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High Temperature Combined Sensible-Latent Thermal Energy Storage

Pierre Garcia[1, a)] and Jérôme Pouvreau[1, b)]

[1]*Université Grenoble Alpes, CEA-LITEN, Thermal Biomass and Hydrogen Department,*
Thermal Energy Storage Laboratory
17 rue des Martyrs, 38054 Grenoble cedex 9, France

a)Corresponding author: pierre.garcia@cea.fr
b)jerome.pouvreau@cea.fr

Abstract. This work aims at proposing innovative Thermal Energy Storage (TES) systems for CSP power plants able to operate with high efficiency thermodynamic cycles working at 600°C. To do this, for CSP plants with gases or molten salts as Heat Transfer Fluid (HTF), high thermal capacity molten salts can be used in thermocline tanks with encapsulated Phase Change Material (PCM) top layer to limit the temperature degradation during discharge and thus increase the utilization rate of the storage system. Aluminum silicon (AlSi) has already been identified to have superior properties for a PCM: high specific energy density and volumetric heat of fusion, good thermal conductivity, low cost, and low environmental impact. A one dimensional dynamic model of combined sensible-latent TES system is presented, taking into account thermal transfer by conduction and convection in axial direction, measured thermo-physical properties for the storage media, and realistic heat losses to the environment. A prototype of molten salt single media thermocline tank is designed and modeled, and a parametric analysis is performed with different amounts of PCM for the same total tank volume. This numerical study shows that a combined sensible-latent molten salt thermocline concept with AlSi as PCM material can slow down the outlet temperature degradation during discharge and increase the storage capacity compared to a sensible only thermocline TES with the same tank volume.

INTRODUCTION

IN-POWER H2020 project aims at developing and integrating new innovative material solutions into CSP technology to increase the efficiency while simultaneously decreasing the energy production cost. These advanced material solutions consist of self-healing and anti-soiling coated mirrors, optimized mirror support structure, high-temperature absorber coating, and high-temperature Thermal Energy Storage materials and designs leading to the reduction of storage system size. Proposed innovative TES materials could operate with high efficiency thermodynamic cycles working at 600°C. To do this, for CSP plants with gases or molten salts as HTF, high thermal capacity molten salts will be used in thermocline tanks with encapsulated PCM top layer to limit the temperature degradation during discharge and thus increase the utilization rate of the storage system. Below the PCM layer, the storage tank operates as a thermocline tank without filler materials (single media thermocline) or with filler materials (dual media thermocline), as shown in Figure 1.

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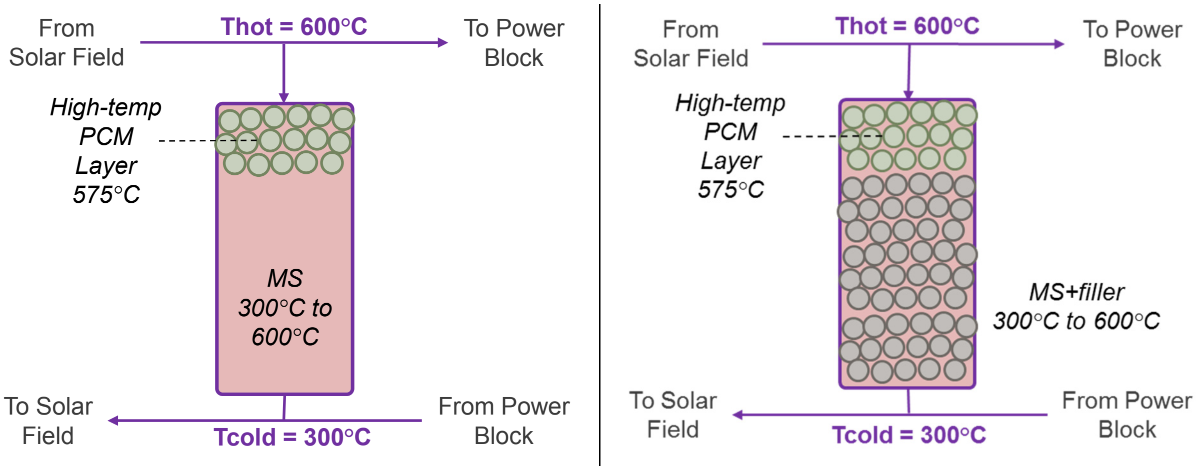

