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Experimental Results from a Pilot Scale Latent Heat Thermal Energy Storage for DSG Power Plants – Advanced Operating Strategies

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Abstract. Since 2013, CEA has been operating a pilot scale high pressure water-steam facility called LHASSA designed to test latent thermal energy storage modules under operating conditions similar to commercial Direct Steam Generation CSP plants. A Phase Change Material (PCM) storage module connected to this facility is composed of aluminum finned steel tubes immerged into sodium nitrate and surrounded by aluminum inserts for heat transfer enhancement. This paper presents the results obtained from the third test campaign on this storage module, consisting in 25 charge-discharge cycles under a wide range of operating conditions (fixed of sliding pressure, complete and partial charge levels…). Thermal performances of the storage test section show a very good repeatability, without any performance degradation compared to the previous test campaigns. Some new operating strategies were successfully tested (charge interruption simulating a cloud transient in the solar field, discharge with fixed pressure and varying mass flows, charge-discharge transition management).

CONTEXT AND OBJECTIVES

To date, there is no commercial solution for large capacity storage systems adapted to Direct Steam Generation solar (DSG) plants. Steam accumulators are widely used but this technology has rather low density and becomes expensive when large capacities are needed [1,2]. Storage technologies using Phase-Change Materials (PCM) are an interesting option as thermal storage systems for DSG plants, as they allow to minimize the steam pressure drop between charge and discharge. The most mature PCM storage technology to date is the shell-and-tube concept, in which the Heat Transfer Fluid (HTF) flows in tubes that go through a tank filled with PCM. Several prototype shell-and-tube modules for steam storage have been built and studied by various groups [3-5]. At CEA Grenoble a shell-and-tubes storage with sodium nitrate as Phase Change Material was connected to the LHASSA testing facility in 2013. Sodium nitrate shows good thermal properties as a PCM but it has a poor thermal conductivity, that is why we had to use fins and inserts to enhance heat transfer on PCM side.

This new test campaign, performed in the framework of the InPower H2020 research project, has a double objective. The first objective, which is also one of the main goals of the InPower project, is to test the durability of PCM storage systems in order to demonstrate that their lifetime can be over 25 years. Most of the latent heat storage prototypes are operated during a few months and then abandoned or dismantled, but with this one we have several years of experience feedback. It is a great opportunity to study the durability of such systems and to improve their operating strategies. The second objective is to investigate advanced operating strategies, such as fixed pressure or modified-sliding pressure operation, or also cloud transients simulation, with the generic purpose of automating the control of the facility. Most of the PCM steam storage prototypes were tested in sliding pressure mode. However, fixed pressure operation or modified-sliding operation can ease the storage integration, by allowing acceptable conditions at turbine inlet all along the discharge process [6]. The present work reports and discusses PCM storage tests with advanced operating strategies, in particular steam discharge at constant power in fixed pressure mode.

DESCRIPTION OF THE TEST FACILITY AND TEST SECTION

CEA has built a pilot scale high pressure water-steam facility called LHASSA (145bar, 350°C), in order to validate at pilot scale the thermo-hydraulic behavior of thermal energy storage modules under operating conditions similar to commercial DSG CSP plants. The PCM storage module connected to this facility is composed of aluminum finned steel tubes immerged into $NaNO_3$ salt (300 kWh_{th}, 6.3 tons, melting temperature of 306°C) and surrounded by aluminum inserts for heat transfer enhancement (see Fig. 1). This test section is highly instrumented: the PCM temperature is measured around 25 tubes at seven locations along the module height, and at three radial positions around the tubes. Water-steam pressure, temperature, mass flow and steam quality are also measured at the inlet and outlet of the test section.

During the charging process of the storage module, steam slightly above saturation is sent from the top to the exchanger tubes where it condenses causing the melting of the PCM. Liquid water level in the storage module is either kept constant and low in sliding pressure mode so that steam could condense all over the tubes height, or moves downwards in fixed pressure mode. Inversely, during the discharging process, liquid PCM solidifies and causes the evaporation of the liquid water coming from the bottom of the test section within the exchanger tubes. In this case, the liquid water level in the storage tubes is either kept constant and high in sliding pressure mode to maintain nearly uniform temperatures all over the module height, or moves upwards in fixed pressure mode.

