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Dynamic modelling of an Organic Rankine Cycle Compressed Heat Energy Storage (ORC-CHEST) system integrated with a cascaded phase change materials (PCM) based packed bed unit

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ABSTRACT

Carnot batteries represent an emerging thermo-mechanical energy storage technology based on the conversion of surplus electricity into medium-low temperature heat, and subsequent conversion of the heat into electricity. A promising configuration of the Carnot battery is represented by the Organic Rankine Cycle Compressed Heat Energy Storage (ORC-CHEST) that combines a high-temperature heat pump (charge phase), an Organic Rankine Cycle (ORC) system (discharge phase) and a thermal energy storage (TES) system. Indeed, TES is a crucial component in the overall ORC-CHEST system, since it thermally links the charge and discharge phases (operating asynchronously) guaranteeing optimal operation and ensuring significantly high round trip efficiencies. Most of literature on ORC-CHEST have so far only focused on preliminary analyses in order to define the general thermodynamic potential and to identify the limits of the overall system. Indeed, a detailed analysis of ORC-CHEST with focus on TES modelling is lacking. This paper presents such an analysis by developing a dynamic numerical model of the discharge phase of ORC-CHEST system with a novel packed bed solution for the TES system. Indeed, we developed for the first time a plant model in MATLAB that blends together algebraic and differential sub-models detailing the transient behaviour of the thermal storage stages and the ORC unit. In addition, a novel configuration of the TES system design is proposed utilizing a cascade of multiple phase change materials (PCMs) in place of the cascade of sensible and single PCM proposed in literature, enhancing simultaneously both the TES energy density and the round trip efficiency of the system. The results are of great interest for academia and industry and contribute significantly to the development of an efficient and cost-effective thermal energy storage system, capable to simultaneously increase the ORC-CHEST round trip efficiency and energy density by 7 % and 77 %, respectively, compared to the state-of-the-art solution.

Keywords: CHEST, ORC, Phase Change Material, Renewable energy, Packed bed.

NONMENCLATURE

Abbreviations

CHEST	Compressed Heat Energy Storage
HP	Heat Pump
ORC	Organic Rankine Cycle
PCM	Phase Change Material
SH	Sensible heat material
TES	Thermal Energy Storage

1. INTRODUCTION

The Organic Rankine Cycle Compressed Heat Energy Storage (ORC-CHEST) system is a specific category of Pumped Thermal Energy Storage (PTES) based on the Organic Rankine cycle that nowadays is gaining significant momentum and interest among other Carnot batteries technologies such as Liquid Air Energy Storage (LAES) [1], Compressed Air Energy Storage (CAES) [2] and Rankine or Brayton heat engines [3]. ORC-CHEST is a long term thermo-mechanical based process, with the highest specific energy among PTES variants (40-100 kWh/m3), suitable for mid-to-large scale applications (10-150 MW/ 80-7200 MWh) [2], without geographical constraints and environmentally safe. The ORC-CHEST system operation can be divided into three phases: charging, storing and discharging. During the charge phase, a high temperature heat pump (HTHP) makes use of electric energy to compress a vapour organic fluid, produced by low temperature heat source. The fluid is then condensed and subcooled by transferring thermal energy with the thermal energy storage (TES), i.e. a cascade of sensible heat material (pressurized water) and phase change material (PCM). A conventional ORC is then operated during the discharge phase by utilizing the thermal energy stored in the TES to drive a turbine feeding the electric energy back to the grid. Due to its thermo-mechanical nature, the system can also provide thermal energy for a potential district heating application [4]. A first pilot plant is currently being built and will be presumably operative in 2021. Among the thermal devices mentioned, the TES plays a key role in order to guarantee a reasonably high ORC-CHEST efficiency (>50 %, [4]). Jockenhöfer et al. [5] carried out a technical investigation on a fully heat integrated subcritical ORC-CHEST proposing a cascaded sensible heat-PCM TES combining a pressurized water storage for the sensible part and a latent heat storage (eutectic mixture of potassium nitrate and lithium nitrate with Tmelt = 133 ºC) for the phase change zones. Aiming to develop a dynamic model of the ORC-CHEST coupled with a 26 MW wind farm located in Spain, Sánchez-Canales et al. [6] carried out a techno economic analysis of the case scenario. The results showed that, with a round trip efficiency above 90 %, the ORC-CHEST is an economically viable energy storage system only when its capital cost (CAPEX) ranges between 235 and 765 k$/MWe. It is worth noting that, despite the work claimed a fully dynamic approach for the whole plant, the TES is modeled with a simple quasi-steady state approach and once again the cascade configuration SH-PCM is proposed to minimize the entropy generation during the heat exchange processes. Implementing the same ORC-CHEST cycle architecture, Hassan et al. [7] performed a steady-state thermodynamic analysis of a 1 MWe ORC-CHEST system, assessing the effect of different refrigerants and cycle configurations for an extensive range of source and sink temperatures. R1233zd(E), R-1234ze(Z) and R-1233zd(E)/R-1233zd(E) were selected as the best working fluids for HTHP and the ORC assuming a system maximum temperature as high as 133 ºC. Trebilcock [8] presented the design and operation modes of a ORC-CHEST system based on the model developed by Sánchez-Canales et al. [6]. The results confirmed the potentiality of the system achieving round trip efficiency values higher than 100 % when using waste heat/cold sources available.

