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New concentrating solar power facility for testing high temperature concrete thermal energy storage

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Abstract

Several thermal energy storage (TES) systems have been developed and tested to be integrated in concentrating solar power (CSP) systems. Recent studies show that concrete as storage media has the potential to become an interesting solution due to its properties such as relatively high specific heat and thermal conductivity, good mechanical properties, a thermal expansion coefficient similar to that of steel pipe and low cost of a material that is easy to obtain and process. This article outlines a new 100 kW_{th} solar beam-down facility for testing high temperature concrete storage at 393 °C and the first project to use the facility for TES testing in collaboration with NEST. Initial concrete characterization and testing results which show promising thermal and mechanical performance, are also presented. The CSP hot oil-loop has been modified and instrumented to perform research and testing of TES systems in real solar radiation conditions. Experimental TES system testing at real scale with a total storage capacity of 1.0 MWh_{th} is planned to begin operation early 2015.

Keywords: Concentrating solar power (CSP), Beam down facility, Thermal energy storage, Concrete, Sensible heat,

1. Introduction

Energy production by renewable sources (wind, solar, etc.) is still not sufficiently developed to respond to the energy demand especially at peak times [1]. Moreover almost all these renewable energies are weather-dependent which leads to an unpredictable electricity production and grid issues. In concentrating solar power (CSP) field, thermal energy storage (TES) systems have the virtue of giving a better use of thermal energy in expanding electricity production time as well as minimizing the difference between supply and demand of energy [2, 3]. One of the main benefits of TES is the reduction or elimination of fluctuating energy generation, which allow the production of energy under more stable conditions. Also, the residual energy from low demand periods can be used to charge a TES, in order to have backup energy for high-demand periods and periods of low solar availability [4].

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For storage media, different kinds of materials have been studied and tested in different TES technologies [5]. Concerning sensible heat storage, liquid media (e.g. molten salts, mineral oils, synthetic oils) or solid media (e.g. ceramic, sand/rock bed, or high temperature concrete) can be used [6]. Concrete is a promising candidate as it has a low cost and is easy to obtain and process directly on site. Also, it is a material with relatively high specific heat, good mechanical properties and a thermal expansion coefficient similar to that of steel [7].

Efforts have been centred on the characterisation of concrete as a solid media and some TES have been already tested for CSP applications. Deutsche Luftraum (DLR) Zentrum built and tested two storage units at the Plataforma Solar de Almeria (PSA) in Spain. The first one was using high temperature concrete and the second one a castable ceramic with storage capacities of 280 kWh_{th} and 350 kWh_{th} respectively [8]. Then, DLR and Ed. Züblin AG implemented in Stuttgart (Germany) a second test module of 474 kWh storage capacity [9, 10]. This module which was using a new concrete mixture with polyethylene fibers was operated between 300 °C and 400 °C and has accumulated more than 370 thermal cycles (from May 2008 to December 2010). The Department of Civil Engineering of the University of Arkansas (UA) evaluated the concrete's performances and worked to develop a concrete to be used as a TES medium as well [11]. The use of concrete as TES presents challenges: the concrete long term durability after thermal cycling, the reduction of cost for the exchanger and partial charge/discharge issues. Some characteristics of the material have to be improved such as reduction of potential cracks and a better thermal conductivity for enhanced heat transfer.

The NEST A.S. Company has been developing an effective high-temperature TES system using concrete as solid media. This innovative concrete mixture developed in collaboration with Heidelberg patented and, commercially called Heatcrete®, is under test for a variety of conditions and properties [12].

The purpose of this paper is to present the ongoing work for testing the NEST TES system at high temperature up to 393°C for parabolic trough applications. The 1.0 MWh Nest storage pilot is currently under construction at the Masdar Institute Solar Platform (MISP) in Abu Dhabi, United Arab Emirates. The CSP facility that will be used for these tests is a concentrated solar beam down optical experiment (BDOE) which was inaugurated in a first phase in 2011 for optical efficiency testing [13]. Currently this facility is under modifications, especially the hot-oil loop, to accommodate, integrate and test different TES systems by producing hot oil at 393 °C exactly as in parabolic trough CSP plants.