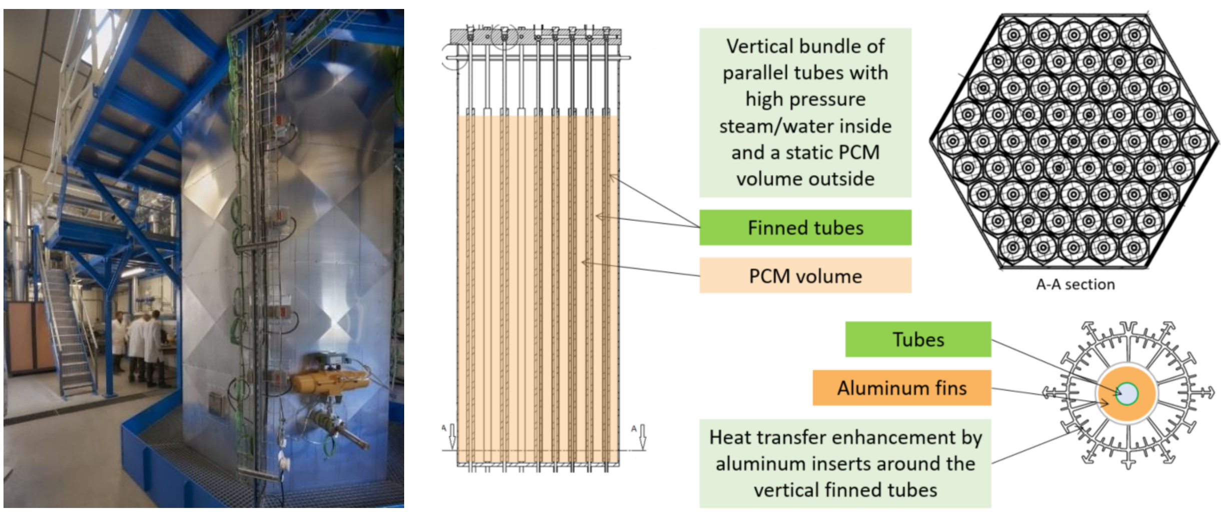


FIGURE 1. Picture (left) and schematic (right) of the PCM module tested during the IN-POWER project

LHASSA facility was operated during 225 days from 2013 to 2015 [5, 7] and then started again in 2019 for the IN-POWER H2020 project with the same test section and the same PCM, after passing a regulatory periodic inspection of the test section and pressurizer consisting in endoscopic visits and wall thickness measurements. Instruments (mass flowmeters, pressure sensors) were calibrated and leakage tests were done. The test campaign started in September 2019, 25 charge-discharge cycles have been performed, exploring a wide range of operating conditions (fixed of sliding pressure, complete and partial charge levels…).

RESULTS FROM THE 2019 TEST CAMPAIGN

Durability Analysis

Thermal performances of the storage test section show a very good repeatability, without any performance degradation compared to the previous test campaigns. To check it, the same test conditions were repeated several times during the three campaigns. Figure 2 shows some of the main storage variables (steam pressure, mean PCM pressure, and liquid water level in the tubes) during a complete charge and discharge cycle in nominal conditions tested in the first campaign in 2013 (C1) and repeated during the third campaign in 2019 (C3). These tests last 17 hours and involve two shifts of two operators each. The facility is operated at design power (50 kW_{th}) in charge and in discharge.