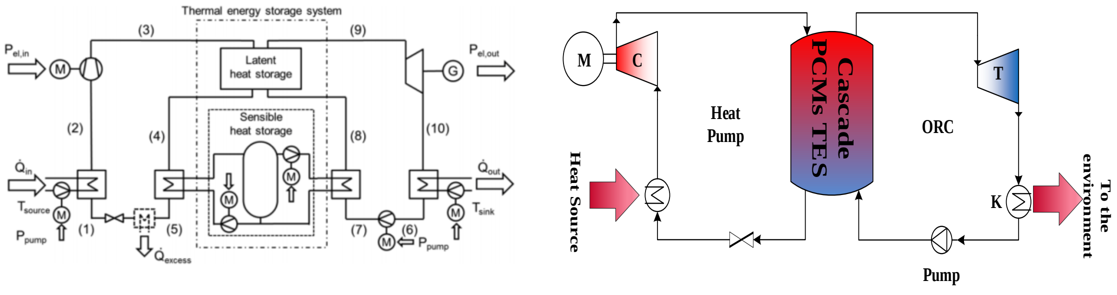
As extensively described in this section, the vast majority of the literature studies on TES for ORC-CHEST application presents 1) a steady state (or quasi steady-state) approach and 2) a cascade SH-PCM configuration. Indeed, none of the works presented delved into an exhaustive technical analysis clearly identifying how the ORC-CHEST system performance is impacted by the dynamic performance of the TES. The present work aims to go a step further, introducing the following novelties: 1) a dynamic approach to fully assess the TES effect on the efficiency of the ORC-CHEST discharge phase 2) a novel TES configuration based on cascade PCMs aiming to increase the energy density and the efficiency of the ORC-CHEST discharge phase.

2. METHODOLOGY AND MODEL DESCRIPTION

2.1 ORC-CHEST process design and study cases

The state-of-the-art architecture of the ORC-CHEST system proposed in literature is shown in Fig. 1a and represents the baseline case scenario. The system consists of three main components (a HTHP, a high-temperature TES and an ORC system) and operates as follows. The charge phase is driven by excess electricity from renewables that is used to compress the working fluid of the HTHP cycle (1–2). After being condensed and subcooled in the cascaded SH-PCM thermal energy storage, the working fluid is throttled to the evaporation pressure by means of an isenthalpic Joule-Thomson process and then evaporated in a dedicate heat exchanger using either an environmental heat source or any available waste heat sources. During discharge, the liquid working fluid is forwarded by the pump to the heat addition process, where it is preheated, vaporized and superheated by transferring heat with the SH-PCM thermal energy storage. The working fluid is then expanded in a turbine and condensed back by exchanging heat with the environment.

Applying the same concept of combining different materials for the TES to enhance the heat transfer process but with a new technical strategy, a novel ORC-CHEST architecture is proposed (Fig. 1b) and represent the alternative to the baseline case scenario. In particular, the cascade SH-PCM thermal energy storage has been replaced by a compact cascaded PCMs, sensibly increasing the energy storage density of the TES.



(a) (b)

Fig. 1. ORC-CHEST process schematic – Baseline (a – Adapted from [4]) and novel case scenario (b).

2.2 ORC model

The ORC unit was designed by using a MATLAB design routine previously presented in [9]. In this work, the design and off-design routines have not been integrated in the same global optimization loop, but used sequentially for simplicity. The working fluid is R1234ze(Z) was chosen, given its low environmental impact, high thermal stability and good thermodynamic performance. The design routine is based on steady-state mass and energy balances on control volumes around the main ORC components. Pressure and heat losses were neglected. The heat exchangers were discretized according to the number of phases (liquid, two-phase and vapor). Given the design temperatures of the heat sources and heat sink, together with the fixed net power output of 1 MWe, the thermal efficiency of the ORC unit was maximized by finding the optimal set of decision variables, e.g., the evaporation pressure, turbine inlet temperature, recuperator effectiveness, pinch-point temperature difference at the evaporator and condenser, condensation temperature and mass flow rate of the heat sources. To estimate the isentropic efficiency of the turbine, the correlations of Macchi and Astolfi [10]for single-stage turbines were used.

