thermal energy storage [6]. Previous research has explored this architecture; for

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instance, Xia et al. [7] proposed a CSCB system featuring an ORC with preheating. However, the findings revealed that the preheating strategy failed to improve the overall system efficiency. This result highlights that while the CSCB concept is promising, effectively modifying the discharge cycle configuration within the CSCB system remains an unresolved challenge, directly hindering the achievement of competitive system efficiency.

In this study, we proposed a sustainable CSCB system framework for grid-scale energy storage applications. To enhance the overall system efficiency, we investigated two modified discharge cycle layouts, in addition to the basic cycle. Moreover, two low-GWP alternative working fluids are also screened for the discharge cycles. Through comparison, the optimal cycle layouts and low-GWP working fluids are identified, followed by a parametric study of the cold storage temperature of the resulting CBCB system.

2. SYSTEM DESCRIPTION

The schematic of the CSCB system is shown in Fig. 1. The system consists of three subsystems: a charging cycle, a cold energy storage (CES) unit, and a discharge power cycle. The charging cycle uses an ammonia-based VCR system, with an aqueous ethylene glycol solution as the secondary coolant. The CES unit uses water-ice as the storage medium with an ice-on-coil configuration. On the discharge side, an ORC is used, with LGH as the heat source and the CES as the cold source. The CSCB system operates by leveraging diurnal variations in ambient temperature and electricity pricing. During nighttime off-peak periods, when ambient temperature and electricity price are lower, the VCR system converts electricity into cold energy and stores it in the CES unit. During peak demand periods, the ORC utilizes the stored cold energy together with the available LGH to generate dispatchable power.

To enhance the efficiency of the CSCB system, two modified ORC configurations are considered, in addition to the simple cycle, namely the recuperated cycle and the regenerative cycle. Recuperation and regeneration represent two primary strategies for improving ORC performance through configuration modification. Fig. 2 presents the T-s diagrams of these two layouts. In the recuperated cycle, the turbine exhaust is used to preheat the working fluid exiting the pump via an internal heat exchanger. In the regenerative cycle, a fraction of the working fluid is extracted at an intermediate turbine pressure and mixed with the pump outlet flow to preheat the working fluid. Within the CSCB system, both modified ORC layouts have the potential to improve the system's overall efficiency, primarily by reducing the cold energy demand on the discharge side. Specifically, recuperation reduces the enthalpy difference across the condenser, while regeneration decreases the mass flow rate of the working fluid.

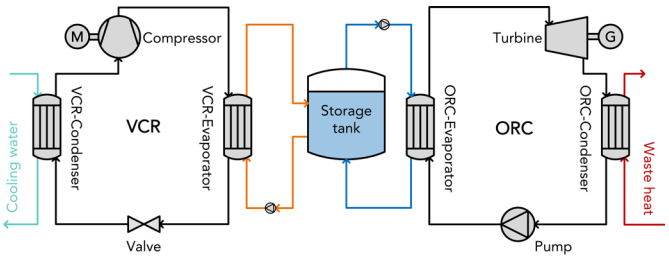

Fig. 1 *Schematic of the cold-storage Carnot battery.*

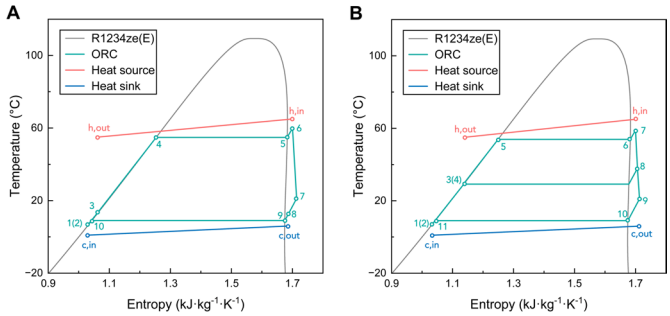

Fig. 2 *T-s diagram of the recuperated cycle (A) and the regenerative cycle (B).*

Regarding working fluid selection, R134a is widely used in low-temperature ORC applications; however, its high GWP raises significant environmental concerns. Thus, two low-GWP alternative working fluids, R1234yf and R1234ze(E), are screened as candidates to replace R134a. The properties of the three working fluids are summarized in Table 1.

Table 1*. Properties of the selected working fluids.*

Fluids	R134a	R1234yf	R1234ze(E)
Type	Wet	Isentropic	Isentropic
T_{cr} [°C]	101.1	94.7	109.4
P_{cr} [bar]	40.5	33.8	36.3
NBP [°C]	-26.1	-29.5	-19.0
ODP	0	0	0
GWP_{100}	1300	<1	<1
ASHRAE	A1	A2L	A2L

3. METHODS

The thermodynamic model of the CSCB is developed based on mass and energy conservation, assuming steady-state operation and isentropic efficiency models for the power components.