2. Concrete material characterization

2.1. Thermal storage capability

The performance of a TES system depends strongly on the material's thermal properties. In an effort to evaluate the thermal properties of concrete at high temperature the UA conducted some tests on different concrete mixtures [14]. DLR improved the design of its high temperature concrete, as well as the thermal properties [10]. From the research already done by UA, DLR and NEST some comparisons can be made between the different concrete mixtures as shown in Table 1. Compared with the different types of concretes (even if the measurements were not made at the same temperature), it can be seen that NEST's mixture presents promising properties. First, a higher thermal conductivity determines the dynamics of operation by increasing the rate of the charging and discharging phases. Together, higher heat capacity and higher density reduce the volume required for a given storage capacity. These are key features since they determines the efficiency of the system as well as its final cost.

Table 1. Material properties of three different concrete mixtures: DLR concrete [8], UA concrete [11], Heatcrete® [12]

Material properties	DLR concrete[1]	UA concrete[2]	Heatcrete®[3]
Density (kg/m^3)	2250	2278	2364
Specific heat capacity (kWh/m^3 K)	0.66	0.61	0.75
Thermal conductivity (W/m K)	1.2	2.16	2.2
Crack initiation	Several cracks	Micro-cracks	No visible cracks

[1]Data obtained at 400 °C; [2]Data obtained at room temperature °C, average values obtained from 26 samples; [3]Data obtained at 340 °C

2.2. Mechanical properties

The mechanical characteristics such as the thermal stability and durability over the working temperature range are important criteria. Ordinary concrete, heated up to 400 °C, explodes violently due to the pressure generated by the superheated water vapor as it dissociates from the cementitious material ($CaCO_311H_2O$) [15]. Concrete has to be modified, with for example polypropylene fibres, to increase the permeability. Referring to the DLR and UA TES testing at high temperature some cracks appear in the concrete and thus decreasing the thermal performance in terms of effective thermal conductivity. Theses cracks could be due to the thermal expansion difference between the steel pipe heat exchanger and the concrete surrounding it or to steep temperature gradients within the concrete. The UA conducted compressive tests from the 26 samples and there was a reduction in the compressive strength from 31% to 84% after thermal cycles [14]. The abrupt reduction in compressive strength after heating the samples is due to local overpressure in the porous system and could damage the internal microstructure of the matrix. Since there is less interaction between the aggregates and the cement paste, the compressive strength is reduced dramatically.

In order to measure the thermal stability of the Heatcrete® material, thermal cycles were performed up to 400 °C on sample (mass=2.6 g) using a thermo gravimetric analysis (TGA) coupled to a Fourier transform infrared (FTIR) spectrometer. After thermal cycling, the sample presents no visual degradation, change of colour, neither crack. The TGA results show slight mass loss of 2.0 %, see Fig. 1. The bigger weight loss appears at the beginning of the tests during the first 40 min and is attributed to both leakage of water vapour trapped into the samples and thermal decomposition accompanied by release of carbon dioxide (according to the data obtained from the FTIR). After reaching and maintaining a temperature of 400 °C on every cycle, there is a small decrease in mass—a mass reduction which becomes progressively smaller over successive cycles. When cooling down the samples, the decrease in mass stabilizes until is heated again at 400 °C. Other thermal cycles have been performed with the same sample and the results show that we don't have more noteworthy loss of mass. This mass loss is insignificant and the Heatcrete® can be considered as stable up to 400 °C. Further studies on Heatcrete® should therefore investigate the effect of thermal cycles such as compressive strength tests.

Some high temperature testing on the storage modular elements were carried out by NEST and have confirmed that the concrete preserved its structural integrity without visible cracks and an excellent contact between HTF tubes and concrete, which gives a good indicator of its reliability during its operational lifetime [12]. During these tests the maximal temperature reached was 300 °C (limited heater capacity) by using air as HTF. These results will be compared to the real scale experiment under construction at Masdar Institute and operational at the beginning of 2015.