Since the temperature of the TES depends on its state of charge, the part-load optimization routine in Ref. [9] was used to optimize the part-load operation of the ORC unit depending on the inlet temperature of the storage. In particular, the net power output of the ORC was maximized by acting on the mass flow rate of the working fluid and of the cooling medium at the ORC condenser, on the opening of a control valve at turbine inlet, and on a bypass valve of the heat source at the inlet of the ORC unit. As a result, the optimal operating conditions (evaporation and condensation pressure, degree of superheating, etc.) ensuring the maximum net power output were achieved.

2.3 Thermal energy storage modeling

A TES packed bed configuration were chosen for its high surface/volume ratio leading to an enhancement of the heat transfer rate, particularly crucial for PCM characterized by low thermal conductivity [11]. In order to mathematically model the TES component, a concentric dispersion model was implemented to compute the thermal behaviour of the TES. Three unsteady one-dimensional energy equations were developed to calculate the transient temperature distribution of the HTF and the storage media within the thermal energy storage. More details of the mathematical model formulation can be found in [12]. For the HTF phase, solid phase and PCM particle:

$$\begin{aligned}\varepsilon\rho_f c_{p,f}\left(\frac{\partial T_f}{\partial t}+u_f\frac{\partial T_f}{\partial x}\right)&=\varepsilon k_f\frac{\partial^2 T_f}{\partial x^2}\\&+h_{fp}a_s(T_s-T_f)\\&+\frac{U_w D\pi}{A_{bed}}(T_{amb}-T_f)\end{aligned} \tag{1}$$

$$\begin{aligned}(1-\varepsilon)\rho_s c_{p,p}\frac{\partial T_s}{\partial t}&=(1-\varepsilon)k_p\frac{\partial^2 T_s}{\partial x^2}\\&+h_{fp}a_s(T_f-T_s)\end{aligned} \tag{2}$$

$$\rho_p c_{p,p}\frac{\partial T_p}{\partial t}=k_p\left(\frac{\partial^2 T_p}{\partial r^2}+\frac{2}{r}\frac{\partial T_p}{\partial r}\right) \tag{3}$$

2.4 Case studies and operating conditions

According to the filler medium adopted in the TES, the two case studies can be classified as:

1) Cascade sensible heat and phase change material (SH+PCM), representing the baseline case study, currently implemented in literature as shown in Section 1. Two pressurized water tanks were chosen for the sensible heat TES section; KNO3-LiNO3 was

chosen as the filler medium for the phase change material (PCM1) section of the TES.

2) Triple cascade PCMs (3PCM), the novel solution for the TES. Each PCM occupies one third of the TES and all are assigned the same latent heat and thermophysical properties as the PCM utilized in SH+PCM case. Nevertheless, different melting temperature were assumed for the 3 PCMs as shown in Table 1.

Table 1 Storage material properties.

Parameter		PCM-1	PCM-2	PCM-3	Unit
ρ_d, Density	Solid	1900	1900	1900	*kg/m³*
	Liquid	1900	1900	1900	
Specific heat	Solid	1.5	1.5	1.5	*kJ/kg K*
	Liquid	1.5	1.5	1.5	
Thermal conductivity	Solid	0.5	0.5	0.5	*W/m K*
	Liquid	0.5	0.5	0.5	
Latent heat		167.3	167.3	167.3	*kJ/kg*
T_{m1}		132.5	119.5	104.5	*°C*
T_{m2}		133.5	120.5	105.5	*°C*
Particle diameter		0.015	0.015	0.015	*m*

In order to compare the different systems, the following assumptions were made:

- The aspect ratio of the TES tank and the operating conditions are the same for all the case studies and are based on the ORC design parameters.
- Similar to packed beds employed in concentrated solar plants, a cut-off criterion for the discharge phase was applied ($T_{cut\text{-}off}$ = 120 °C). Indeed, depending on the heat transfer process in the cold box a minimum threshold temperature of the TES outlet fluid was set: once this temperature limit was reached, the TES discharge process was considered terminated.
- The numerical results have been reported for steady state temperature profiles established in the TES, approximately after about 9 complete charging and discharging cycles.

