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Experimental analysis of heat transfer in passive latent heat thermal energy storage systems for CSP plants

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Abstract

Thermal energy storage is a key factor for efficiency, dispatchability and economic sustainability of concentrated solar plants. The latent heat storage systems could ensure a significant reduction in construction costs and environmental impact, because of its high storage energy density. In LHTES, the heat transfer between the heat transfer fluid and the storage system is strongly limited by the reduced thermal conductivity of the storage media. For operating temperatures between 200 and 600°C, the most used storage media are salts. In order to evaluate solutions which promote the thermal conductivity, by increasing the exchange surface and/or the addition of nanoparticles to the storage media, Enea set up a small facility to test some storage concepts. In this facility, a diathermic oil flows through three elementary "shell-and-tube" storage systems, connected in series, reaching a maximum temperature of about 280°C. The elementary storage systems are filled with a mixture of sodium and potassium nitrates salts, which melt at about 225°C. Moreover a small percentage of alumina and silica nanoparticles were added to this mixture. The results of the experiments show an increase of the thermal diffusivity of the medium not only for the presence of fins on the heat transfer tubes but also because of convective flows within the melted fraction were established. These phenomena strongly reduce the charging times of the system (by about 30%). Instead, the presence of nanoparticles increases the thermal capacity and the thermal conductivity of the storage system but seems not to have a relevant effect on the thermal diffusivity of the mixture. This behavior depends on the type of used nanoparticles, which can significantly change over time some characteristics of the storage medium, in which they are dispersed, leaving other characteristics unchanged, according to mechanisms which are still to be well understood.

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Keywords: Thermal storage; Heat transfer; Phase change material; Nanoparticles

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1. Introduction

CSP plants can give, in a medium-term perspective, a significant contribution to the development of a sustainable electricity production, through their construction in favorable areas. They use concentrators to

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collect direct solar radiation onto a solar receiver, where it is absorbed, converted into heat at a high temperature and transferred to the application by means of a HTF. Solar energy may be employed both in thermal cycles for the production of electrical energy as well as to process heat in various industrial installations[1].

Nomenclature

ATES	Advanced Thermal Energy Storage	LHTES	Latent Heat Termal Energy Storage
CSP	Concentrated Solar Power	NFPCM	NanoFluid Phase Change Material
c_p	Heat capacity	TES	Thermal Energy Storage
HSM	Heat Storage Medium	α	Thermal diffusivity
HTF	Heat Transfer Fluid	k	Thermal conductivity
LEC	Levelized Energy Cost	ρ	Density

The main objective of the research on CSP systems is the reduction of the LEC, making large and small size CSP plants more and more competitive with traditional power plants supplied by fossil fuels. This objective is, as clearly shown in the DOE "Sunshot Initiative", to reach the 6 cent/kWh$_e$ before 2020, starting from the actual 21 cent/kWh$_e$ (2010), with a cost similar to no-renewable power production systems. A key technological issue is to integrate CSP plants with low cost TES systems [2]-[4] in order to increase the solar contribution and improve efficiency and operation hours. LHTES using PCMs have been gaining importance in such fields as solar energy storage systems ([5]-[6]). This is mainly due to their higher energy storage density and their ability to supply heat at a constant temperature ([6]-[9]). So far, molten salt mixtures have been identified as the best and least expensive media to store latent heat at high temperatures. A LHTES system has the following three main features: (i) a PCM suitable for the desired temperature range; (ii) a container for the PCM; (iii) a heat transfer surface required for transferring the heat from heat source to PCM and from PCM to the heat sink. The main technological problem for LHTES systems at high temperature is the insufficient thermal conductivity of the available PCMs: the most suitable materials provide a conductivity of 0.5-1 W/(mK). Therefore, the design of the heat exchanger must consider the most effective solutions to increase the thermal conductivity inside the storage material. The objective of the present work is to study the heat transfer characteristics in a basic latent heat thermal storage system for CSP plants operating at medium temperature (200-250°C), through experimental tests conducted on elementary LHTES systems with different phase change materials.

Table 1. Thermo-physical properties of the storage media

Property	Units	PCM	NFPCM
Density	kg/m^3	1850	1850
Heat capacity	J/kg.°C	1700	2000
Thermal Conductivity	W/m.°C	0.70	0.9
Melting Temperature	°C	225	222
Latent Heat	kJ/kg	110	127

2. Thermal Energy Storage Materials

To perform the present evaluation, two kinds of storage materials have been selected. The first one was a binary eutectic salt ($NaNO_3$-KNO_3 60-40%wt, solar salts) PCM with a melting temperature of about 225°C. The second one was a NFPCM composed by the previous solar salts doped with a small quantity (1%wt) of nanoparticles (20-200nm) of SiO_2-Al_2O_3, to improve its thermo-physical properties[9]. In general, a nanofluid has: i) a significant increase of thermal conductivity and heat capacity; ii) a more efficient heat transfer (thermal effusivity: $(k\rho c_p)^{1\backslash 2}$); iii) a high sedimentation stability, due to the limited size and weight; iv) a negligible erosion of the duct surfaces. Table 1 shows the main characteristics of the PCMs.