The isentropic efficiency and power consumption of the compressor are expressed as:

$$\eta_{\mathrm{Com}} = \frac{h_{\mathrm{out,is}} - h_{\mathrm{in}}}{h_{\mathrm{out}} - h_{\mathrm{in}}} \quad (1)$$

$$W_{\mathrm{Com}} = \dot{m}_{\mathrm{ch}}(h_{\mathrm{out}} - h_{\mathrm{in}}) \quad (2)$$

The isentropic efficiency and power output of the turbine are given by:

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

$$W_{\mathrm{Tur}} = \dot{m}_{\mathrm{dc}}(h_{\mathrm{in}} - h_{\mathrm{out}}) \quad (4)$$

where $h_{\mathrm{out,is}}$ represents the enthalpy at the component outlet corresponding to an isentropic process.

The heat transfer rate in the heat exchanger is expressed as:

$$\dot{Q}_{\mathrm{HEX}} = \dot{m}_{\mathrm{h}}(h_{\mathrm{h,in}} - h_{\mathrm{h,out}}) = \dot{m}_{\mathrm{c}}(h_{\mathrm{c,out}} - h_{\mathrm{c,in}}) \quad (5)$$

The charge efficiency (COP of the VCR system), defined as the ratio of cold energy output to work input, is expressed as:

$$\eta_{\mathrm{ch}} = \frac{\dot{Q}_{\mathrm{CES,ch}}}{\dot{W}_{\mathrm{VCR}}} \quad (6)$$

Unlike the thermal efficiency of a power cycle, a performance metric termed the discharge efficiency is defined as the ratio of the net power output to the input cold energy:

$$\eta_{\mathrm{dc}} = \frac{\dot{W}_{\mathrm{ORC}}}{\dot{Q}_{\mathrm{CES,dc}}} \quad (7)$$

The round-trip efficiency (RTE) is defined as the ratio of total electricity output to the total electricity input:

$$\mathrm{RTE} = \frac{E_{\mathrm{dc}}}{E_{\mathrm{ch}}} = \eta_{\mathrm{ch}} \cdot \eta_{\mathrm{st}} \cdot \eta_{\mathrm{dc}} \quad (8)$$

4. RESULTS AND DISCUSSION

The CSCB systems are simulated in *MATLAB* using a self-developed program. The thermophysical properties of the working fluids are obtained by calling the REFPROP database. The essential input parameters utilized for system design and simulation are listed in Table 2.

***Table 2**. Design parameters of the CSCB systems.*

Parameter	Value
Nighttime/daytime temperature	15/25°C
Turbine efficiency	85%
Compressor efficiency	80%
Pump efficiency	75%
Motor/generator efficiency	98%
PPTD in condenser/evaporator	3 °C
PPTD in recuperator	5 °C
Superheat degree of VCR	2 °C
Superheat degree of ORC	5 °C
Cold storage temperature	0 °C
Cooling/chilled water temperature rise	5 °C

4.1 Discharge cycle layout comparison

Fig. 3 illustrates the discharge efficiency (η_{dc}) for the three discharge cycle configurations as a function of heat source temperature. The LGH temperature range of 50-90 °C represents typical waste heat conditions prevalent in industrial applications. The results reveal that the recuperated cycle provides a modest yet discernible improvement in η_{dc}, slightly surpassing the basic cycle. On the other hand, increasing the LGH temperature from 50 °C to 90 °C results in a substantial performance enhancement, with the η_{dc} nearly doubling from 8% to 16%. In comparison, the regenerative cycle exhibits a more pronounced improvement than the recuperated cycle, and this efficiency enhancement becomes increasingly significant at higher LGH temperatures. At an LGH temperature of 70 °C, the η_{dc} values for the three cycles are 12.0%, 12.5%, and 12.9%, respectively. Thus, the improvements provided by the recuperated and regenerative cycles relative to the basic cycle are 4.2% and 7.3%, respectively.

