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THERMODYNAMIC ANALYSIS OF PUMPED THERMAL ELECTRICITY STORAGE INTEGRATED WITH ORGANIC RANKINE CYCLE DURING CHARGING PROCESS

Xiaonan Yu [1], Zhi Li [1,2], Yiji Lu [1,2*], Rui Huang [1], Xiaoli Yu [1,2], Anthony Paul Roskilly [1,2]

1 Department of Energy Engineering, Zhejiang University, Hangzhou 310027, China

2 Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle NE1 7RU, UK
[*]Corresponding author Email: luyiji0620@gmail.com

ABSTRACT

This paper proposed a new configuration of heat recovery cycle integrating PTES with ORC. A thermodynamic model was built to study the charging process of PTES. A parametric analysis has been conducted to evaluate the performance of the charging process. This paper defined the efficiency of the charging process of PTES with/without ORC. The isentropic efficiency of compressor/expander, the pressure ratio, and the designed temperature have been chosen to analyze the performance of the charging process. The proposed solution can be potentially used to improve the round-trip efficiency of PTES.

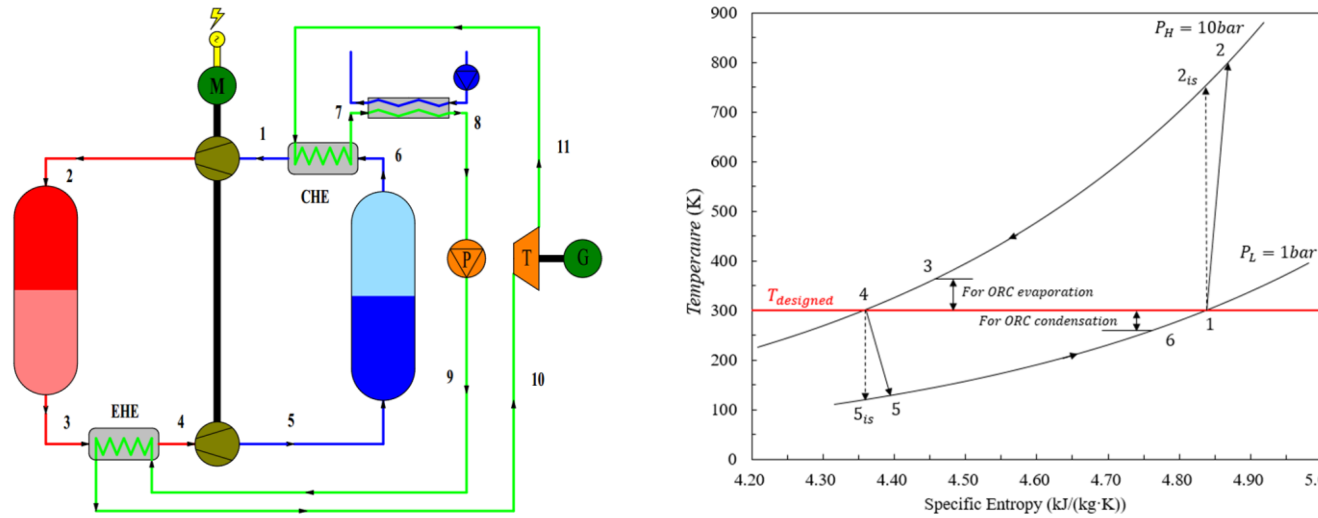
Keywords: Pumped thermal electricity storage, Organic Rankine cycle, Performance analysis, Heat recovery

NOMENCLATURE

Abbreviations	
EHE	Evaporation Heat Exchanger
CHE	Condensation Heat Exchanger
Symbols	
e	Energy transferred per unit of time (J/s)
E	Energy transferred (J)
η	Efficiency (-)
h	Specific enthalpy ($J/(kg \cdot K)$)
$\dot{m}$	Mass flow rate (kg/s)
Q	Thermal power (W)
T	Temperature (K)
τ	Time (s)
W	Power (W)
Superscripts and Subscripts	
ar	Argon
c	Cold bed
ch	Charging process
com	Compressor
exp	Expander
h	Hot bed
st	Stored
th	Thermal
tr	Transferred

1. INTRODUCTION

It is generally agreed that more than 20% penetration from intermittent renewable sources such as wind and solar converting to electricity will greatly destabilize the power grid system [1]. Electrical energy storage has been demonstrated as an important and necessary solution to recover the intermittent renewables.