3. Experimental Apparatus

In this work, in order to start a cognitive survey of the phenomena involved and evaluate the related advantages and problems, we took into consideration the conventional "shell and tube" configuration, in which the HTF (diathermic oil) flowed into the tube and the selected PCM was in the shell. Two tube configurations were realized: a finned one with the central tube (Fig. 1) equipped with a metallic fin system to increase the conductivity, and a plain one, with the aim to analyze the heat transfer in absence of these fins. AISI 316L steel was used for tubes, fins and vessels and 100mm rock wool for the thermal insulation of the system.

(a) (b) (c)

Fig. 1. LHTES shell and tube configuration: (a) finned tube; (b) elementary systems; c) complete systems

Before starting the experimental tests, all the LHTES were weighed both empty and full of PCM or of NFPCM in order to evaluate the amount of storage medium loaded in the system. About 3 kg of PCM were loaded in each elementary TES in the case of the plain tube. Slightly less, 2.9 kg in the case of the finned tube configuration were loaded. A complete LHTES element weighted about 15 kg.

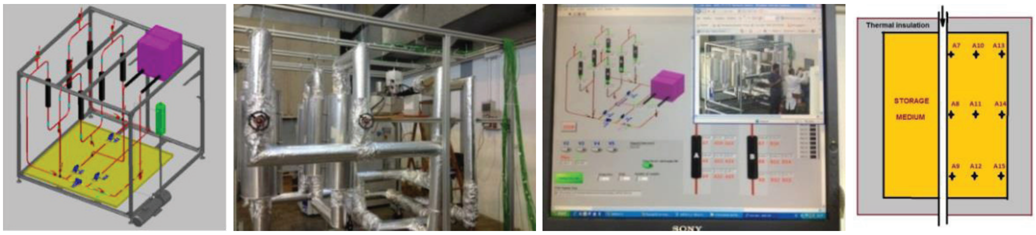


Fig. 2. ATES plant: block diagram, view, control panel for checking and ATES control and positioning of thermocouples

A new test section, named ATES was designed and created to perform the experimental tests on the developed LHTES systems. Fig. 2 shows the plant suspended from a metallic frame by means of some tie rods. This option makes it easier for thermal expansions due to the high operating temperature.

The plant consisted of a thermal storage, a circulation system and a heating/cooling equipment. Twelve storage vessels (heat accumulators) were created to host the PCM and to allow it to heat and cool by the thermal oil flowing into the tube. Six of them were filled with the conventional solar salt and the others with the same mixture but including 1%wt of nanoparticles. Because of the necessity to reduce the circuit pressure drops and allow, at the same time, a turbulent flow also using the integrated pump of the thermal circulator, only 6 of these accumulators, filled with the same material, were installed in the plant.

Nevertheless, they were arranged in two rows with the possibility to use them alternatively by proper valves. The accumulators of each row differed for being supplied with plain or finned tubes. In order to test different mixtures the previous accumulators were mechanically substituted with the other six. In this way, it was also possible to avoid long no-operative time due to the draining, cleaning and filling of the same accumulators. Table 2 summarizes the sizes of this equipment.

Table 2. some plant characteristics

vessel			**tube**		
diameter	70	mm	diameter	14	mm
length	700	mm	thickness	1	mm
thickness	3	mm	PCM shell thickness	27	mm
insulation thickness	100	mm	**conductivity**		
kind of insulation	rock wool		steel	20	W/m/K
storage length	1.5 or 3	m	PCM	0.5	W/m/K
heat transfer coefficients			insulation	0.04	W/m/K
thermal oil	662-995	$W/m^2/K$			
air	5	$W/m^2/K$			