FIGURE 1. IN-POWER combined sensible-latent thermocline TES without fillers (left) and with filler (right)

MATERIAL AND SYSTEM DESCRIPTION

Combined Sensible-Latent TES Systems

Combined sensible-latent TES systems were already reported in the literature. Galione [1] considered a dual media thermocline tank (solar salt and quartzite) with two PCM layers (potassium hydroxide), at the top and at the bottom of the tank, with the objective to reduce the thermocline degradation throughout charge/discharge cycles thanks to the thermal buffering effect of the PCM layers. Such TES concepts were numerically tested and their thermal performances were compared against other designs of single-tank systems and with a reference two-tank molten-salt system, showing that this multi-layered solid-PCM concept is an interesting option for thermal storage in CSP facilities.

Other recent studies consider combined sensible-latent TES systems with AlSi12 as PCM [2-6] but none of them using molten salts as Heat Transfer Fluid (HTF). Kotze [2] proposed a storage system concept integrating TES and steam generator into one unit with eutectic sodium–potassium alloy (NaK) as HTF and metallic PCM as storage medium. As NaK is highly reactive with water, this TES concept requires a safe physical separation between NaK and water-steam: the TES tank consists in a shell-and-tube heat exchanger with PCM (AlSi) on the shell side, and two separate tube circuits for the primary HTF loop (NaK) and steam generation loop. The storage tank is divided into three separate sections, each serving as a distinct part of the steam generator (boiler, superheater, and reheater). In commercial implementations of this concept, three different PCM would have to be selected to better match temperature of the steam. Thermodynamic and heat transfer analyses showed that such a design is feasible, even if the author points out that further analyses are necessary to assess its economic benefit. A prototype thermal energy storage test rig has been built and tested as to better understand the behavior of latent heat thermal energy storage, using AlSi as PCM and quenching oil as HTF in the unique tube of the test section [7]. A numerical model was developed and compared with the behavior of the test rig during discharge, showing reasonable accuracy to simulate the latent heat thermal energy storage.

Zanganeh [3] investigated a high-temperature thermocline TES concept, using air as the heat-transfer fluid and integrating PCM to stabilize the discharging outflow air temperature. A lab-scale prototype was built and tested, containing layer of encapsulated phase change material (AlSi12 in stainless steel tubes) on top of a packed bed of rocks. A two-phase transient heat transfer model of the thermal storage cycle was experimentally validated with measured temperatures from the lab-scale prototype. Tests show a stabilization of the outflow air temperature around the melting temperature of AlSi12, possibly extending the discharge time for the downstream application. The thermo-fluid dynamics behavior of this prototype was later analyzed by a computational fluid dynamics approach, both sensible and latent heat sections of the storage being modeled as porous media [4].

Hernandez [5] developed and validated a two-phase model in order to describe the thermal performance of a combined sensible-latent thermal storage system, using steel slag as sensible packed-bed material, encapsulated AlSi metal alloy as phase change material and air as heat transfer fluid. The model was validated with data from the literature[3, 8], showing the enhanced performance of combined sensible-latent storage compared to purely sensible system. The analysis of the proposed real scale TES system with different thickness of PCM layers showed that an optimal design with a 5% vol. top PCM layer can overcome the limitations of the only sensible packed bed technology, without oversizing the storage.

Rea [7] presented the design and initial experimental results of a lab-scale prototype of a latent heat thermal storage system using 50 kg of Al-Si alloy as a PCM, embedded sodium heat pipes to distribute heat, and a valved thermosyphon to control heat flow from the thermal storage tank to thermoelectric generators. This system was able to distribute heat from an electrically generated heat input simulating solar flux to and from the PCM with small temperature gradients, and controllably dispatch the heat to thermoelectric generators.