Table 2. Technical input data for the TES system under study.

Parameters	Value	Unit
Aspect Ratio (H/D)	1.5	-
HTF, Heat Transfer Fluid	Therminol D-12	-
$\dot{m}_{HTF,d}$, Discharge HTF mass flow	70.85	*kg/s*
t_d, discharge time	3	*h*

2.5 Key performance indicators

The results of the simulations will be presented in the next section with reference to the following performance parameters. Directly connected to the round trip efficiency of the CHEST system, the ORC thermodynamic efficiency evaluates the performance of the discharge phase:

$$\eta_{\mathrm{ORC}} = \frac{\int_0^{t_d} P_{net,\mathrm{ORC}}\,dt}{\int_0^{t_d} \dot{Q}_{\mathrm{d,TES}}\,dt} \tag{4}$$

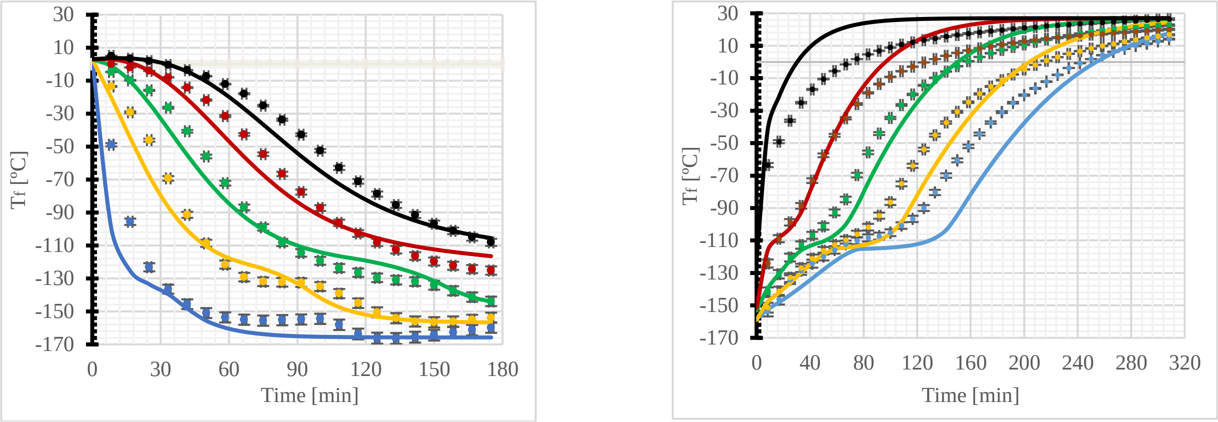
where $P_{net,ORC}$ $[kW_e]$ is the instantaneous net electric power produced during the discharge phase by the ORC unit and $\dot{Q}_{d,TES}$ $[kW_{th}]$ is the instantaneous thermal power transferred to the ORC unit from the TES. Energy density ϕ [kWh_e/m^3] is calculated as the ratio between the electrical energy produced and the volume of the TES:

$$\varphi = \frac{E_{el,ORC}}{V_{TES}} \tag{5}$$

3. RESULTS AND DISCUSSION

3.1 Thermal energy storage model validation

In order to validate the numerical model of the PCM-TES, the experimental results obtained from the test rig developed at TESLAB@NTU and described in [12] were used. It consists of two different open loops, corresponding to the TES charge and discharge phases, using nitrogen as the main heat transfer fluid. The operational conditions of the experimental set-up can be found in [12] . As it can be seen from Fig. 2, there is both a good quantitative and qualitative agreement on the results of the model compared to the measured values, with an overall mean absolute percentage error (MAPE) lower than 6 % and 4 % for the measured temperatures in charge and discharge phase, respectively.



(a) (b)

Fig. 2. Validation of PCM TES model – Charge (a) and discharge (b) phases.

3.2 *Technical analysis*

Assuming the technical input data shown in Section 2.4, two different scenarios corresponding to two different CHEST configurations were assessed. The effect of the different TES configuration over the CHEST performance has been summarized in Fig. 3. It can be seen that the implementation of the PCM cascade solution allows to approximately 80 % larger energy density of the system. In addition, the novel configuration significantly increases the ORC net electric efficiency by 7 %, in turn enhancing the global performance of the system. The reasons behind the thermodynamic superiority of the novel configurations can be explained as follows.