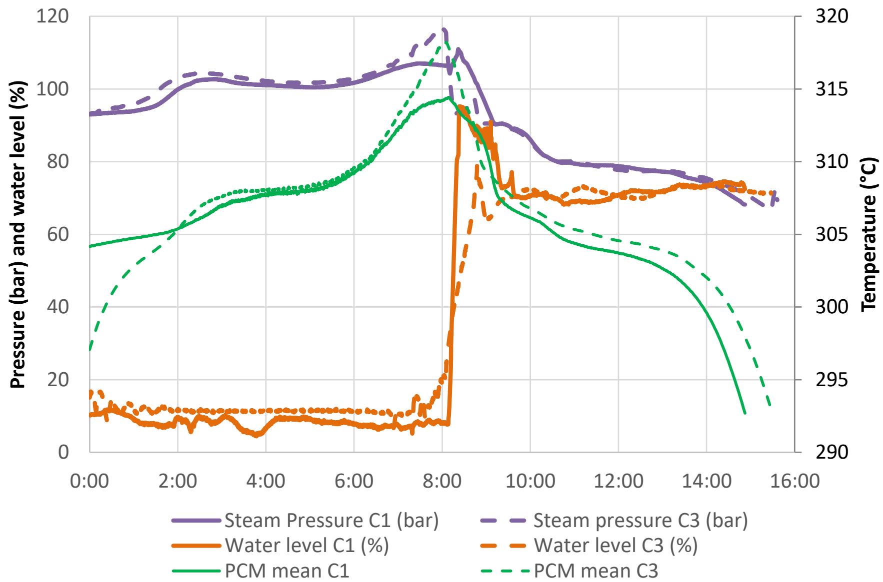


FIGURE 2. Steam pressure (in purple), liquid water level in the tubes (in orange), and average PCM temperature (in green) during a complete charge and discharge cycle in nominal conditions: results from the first campaign (C1) in continuous lines, results from the latest campaign (C3) in dotted lines

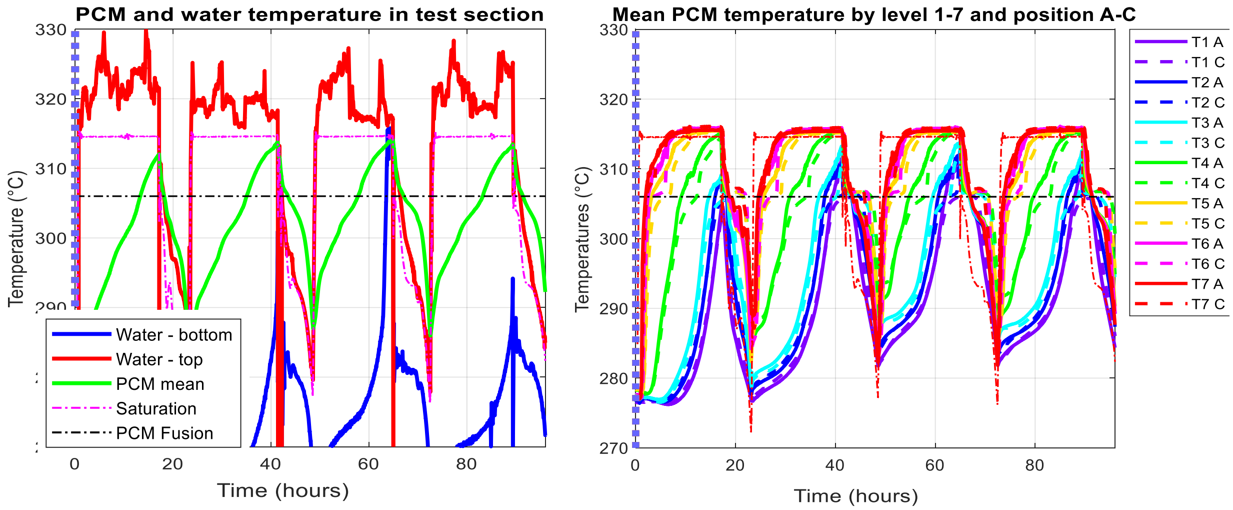
Very similar performances were obtained, as it can be observed in Fig.2 representing the pressure (in purple), the liquid water level in the tubes (in orange), and the average PCM temperature (in green): curves in dotted lines, from the latest campaign (C3), are close to the curves in continuous lines from the first campaign (C1), specially pressure variations. Some slight differences can be seen in the mean PCM temperature variations, they can be mainly attributed to the fact that the initial temperature of the storage module was lower in C3 and that the steam mass flow was not constant in charge in C1. The charged and discharged energy can be estimated from enthalpy balances on HTF flows at the inlet and outlet of the storage module, the end of discharge being defined by a steam pressure minimum threshold (68 bars in the first case and 75 bars in the second case). Steam outlet enthalpy in discharge is assessed thanks to an energy balance at the boundaries of the condenser. From these data storage efficiencies can be calculated, leading to very similar results for both test campaigns, as shown in Table 1 below.