(a) (b)

Fig 1 Schematic diagram of PTES with ORC

Energy Storage Technologies (EST) can store electrical energy in other forms when it is over-filled, and the stored energy can be later converted into electrical energy when the power supply is insufficient, which balance the grid peak and off-peak. Currently, established mature or in-developing large-scale electrical storage technologies include Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), batteries, Superconducting Magnetic Energy Storage (SMES) [2] and Pumped Heat Energy Storage (PHES) or Pumped Thermal Electricity Storage (PTES) [3,4]. This paper proposes a new configuration of cycle integrating PTES with ORC. A thermodynamic analysis has been conducted to demonstrate the feasibility of the system and evaluate the potential system performance. The efficiency with/without ORC and the highest temperature of the charging process of PTES have been studied.

2. PAPER STRUCTURE

2.1 System configuration

Fig. 1 (a) shows the schematic diagram of the presented system in the charging process of PTES, and Fig. 1 (b) is the corresponding T-s diagram. During the charging process, argon as the working fluid is compressed from point 1 which is at designed temperature T_{designed} and low pressure P_L to point 2 with the highest temperature T_{max} and high pressure P_H of a single cycle; then argon comes into the hot bed, in which it releases its thermal energy to the material within the hot bed in the form of latent heat or sensible heat isobarically; at the outlet of the hot bed (point 3) the temperature of the argon is higher than the designed one because of irreversibility, hence, a heat exchanger (EHE) located between the hot bed and expander is needed to maintain the inlet temperature of the expander within the designed conditions [5]; argon at P_H and T_{designed} (point 4) expands to the lowest temperature and P_L (point 5); at the next stage, argon absorbs thermal energy from the cold bed, whose temperature goes down followed by the previous step; the outlet temperature of the cold bed is lower than T_{designed} (point 6), so another heat exchanger (CHE) should be installed between the cold bed and compressor to keep the compressor inlet temperature at T_{designed}. Substantially, the two heat exchangers are used to maintain the highest temperature and the lowest temperature of the process.

In the conventional PTESs some researchers have presented, the heat of EHE is directly rejected to the ambient and the heat of CHE is received from external heat source [6]. Other researchers also considered using heat recovery for PTES. For example, Graeber Carsten et al. [7] designed a PTES with regenerator. Alberto Benato et al. [8] proposed an innovative plant configuration which adopts an electric heater to convert electricity into thermal energy. This paper presents a new kind of idea that EHE and CHE are respectively used as evaporator and condenser of ORC as showing in Fig 1 (a).

2.2 Calculation methods

PR equation has been used as the computational model for thermodynamic properties [9]. The parameter subscript of the state point is shown in Fig 1(a).

The power accepted by argon in compression is:

$$W_{ar,com} = \dot{m}_{ar}(h_2 - h_1) \quad (1)$$

where $\dot{m}_{ar}$ is the mass flow of argon. The pressure ratio and the isentropic efficiency as defined as:

$$\pi = \frac{p_2}{p_1} \quad (2)$$

$$\eta_{is} = \frac{h_{2s} - h_1}{h_2 - h_1} \quad (3)$$

The energy stored by hot bed material is:

$$e_h = \dot{m}_{ar} C_p^h (T_2 - T_{designed}) \quad (4)$$

where C_p^h is the average specific heat of material in the hot bed and T_2 is the highest temperature (T_{max}) of the charging process. The heat rejected by EHE is:

$$Q_{ar,EHE} = \dot{m}_{ar}(h_3 - h_4) \quad (5)$$

The power generated by the expander can be expressed as:

$$W_{ar,exp} = \dot{m}_{ar}(h_4 - h_5) \quad (6)$$

Similar to Eq.(4), the heat absorbed by argon from cold bed material is:

$$e_c = \dot{m}_{ar} C_p^c (T_{designed} - T_5) \quad (7)$$

where C_p^c is the average specific heat of material in the cold bed. The heat absorbed by CHE is:

$$Q_{ar,CHE} = \dot{m}_{ar}(h_1 - h_6) \quad (8)$$

The energy released to the hot bed and the energy absorbed from the cold bed are:

$$E_h = e_h \tau_{ch} \quad (9)$$

$$E_c = e_c \tau_{ch} \quad (10)$$

where τ_{ch} is the period of the charging process.