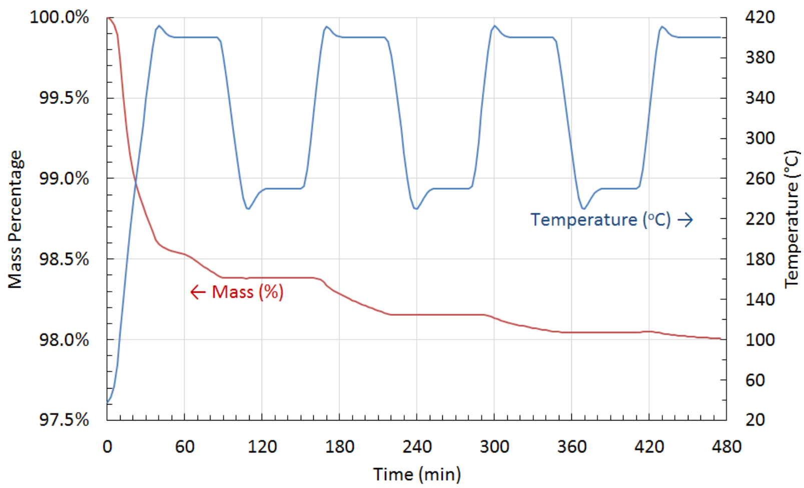


Fig. 1. TGA experimental results from Heatcrete® sample

3. Solar testing facility

3.1. Concentrated solar beam-down optical experiment

The research installation is composed of a heliostats field arranged in 3 rings surrounding the central tower. The sunlight is reflected from each heliostat toward secondary mirrors placed on the top of the tower, and is then reflected again to a solar receiver located at the bottom of the tower on the ground, see Fig. 2. The thermal energy is then collected in the solar receiver through a heat transfer fluid (HTF).

The main benefits of this kind of technology are to use a small tower and the solar receiver is located at ground level (easier construction, maintenance and operation) but due to the secondary mirrors the optical efficiency is lower that for a conventional tower system.

An analysis of the beam down optical experiment (BDOE) performance was carried out at two temperatures, 300 °C and 600 °C [13]. The results are shown for a daily average in Table 2.

(a) (b)

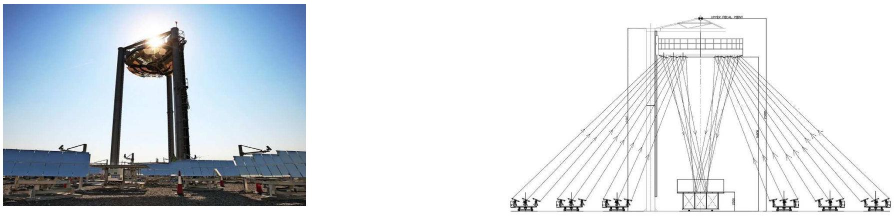


Fig. 2. (a) Experimental beam down facility; (b) Schematic illustration of the beam down solar concentration

Table 2. Masdar BDOE simulated performance results [13]

Operating Temperature	300 °C	600 °C
Optical efficiency (%)	32-37	32-37
Receiver efficiency (%)	71	68
Thermal plant efficiency (%)	28	24
HTF useful power (kW_{th})	105	89

The BDOE heliostat field comprises 33 ganged-type heliostats each of 8.5 m^2 reflector area representing a total area of 280 m^2. Heliostats are arranged in three circles surrounding the tower with a maximum distance from the origin (solar receiver) of 18 m.

Each heliostat is composed of 42 individual mirror facets arranged in three banks, Fig. 3. (a). The elevation and azimuth angles are calculated to track the sun and redirect the solar radiation toward the top of the tower at the focal point. A sunsensor focused on the central facet of each heliostat provides reflected ray feedback for heliostat pointing control in real time the position of the heliostat such that the image of the sun is always at the center of the mirror.