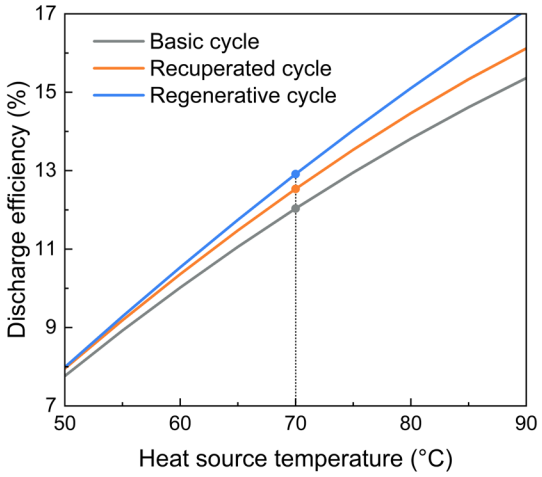

***Fig. 3** Variation of discharge efficiency with the temperature of LGH*

4.2 Low-GWP working fluid substitution

Beyond the comparative analysis of cycle layouts, the thermodynamic performance of the discharge cycles utilizing low-GWP working fluids is investigated, as depicted in Fig. 4. The transition to low-GWP fluids yields configuration-dependent performance characteristics in discharge efficiency. Specifically, detrimental efficiency effects are observed in the basic and regenerative cycles, while the recuperated configuration demonstrates an improved performance. A comparative evaluation of the two tested low-GWP working fluids reveals that R1234yf delivers inferior performance compared to R1234ze(E) across all three configurations. Substituting R134a with R1234ze(E) results in only a marginal η_{dc} reduction in the basic and regenerative cycles. Conversely, R1234ze(E) exhibits superior efficiency in the recuperated cycle.

Therefore, the adoption of R1234ze(E) enables the CSCB system to maintain or enhance efficiency levels.

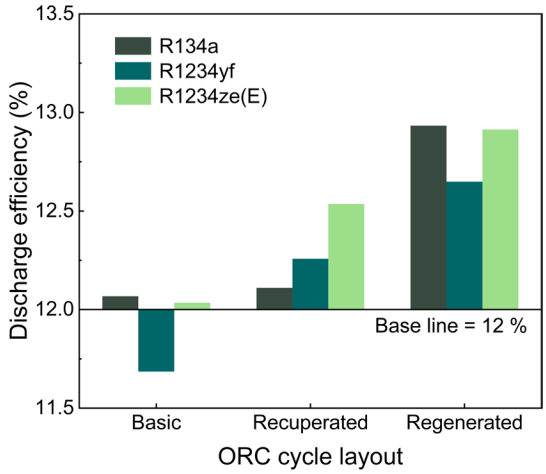

Fig. 4 *Discharge efficiency using low-GWP working fluids*

4.3 System key parameter investigation

Fig. 5 shows the effect of cold storage temperature on RTE of the CSCB. As illustrated, the RTE exhibits an upward trend with an accelerating growth rate. This phenomenon occurs because, as the cold storage temperature increases, the η_{dc} of the ORC declines. However, the COP of the VCR increases significantly, and this enhancement in COP dominates the overall RTE trend. Furthermore, increasing the cold storage temperature from −20 °C to 0 °C and from 0 °C to 10 °C results in comparable improvements in the RTE. Due to the reduced efficiency of the discharge power cycle, the required cold storage capacity inevitably increases with higher cold storage temperature, which is an important consideration for system cost. Therefore, the use of ice as the storage medium represents a reasonable trade-off, particularly for achieving grid-scale, long-duration energy storage. Under this scenario, using a regenerative ORC with R1234ze(E) enables the CSCB system to achieve a theoretical RTE of around 78.3%.

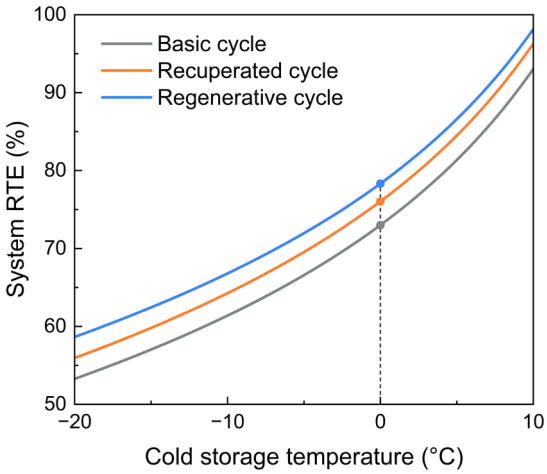

Fig. 5 *Effects of cold storage temperature on system RTE*

5. CONCLUSIONS

This study aimed to enhance the performance of the CSCB system from the discharge cycle perspective. Based on the proposed CSCB system framework, two modified discharge cycle layouts using two low-GWP working fluids were investigated. Moreover, the effect of the cold storage temperature on the CSCB system performance was investigated. The main conclusions are as follows:

1) The discharge cycle employing the regenerative configuration demonstrates an efficiency gain of 7.3% over the baseline, whereas the recuperated cycle yields a 4.2% improvement.

2) Compared to R1234yf, R1234ze(E) is the optimal alternative working fluid across all discharge cycles.

3) Increasing the cold storage temperature enhances the system RTE. An RTE of approximately 78.3% can be achieved when an ice-based cold storage medium and a regenerative discharge cycle utilizing R1234ze(E) are employed.

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