Then, the energy stored by material and the net power input during the whole charging process can be calculated as Eq.(11) and Eq.(12) respectively:

$$E_{st} = E_h - E_c \quad (11)$$

$$E_{net,ch} = (W_{ar,com}/\eta_e - W_{ar,exp})\tau_{ch} \quad (12)$$

where η_e is the efficiency which the electricity transfers into compressor work.

Finally, the efficiency of the charging process can be expressed as,

$$\eta_{ch} = \frac{E_{st}}{E_{net,ch}} \quad (13)$$

For ORC，the thermodynamic analysis is simplified as showing from Eq.(14) to Eq.(21).

$$W_{ORC,pump} = \dot{m}_{ORC}(h_9 - h_8) \quad (14)$$

$$Q_{ORC,EHE} = \dot{m}_{ORC}(h_{10} - h_9) \quad (15)$$

$$W_{ORC,exp} = \dot{m}_{ORC}(h_{10} - h_{11}) \quad (16)$$

$$Q_{ORC,CHE} = \dot{m}_{ORC}(h_{11} - h_7) \quad (17)$$

$$Q_{ORC,cond} = \dot{m}_{ORC}(h_7 - h_8) \quad (18)$$

$$W_{cw,pump} = \frac{\dot{m}_{cw} g H_{cw}}{1000\eta_{cw,pump}} \quad (19)$$

$$W_{net,ORC} = W_{ORC,exp} - W_{ORC,pump} - W_{cw,pump} \quad (20$$

$$\eta_{th,ORC} = \frac{W_{net,ORC}}{Q_{ORC,EHE}} \quad (21)$$

where $\dot{m}_{ORC}$, $\dot{m}_{cw}$, g, H_{cw}, $\eta_{cw,pump}$, $W_{ORC,pump}$, $Q_{ORC,EHE}$, $W_{ORC,exp}$, $Q_{ORC,CHE}$, $Q_{ORC,cond}$, $W_{cw,pump}$, $W_{net,ORC}$, $\eta_{th,ORC}$ are the mass flow of ORC working fluid, the mass flow of cooling water, acceleration of gravity, the head of cooling pump, the total efficiency of cooling pump, the power consumed by ORC compressor, the heat absorbed by from EHE, the power generated by ORC expander, the heat rejected to CHE, the power consumed by cooling pump, The net power output and the thermal efficiency of ORC system, respectively.

Hence, this paper defined the efficiency of the charging process of PTES with ORC:

$$\eta_{ch,ORC} = \frac{E_{st} + W_{net,ORC}\tau_{ORC}\eta_{tr}}{E_{net,ch}} \quad (22)$$

where, τ_{ORC} and η_{tr} represent the performance period of ORC and the efficiency during $W_{net,ORC}$ transfers into stored energy of PTES, respectively.

This paper chose the isentropic efficiency of compressor/expander, the pressure ratio and the designed temperature to analysis the efficiency and the highest temperature of the charging process of proposed PTES. The model has been coded in Matlab and all the properties of argon and working fluids of BORC are from NIST REFPROP.

3. RESULTS AND DISCUSSION

Fig 2-4 show the results of efficiency with/without ORC and the highest temperature in the charging process with the parameters changes.

From the results shown in Fig 2, because as the isentropic efficiency increases, the system irreversibility decreases, and the heat added due to irreversibility decreases correspondingly, as a consequence, T_{max} decreases. Although isentropic efficiency has little effect on η_{ch}, which is depicted in Fig 2, however, since T3 which is also the heat source temperature of ORC decreases as T_{max}, leading to the decrease of $W_{net,ORC}$, finally, $\eta_{ch,ORC}$ drops.

From the results showed in Fig 3, larger pressure ratio means higher T_{max}, which is consistent with what's shown in Fig 3. Because of the increase of π, both E_{st} and $E_{net,ch}$ increase but the increase rate of E_{st} is larger, which results in the increase of η_{ch}. When it comes to $\eta_{ch,ORC}$, with T_{max} which positively correlated to the heat source temperature of ORC increases, $W_{net,ORC}$ increases, finally, also increases the $\eta_{ch,ORC}$.