Fig. 4 reports the dynamic behaviour of the HTF temperature at the outlet of the TES during the CHEST discharge phase for the different configurations. Due to the thermocline phenomena approaching the outlet section of the TES during the discharge phase, where the HTF is heated up by the thermal energy stored by the particles, the temperature of the HTF at the outlet of the TES decreases over the time. Since this temperature corresponds to the inlet temperature of the HTF in the ORC evaporator, a decrease of the instantaneous ORC net electric efficiency occurs over the time resulting in a lower round trip efficiency due to the part-load performance of the ORC unit. For a temperature of the HTF below 120 °C, the ORC unit stops the operation.

The increase of HTF outlet temperature over time is mitigated by the presence of the cascade phase change process. Indeed, in the 3PCM configuration, the TES system is able to deliver thermal energy at higher temperature than the SH+PCM configuration resulting in a higher ORC net electric efficiency as shown in Fig. 4b. In fact, the PCM layers are not only capable to increase the total energy density (with respect to SH+PCM configuration), but also act as thermal "buffer" by keeping the outflow temperature within the cut-off temperature threshold of 120 °C for a longer time. Indeed, the phase change temperature transition allows the system to discharge for a longer time period before the cut-off criteria is prompted. Therefore, there is an increase in the operating time (since the processes can continue while the outflow temperatures remain within these ranges), and thus in the amount of thermal energy which can be effectively withdrawn, resulting in a high efficiency in the use of the total storage capacity and a time averaged higher temperature at the inlet of the ORC evaporator.

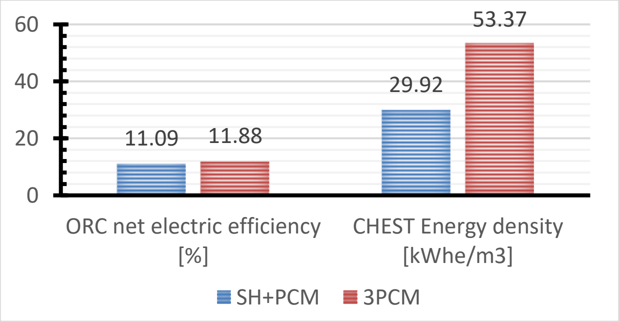
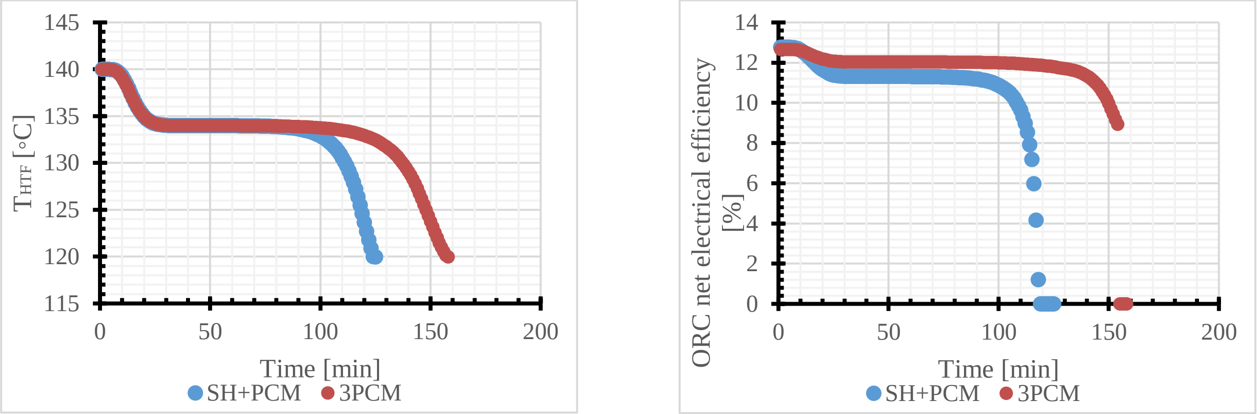


Fig. 3. Performance indicators for SH+PCM and 3PCM configuration.



(a) (b)

Fig. 4. Outlet HTF temperature as a function of time and ORC net efficiency for the discharge phase for the two different configurations (SH+PCM and 3PCM).

4. CONCLUSIONS

The current work has analyzed the influence of a novel TES configuration based on three cascade phase change material on the performance of a CHEST system. A dynamic model of the thermal energy storage has been developed and validated in order to assess the potential thermodynamic advantage of the proposed solution. The study showed that the implementation of a cascade PCM configuration significantly enhanced not only the CHEST energy storage density by more than 77 % but also the performance of the CHEST discharge phase. Indeed, by leveraging on the positive effect of the thermal buffer triggered by the cascade PCM, the TES can deliver a higher time averaged thermal power to the ORC evaporator enhancing the total electricity production of the CHEST plant.

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