PCM Selection

TES materials must have a high energy density per-unit mass or per-unit volume, that is to say a high density and a high specific heat (for sensible heat storage) or a high latent heat (for latent heat storage). The following technical requirements should also be taken in consideration when selecting a PCM for thermal storage purposes: thermal conductivity, mechanical and chemical stability, chemical compatibility with heat exchanger and/or container, low cost, and process-adapted temperature and pressure operational ranges. Contrary to many PCMs, metallic phase change materials have high thermal conductivity, allowing high charging and discharging rates of TES system, and can operate at temperatures exceeding 500°C. Many metals were found to be highly suitable as PCMs (in the temperature range of 400–750°C), with advantages over inorganic salts (higher heat of fusion and thermal conductivity, lower volume required per stored energy). Aluminum silicon (AlSi12 with melting temperature of 575°C) has been identified to have superior properties for a PCM: high specific energy density and volumetric heat of fusion, good thermal conductivity, low cost, and low environmental impact [9]. As compatibility between PCM and containers is a critical point, innovative anti-corrosive layers under development at CEA are currently tested in the framework of the IN-POWER project to avoid creep corrosion. Kotzé et al. [2, 7] also selected the eutectic alloy of aluminum and silicon, AlSi12, as one of the best candidates as metallic PCM based on a review of the literature. Finally, aluminum–silicon alloys are relatively stable through several heating and cooling cycles [10].

MODEL DESCRIPTION AND VALIDATION

A one dimensional dynamic model of combined sensible-latent TES system was developed, taking into account thermal transfer by conduction and convection in axial direction (along the height of the tank), measured thermo-physical properties for the storage media, and realistic heat losses to the environment. To do this, existing continuum thermodynamics models of dual-media thermocline systems [11] were extended with the additional use of a top PCM layer. This model has been adapted in Modelica language within the Dymola platform.

To our knowledge, there is no existing experimental facility of molten salt thermocline storage with PCM top layer. To validate our model we chose to compare its results with experimental data from a combined sensible latent packed bed tank of rocks and AlSi with air as HTF [3]. AlSi and stainless steel capsules are considered as a unique material by using mean values of specific heat, density, and thermal conductivity. Thermal gradients inside solids (PCM capsules and rocks) are considered negligible: this assumption can be made when the conduction resistance in the solids is negligible compared to the convection resistance, that is to say when the dimensionless Biot number is lower than 0.1 [12]. A quite good agreement of the simulated results can be observed in Figure 2 for both latent and sensible section. Radiative heat transfers are neglected, which could partially explained the deviations from experimental results.

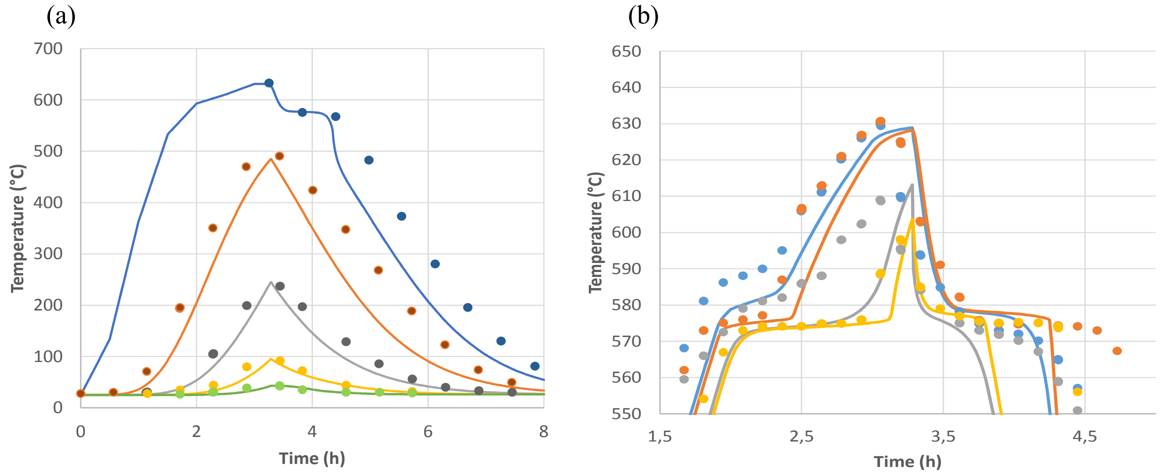

FIGURE 2. Experimentally measured (markers, from [3]) and simulated (curves, this work) temperatures during charge and discharge: packed bed and inlet (top) temperatures in the sensible section (a); PCM and air temperatures in the latent section (b)