As shows in Fig 4, with the T_{designed} increases, T_{max} increases linearly, that's because at the same compression ratio, the pre-compression temperature (T_{designed}) increases, contributing to the post-compression temperature (T_{max}) increases, too. However, because with the T_{designed} increases, both E_{st} and $E_{net,ch}$ drop and E_{st} goes down even faster, which results in the decrease of η_{ch}. As for $\eta_{ch,ORC}$, the energy which ORC could produce drops, leading to $\eta_{ch,ORC}$ drops, too.

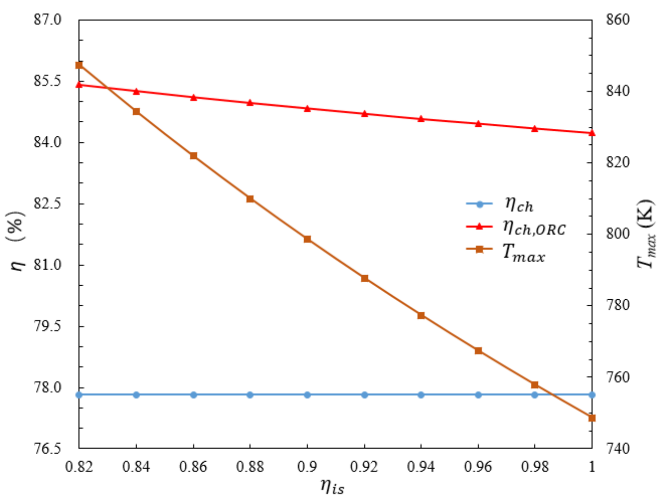


Fig 2 Performance with the isentropic efficiency changes

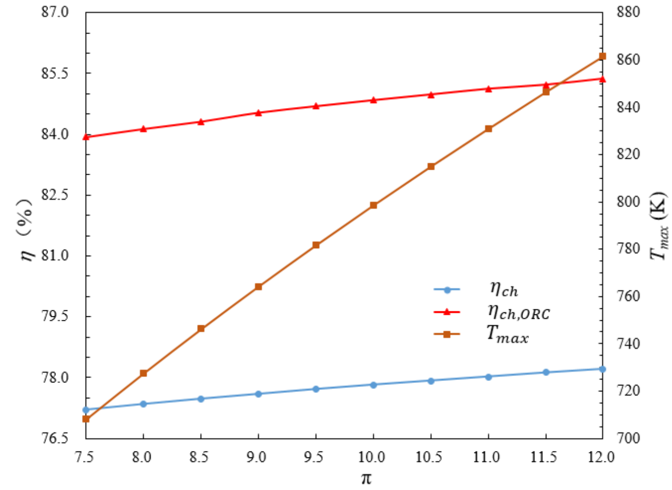


Fig 3 Performance with the pressure ratio changes

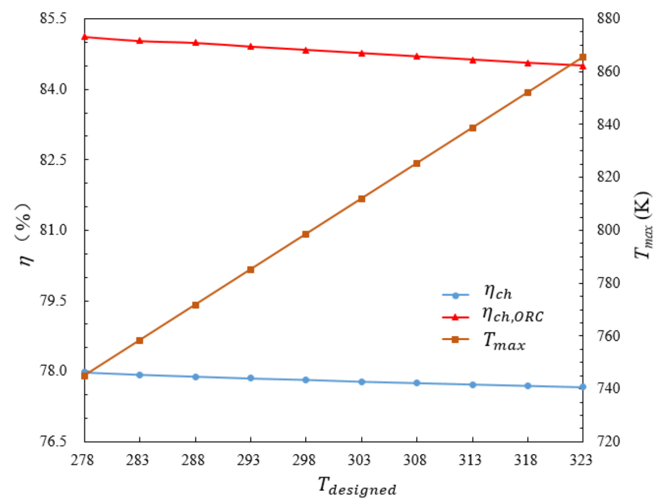


Fig 4 Performance with the designed temperature changes

4. CONCLUSIONS

This paper presented a new kind of PTES configuration combined with ORC to recovery the waste heat in the EHE and CHE during the charging process. A thermodynamic model was built, then a parametric analysis was conducted. The results showed that, as the isentropic efficiency increased, T_{max} and $\eta_{ch,ORC}$ dropped while η_{ch} remained constant. With the increase of pressure ratio, all three parameters increased significantly. When T_{designed} increased, both η_{ch} and $\eta_{ch,ORC}$ increased, too, while T_{max} decreased.

More attention would be paid in the performance of discharging process and the whole round-trip process in future research.

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