TABLE 1. Comparison of the thermal performances of the storage module from two reference tests from 2013 and 2019

(End of discharge criterion)	**2013 test campaign**	**2019 test campaign**
Charged Energy	325 kWh_{th}	374 kWh_{th}
(Final steam pressure: 68.5 bars)		
Discharged energy	306 kWh_{th}	342 kWh_{th}
Storage efficiency	94%	92%
(Final steam pressure: 75 bars)		
Discharged energy	249 kWh_{th}	284 kWh_{th}
Storage efficiency	76%	76%

Semi-automated control was also considered, by operating various consecutive charge-discharge cycles: the storage was charged during night (without any human presence) at fixed pressure with a reduced thermal power

(25 kW_{th}), and discharged during the day, in sliding pressure mode at design thermal power (50 kW_{th}). Here again the four cycles show very reproducible results, as shown on Fig. 3. As expected, in charge at fixed pressure PCM temperatures are stratified along the tank height, while in discharge in sliding pressure mode PCM temperatures are much more uniform.



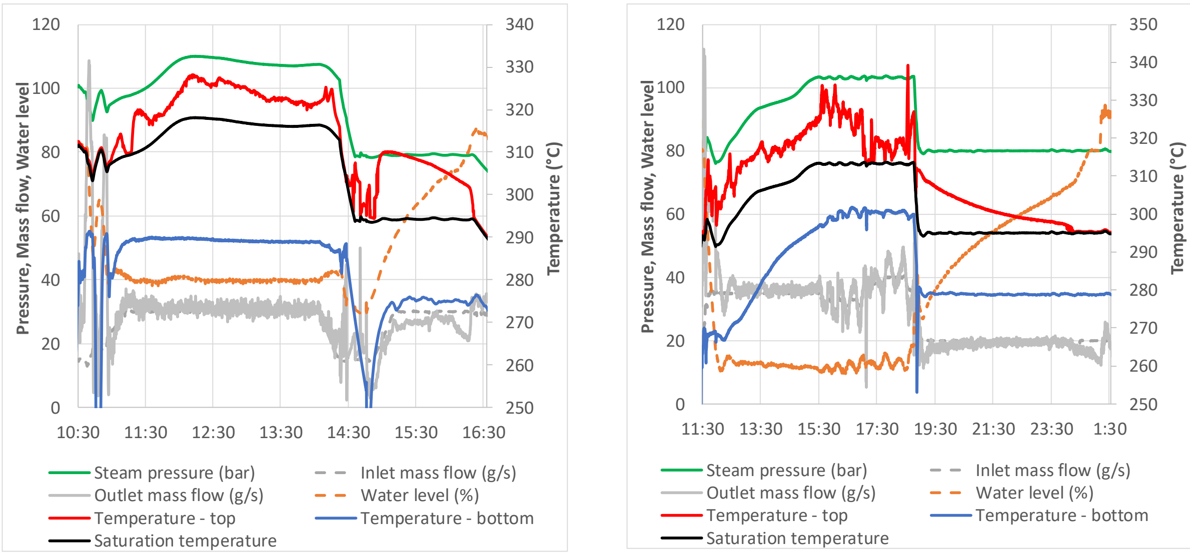
(a) (b)

FIGURE 3. (a) Mean PCM and water temperatures at different locations, and (b) level-averaged PCM temperatures (T1 indicating the bottom of the tank and T7 indicating the top of the tank) during four consecutive complete charge and discharge cycles

Advanced Operating Strategies

Some new operating strategies were successfully tested (charge interruption simulating a cloud transient in the solar field, discharge with fixed pressure and varying mass flows, charge-discharge transition management). Some experimental test results from two charging-discharging cycles with steam discharge at fixed pressure are shown in Fig. 4. In such tests, the objective is to produce a stable steam mass flow (and thus constant thermal power) at constant pressure. This is achieved by gradually increasing the liquid water level in the storage tubes to increase the heat exchange surface where evaporation occurs. Figure 4a presents a partial storage cycle with sliding pressure in charge (from 11 AM to 2:15 PM) and an outlet steam pressure controlled at 80 bars in discharge (from 2:30 PM to 4:30PM). Liquid water level in the storage tubes is controlled at 40% in charge and increases from about 30% to 90% during discharge. Figure 4b shows a complete storage cycle, that is to say that all the PCM active volume is melted in charge and solidified in discharge. An advanced pressure control was tested in charge: in sliding mode from 11:30 AM to 3:30 PM, and then fixed at 102 bars from 3:30 PM to 6:45 PM. Outlet steam pressure is controlled at 80 bars in discharge with a reduced mass flow. Liquid water level in the storage tubes increases from about 15% to 100% during discharge.