STORAGE DESIGN

As previously reported, some recent studies have shown the interest of adding a top layer of PCM in a packed bed [5] or in mid-temperature molten salt thermocline [1] TES. IN-POWER combined sensible-latent TES design has been modeled and its thermal performances are compared to thermocline storage without PCM. The TES system consists in a molten salt (Solar Salt, 60% $NaNO_3$ and 40% KNO_3 by weight) single media thermocline tank, with a top layer of encapsulated AlSi. Solar Salt properties are taken from Ferri [13], and AlSi capsules properties are taken from Zanganeh [3]. The reference design of the simulated tank is presented in Table 1. A parametric study was done replacing a variable fraction of the salt by a PCM top layer, the total tank volume being left constant.

TABLE 1. Reference design of a 90 MWh_{th} molten salt thermocline tank

Design parameter	Unit	Value
Hot temperature	°C	600
Cold temperature	°C	290
Design mass flow	kg/s	34.9
Design salt mass	tons	754
Tank height	m	14
Tank diameter	m	7.57
Tank volume	m^3	630

In Figure 3a, simulated outlet temperatures profile in discharge are presented for TES subjected to the same charge and discharge conditions such as inlet temperatures and flow rates and final charging outlet temperature (350°C) for a TES previously charged at 585°C. In such conditions a 15% (in volume) PCM layer can extend the discharge time with outlet temperature over 550°C by up to 12% for the same TES volume. In Figure 3b, the same simulation is done for a TES previously charged at 600°C. In such conditions a 15% (in volume) PCM layer can extend the discharge time by up to 10% for the same TES volume. In both cases it can be observed that the PCM layer lowers the outlet temperature during the first period of the discharge, and then then increases the outlet temperature in the second part of the discharge for outlet temperature below 570°C.

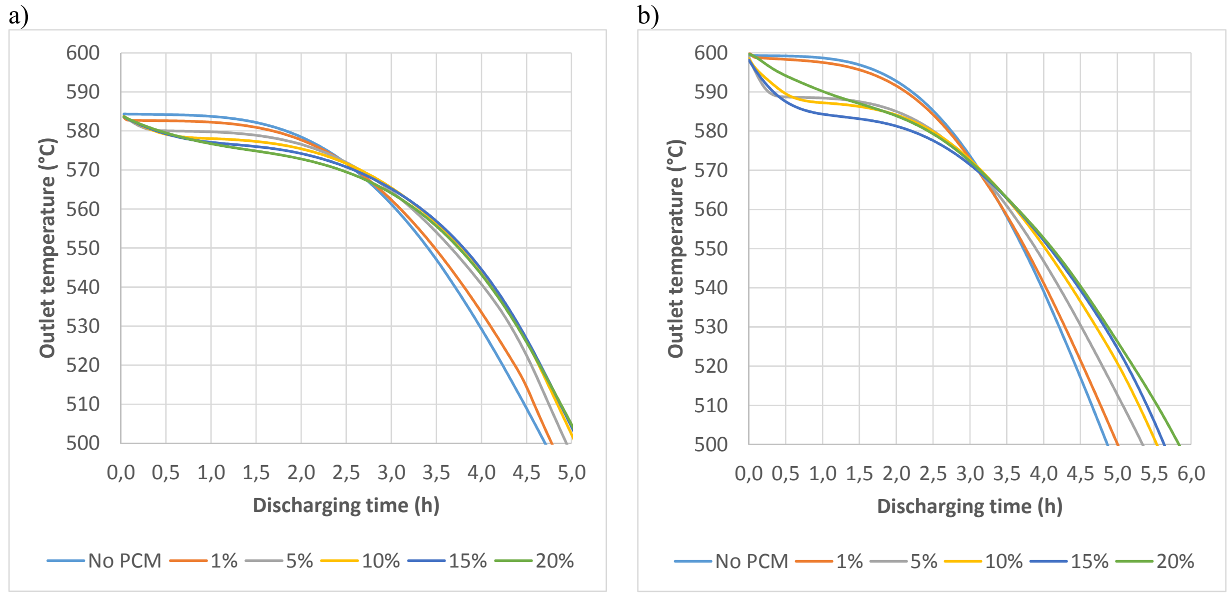

FIGURE 3. TES outlet temperature during discharge for different amounts of PCM, for a 90 MWh_{th} storage tank (left: TES charged at 585°C; right: TES charged at 600°C)