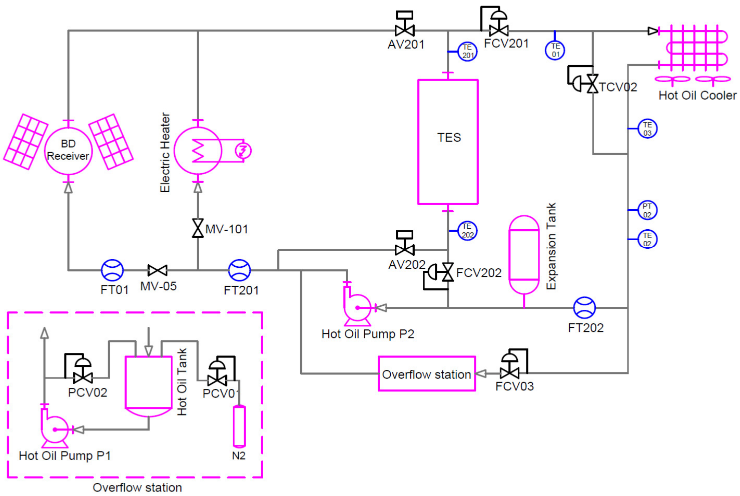
The secondary mirrors, mounted on the top of the 19 m height tower, consist of three multi-faceted rings, Fig. 3. (b). The rings of the secondary mirrors correspond to the heliostats rings on the ground, hence each secondary mirror facet is used for a specific heliostat. The secondary mirrors are static and angled to reflect radiation to the center of a solar receiver.

The solar receiver with an aperture area of 2.25 m^2 is placed at the bottom of the central tower at 1.8 m height from the ground level, Fig. 3. (c). The receiver is composed of steel pipes in which the HTF (in this case synthetic oil) flows to collect the thermal energy.

Fig. 3. Solar beam down components (a) Heliostat [13]; (b) Central tower secondary mirrors; (c) Solar receiver [16]

3.2. New hot oil-loop design for thermal energy storage testing

The hot oil-loop has been modified and instrumented to perform research and testing of many types of TES systems under real solar radiation conditions. The process flow diagram is presented in Fig. 4. Synthetic oil is used as heat transfer fluid to collect the thermal energy either in the solar receiver or by an electrical heater, both 100 kW_{th} power capacity, to reach a maximal temperature of 393 °C. The electric heater enables solar irradiation of any climate conditions to be simulated and also the slow dehydration of concrete during the first heating of the TES unit. The purpose of the oil loop is to control oil flow and measure the efficiency of the TES during the charge and the discharge phases. During the charge phase, automatic valve AV202 is closed and AV201 is opened. Cold oil is supplied by pump P2 to be heated by either the solar receiver or the electric heater and, as it flows through storage, to transfer heat to the concrete by convection and conduction. During the discharge phase, automatic valve AV202 is opened and AV201 is closed. Cold oil is supplied by pump P2 to recover energy through the TES and the heat is then dissipate by the air-cooler.



Design parameters	
HTF	Downtherm® A
Design pressure	16 bar
(Dis)charging time	5h
T_{in}, charging	390 °C
T_{in}, discharging	290 °C
HTF flow rate	0.1 - 1.0 kg/s
HTF useful power	100 kW_{th}

Fig. 4. Process flow diagram and design parameters for testing of TES systems

Control valves and variable speed pump are used to modulate and control the temperatures and thermal power during the charge and discharge phases.

4. Conclusions

Concrete based storage technology is an attractive alternative for storing sensible heat in CSP power plants. The thermo-physical and mechanical properties of the concrete such as the density, heat capacity, thermal conductivity, thermal expansion and durability which determine performance for this kind of storage system over many years of operation. The concrete mixture proposed by NEST has proved, through the first laboratory and prototype tests, to be thermally and mechanically superior. A new concentrating solar power (CSP) research facility was designed to integrate and test TES technologies. This special research facility provides a modular control strategy for charging and discharging the TES system. The coming experimental NEST pilot will be composed of 4 units integrated in the same shelter with a total storage capacity of 1.0 MWh_{th} (250 kWh_{th} each) and is planned to be in operation early 2015.

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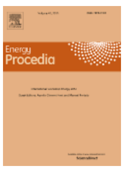

Biography

Dr. Martins obtained his Ph.D. in Engineering Science in 2010 at the PROMES CNRS Laboratory in France. He worked on ocean thermal energy conversion at the PIMENT laboratory in the Reunion island in 2011, then worked on solar thermal systems as head of research and development at SAED company in south of France. In 2014, he joined the thermal energy storage research group at Masdar Institute of Science and Technology in the United Arab Emirates.