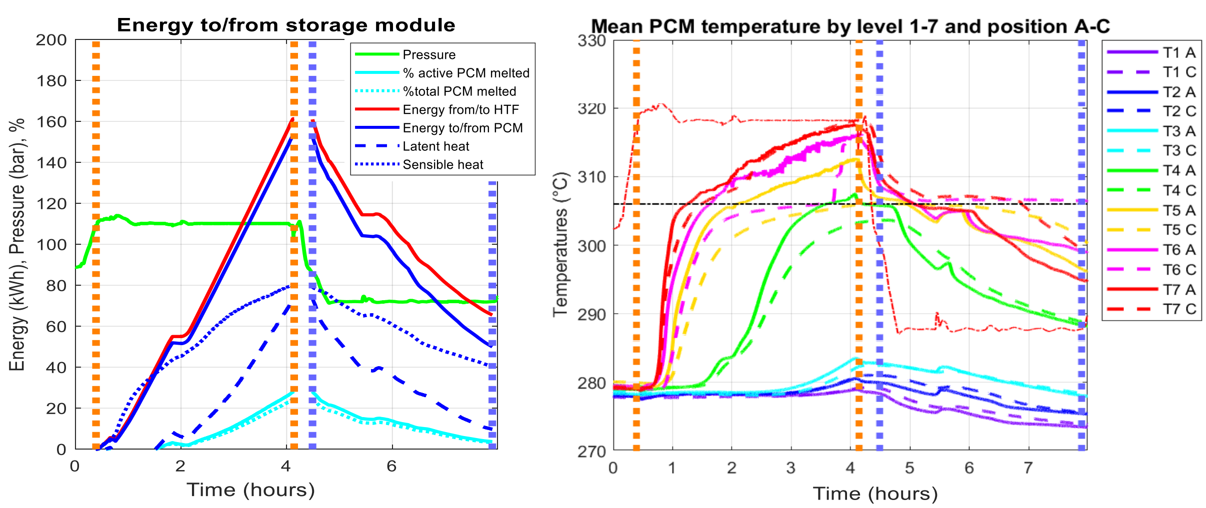
Such steam discharges at constant pressure and constant mass flow could be beneficial for the steam user, in particular for steam turbines or steam networks designed to operate in stable conditions. Other hybrid control strategies like sliding-then-fixed pressure were also successfully tested.



(a) (b)

FIGURE 4. Pressure, mass flow, liquid level, and temperatures on water-steam side in the PCM storage section a) During a partial storage cycle (on September 16th); b) During a complete storage cycle (on December 3rd)

Another control objective was to test the storage system behavior during a cloud transient: therefore, it was simulated by stopping temporarily the steam flow during the charge process. Similarly, the steam production was stopped during discharge to see how the storage behaves when the steam consumption is temporarily off. Such flow stops last about 30 minutes each; they can be observed in Fig.5 two hours after the beginning of the test in charge, and about five hours and 30 minutes after the beginning of the test in discharge. Figure 5a shows energy balances of the storage system, and Fig. 5b shows the PCM temperatures at different altitudes. In both charge and discharge, no control difficulties were encountered and the thermal performances were not altered.



(a) (b)

FIGURE 5. (a) Stored energy, PCM melted mass fraction and water pressure, and (b) level-averaged PCM temperatures (T1 indicating the bottom of the tank and T7 indicating the top of the tank) during a partial storage cycle with 30-minute flow stops in charge and in discharge. Charging periods are represented between dashed orange lines, and discharging period are represented between dashed blue lines.

CONCLUSIONS AND PERSPECTIVES

To conclude, this new test campaign gave encouraging results on the durability of such PCM storage systems, as no signs of degradation of the storage performances were observed after 6 years and 80 charge-discharge cycles. Nevertheless, more data is still needed to better estimate the lifetime of such technologies. That is why a dedicated new facility called DURASSEL has been built and commissioned to study the corrosion of pressurized finned tubed submerged in sodium nitrate, with the objective to analyze tube samples after hundreds of melting and solidification cycles. This facility will allow to better understand the corrosion mechanisms, thanks to microstructural analyses of tubes and fins, PCM analyses by Inductively Coupled Plasma (ICP) and calorimetry measurement, and a monitoring of the gas composition above the PCM under air or nitrogen.

Moreover, this test campaign allowed us to investigate advanced control strategies, to improve the procedures towards automated tests, and to gather new experimental data to validate our dynamic models. Finally, repeated tests proved that steam can be discharged at constant pressure and at constant mass flow during more than five hours.

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