The heat exchange coefficient was assessed through the Sidis-Tate formula [11] considering the Reynolds, Prandtl and Nusselt numbers from 160 to 280°C and considering an internal speed of the thermal oil of about 1 m/s (≈ 9 l/m). Since Reynolds number in the considered temperature range was always superior then 10000, it was possible to assume the turbulence of the flow, which made easier the temperature collection by the thermocouples. The circulation system was made of AISI 316L-DN16 tubes, and included a flow-meter able to send data remotely, 7 on/off valves for the vents, drains and tucks and 1 manual control valve to manage the oil speed. In addition, this system had 4 electro-valves, which could also be controlled remotely by LabView®. On the remote display it was possible to see and log all the data related to the temperatures and flows. The oil heating and cooling was ensured by the thermo-cryostat Julabo® HT30M1CU. It had a heating power of 3 kW and a cooling power up to 15 kW and included an expansion tank of 2 l. The oil handling system foresaw the possibility of 3 different kinds of circulation: clockwise, preferable for the charge phase; counter-clockwise, for the discharge step and the by-pass of the accumulators. Therminol66® was the oil chosen as thermal fluid for its non-toxicity, auto-ignition temperature (< 370°C) and low vapor pressure (e.g.: 0.3 bar at 300°C). In order to detect the temperatures inside the PCM and during the thermal fluid path, 32 thermocouples were installed: 9 inside the first accumulator of each series, 14 along the piping, 1 for the external temperature of one accumulator, and 1 for room temperature (Fig. 2). Four kinds of tests were carried out: PCM with plain (Test 1) or finned (Test 2) tubes, NFPCM with plain (Test 3) or finned (Test 4) tubes; each test was repeated 2 or 3 times to verify the repeatability of the results. During these ones, the oil temperature followed the trend shown in Fig. 3. Four distinct phases could be clearly identified: the heating phase from room temperature to 200°C, the system charging phase up to 280°C, the system discharging phase up to 150°C and finally the cooling phase. In each phase the target temperature was maintained constant for a long time to reach a quasi-stationary regime in order to evaluate the related energy losses.

4. Results and discussion

4.1. Temperatures

The HTF temperatures was measured both at entry and exit of each section of the tested storage system. They closely follow the trend of the thermo-cryostat setting temperature. At the entrance of the storage section (A1) the oil temperature was about 5°C lower than the target, due to the heat losses along the path. The exit temperature of the storage section (A6) was very close to the input one: in fact, the thermal drop was about 1-2°C with a maximum of 3°C at the start of the TES system charging phase. In Fig. 4 the temperature evolution for the test 1 is shown. The other tests showed an identical trend. The HSM temperature was measured in the first of the three TES constituting a storage assembly, in 9 points, on three sections (upper, medium, lower) and three radial positions (internal, medium, external) as displayed in Fig. 2. The temperature evolutions in the middle section are shown in Fig. 5.

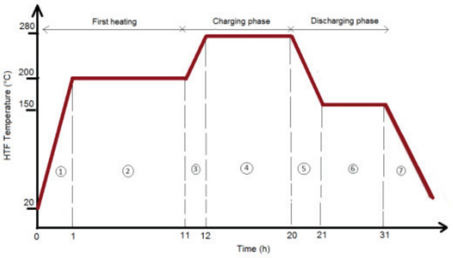


Fig. 3. HTF temperature evolution during a single test

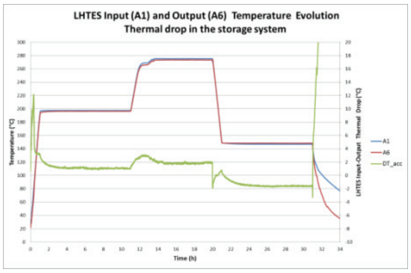
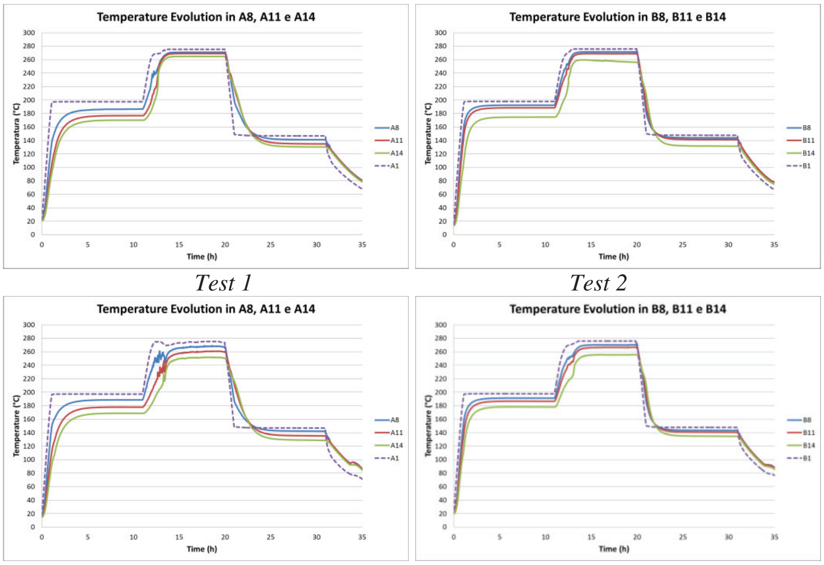