In Figure 4, the amount of energy coming out of the TES during discharge is shown as a function of the temperature degradation in discharge (defined as the difference between the nominal inlet temperature in charge and the outlet temperature in discharge), for different PCM fractions in a tank previously charged at 600°C. Temperature degradation in discharge is a restrictive parameter for the downstream component of the facility (power block, process heat consumer, …), that is why it is often considered as a relevant criterion to define the end of discharge. If the heat can be recovered at a temperature level down to 100 K lower than it was produced, about 60 MWh_{th} can be discharged from a 100% molten salt thermocline tank, whereas 72 MWh_{th} can be discharged from a storage where 20% of the molten salt is replaced by PCM.

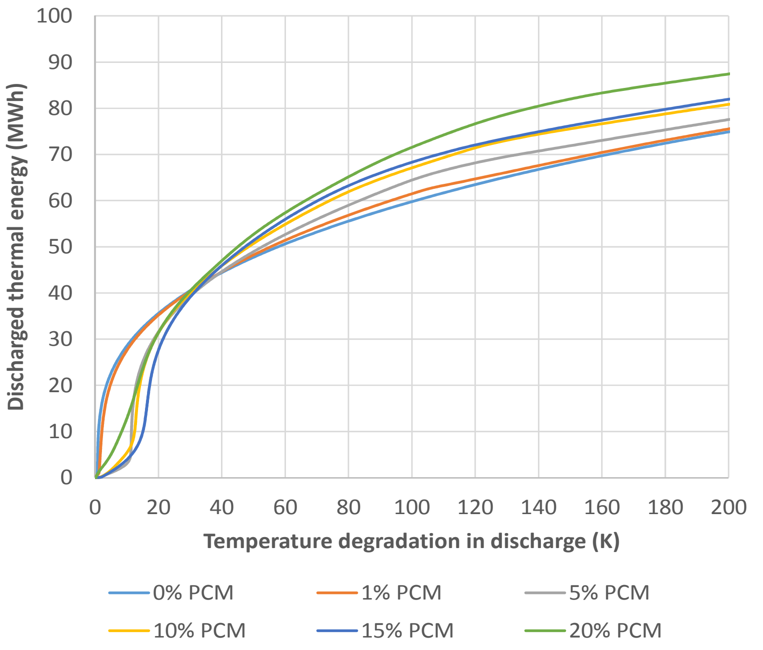

FIGURE 4. TES discharged thermal energy as a function of the outlet temperature degradation for different amounts of PCM, for a 90 MWh_{th} storage tank

OUTLOOK

This numerical study shows that a combined sensible-latent molten salt thermocline concept with AlSi as PCM material can slow down the outlet temperature degradation during discharge and increase the storage capacity compared to a sensible only thermocline TES with the same tank volume.

However, compatibility issues between AlSi and molten salts may raise safety concerns. Indeed, contact between molten aluminum and nitrates or other oxidizers may cause an explosion. To mitigate this risk, the following options may be considered:

- to decrease the leakage risk of AlSi capsules within the salt through an innovative TES design,
- to change the PCM: back-up solutions have been identified, but with lower thermal performances,
- to use the PCM in alternative regenerative-type TES with gas as heat transfer fluid instead of nitrate salts.

This simulation model of the PCM storage will be further validated with tests results from IN-POWER partners. It will be used to design and size high temperature thermocline storage for commercial scale CSP plants. Parametric studies will be performed to optimize tank geometry and operating strategies. Through this work, we will develop a cost-performance model to determine the unit cost of storage capacity (€/kWh) for a given operating temperature range and storage materials combination. This techno-economic model will allow to determine the optimal PCM fraction for this combined sensible-latent TES system.

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