Fig. 4. HTF temperature evolution during Test 1



Test 1

Test 2

Test 3

Test 4

Fig. 5. HSM temperatures evolution in the middle section of the first TES

4.2. Energy Balance

From the measurements of the fluid flow rate and its temperature drop, it was possible to evaluate the thermal power absorbed by the TES:

$$P_{TES} = \dot{m} c_{p,HTF} \left(T_{A1} - T_{A6} \right) \tag{1}$$

During the evolution of the absorbed power through the charging and discharging phases of the TES system, after a first peak, the absorbed power decreased, reaching a steady state value: this value represented the heat loss towards the environment at the reference temperature of the storage system,

P_{LOSS}. If these losses were removed from the absorbed power, the useful power to the TES was obtained:

$$P_{USE} = P_{TES} - P_{LOSS} \tag{2}$$

Its integral over time was the stored energy for each phase (Q_{charge} e $Q_{discharge}$). In table 3 the summary of these energy evaluations, together with the temperature and the charging and discharging time, is shown. During these phases, the complete melting and solidification of the HSM occurred. Taking into account the amount of HSM in the storage system was about 9 kg, the latent heat was respectively about 275Wh for the PCM and 310Wh for the NFPCM. The data processing was done as specified in [10].

Table 3. Summary of results for charging and discharging phases

TES system data	Units	*Charging phase*				*Discharging phase*			
		Test #				Test #			
		1	2	3	4	1	2	3	4
Temperature	°C	280	280	280	280	150	150	150	150
Charing/Discharging time	h	4	3.5	6	4	6	4	7	4
Lost power	W	705	517	536	678	537	444	491	250
Charged/Discharged energy	Wh	922	1260	683	803	1268	1144	1091	1202

4.3. Discussion

The analysis of the experimental results leads to the following considerations:

- In the PCM, the low thermal conductivity and thus diffusivity ($\alpha=k^*(\rho^*cp)^{-1}$) is compensated, in the liquid phase and if there is absence of physical limitations (plain tubes), by the start of convective flows that facilitate the heat transfer, as shown by the reduced charging time and by the comparison of the temperatures evolution.
- In the NFPCM, despite a substantial invariance of the thermal diffusivity, the thermal capacity (15-20%) and the thermal effusivity are increased. However, the charging phase is slower (6 hours, +30%) manifesting a purely conductive behavior also in the liquid phase. This is probably due to the increased viscosity of the HSM, which hinders the start of convective flows;
- The use of finned tubes highlights the promotion of the thermal conductivity. The charging and discharging times appear more content (-30%) and substantially independent from the storage medium;
- The charging phase test, with the plain tube and PCM, shows times comparable to those of the TES with finned tubes. In this case, the heat transfer is mainly convective and has effects similar to those when fins are present;
- In the TES system with NFPCM and finned tubes, the greater heat capacity, coupled with the lower discharge times, allows the system to deliver a higher average project power (about 30%).

5. Conclusion

The thermal behavior of a "shell and tube" LHTES system was analyzed, both by increasing the exchange surface (fins) and by changing the thermal properties of the PCM (addition of nanoparticles, NFPCM), by means of experimental tests conducted on a dedicated facility (ATES). As expected the tests show the relevant effect of the exchange surface increase on the promotion of the PCM conductivity. However, the use of NFPCM, while improving the heat transfer towards the outside (thermal effusivity) and the storage capacity, does not show advantages in terms of thermal diffusivity. Indeed, the charging time of the system appears to be similar in the case of finned tubes and even more so if the tubes are plain. The last data is actually influenced by a physical phenomenon with amazing effects. Testing a TES with a plain tube and simple solar salts such as PCM, under the employed test conditions, we noted, comparing the temperature evolution and the charging times, the beginning of convection flows within the melted fraction. These flows have largely improved the thermal exchange and the heat transport of the medium. Their effect is found to be comparable, if not superior, to that exercised by the fins. This phenomenon could be explained also by the Agyenim observations, in fact he claims [12]: "*Phase change problems, first treated as pure conduction controlled, has in recent times moved to a different level of complexity with added convection in the melt being accounted for*". Said convective flows, however, are not found in the NFPCM because, probably, the presence of nanoparticles significantly increases the viscosity of the fluid and inhibits the starting of the flows. In the future, in order to exploit the phenomena highlighted here and to design a more compact and efficient TES system, it will be necessary to perform tests on a large-scale prototype.

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