Influence of solar heat sources on packed bed TES performances

Aubin Touzo, Regis Olives, Guilhem Dejean, Doan Pham Minh, Mouna El-Hafi, Xavier Py

Influence of Solar Heat Sources on Packed Bed TES Performances

Aubin Touzo[1, 3, a)], Regis Olives[1, b)], Guilhem Dejean[2, c)], Doan Pham Minh[3, d)], Mouna El Hafi[3, e)], Xavier Py[1, f)]

[1] *CNRS-PROMES Laboratoire PROcédés, Matériaux et Energie Solaire, Tecnosud, Rambla de la Thermodynamique, 66100 Perpignan, France.*
[2] *SAS Eco-Tech Ceram, Espace Entreprises Méditerranée, Rue Edouard Belin, 66600 Rivesaltes, France*
[3] *Université de Toulouse, IMT Mines Albi, UMR CNRS 5302, Centre RAPSODEE, Campus Jarlard, 81013 Albi, cedex 09, France*

[a)] Corresponding author: aubin.touzo@promes.cnrs.fr
[b)] olives@univ-perp.fr
[c)] guilhem.dejean@ecotechceram.com
[d)] doan.phamminh@mines-albi.fr
[e)] elhafi@mines-albi.fr
[f)] py@univ-perp.fr

Abstract. The influence of solar constraints is investigated on the Eco-Stock®, a commercial packed bed developed by the company Eco-Tech Ceram (1.9 MWhth at 525°C). The first test takes into account the simulated solar power variation along the day. Power variation has a minor impact on the packed bed performance, with a 3% decrease on the yield at 0.8 of cutoff temperature. Numerical results match the experiment, proving the model to handle properly power variation. The second test takes into account intermittencies, due to potential clouds. The stand-by phases had a major impact, reducing the yield by 13% at 0.8 of cutoff temperature, due to heat losses and both axial and radial stratification.

INTRODUCTION

To replace the two tanks molten salt storage used in Concentrated Solar Plant (CSP), the thermocline Thermal Energy Storage (TES) provides a potential cost reduction[1]. At high temperature, air is used as heat transfer fluid circulating in a packed-bed, filled with alumina beads as TES material. The Eco-Stock® is a modular storage unit of 28 tons designed to recover waste heat and transposed here to simulate a CSP. The influence of operating condition has been investigated by Lopez-Ferber *et al.* on a 300 kg prototype unit[2]. In this work, the influence of solar heat sources on the thermocline, such as variation of temperature, flowrate and intermittencies, are experimentally investigated using this commercial TES unit.

EXPERIMENTAL SETUP

The experimental setup is made of a packed-bed storage unit, a skid and an electrical cabinet (see Figure 1) to the right, center and left respectively. The packed-bed is a tank of dimension 1.7 x 1.7 x 3.08 m^3, filled with 16 tons of bauxite media (30 mm characteristic diameter) and insulated thanks to a 100 mm layer of refractory bricks. This storage unit weights 28 tons in total (ceramic medium, insulation and tank), which makes transportation by truck possible. The packed-bed has been able to store up to 1.9 MWhth at 525°C during a reference test described in a previous work[3]. The skid is a system which enables to properly handle the air flux in the storage using the air admission, a fan, an electric air heater (500 kWe), a chimney and a set of valves.

SolarPACES 2020
AIP Conf. Proc. 2445, 160017-1–160017-7; https://doi.org/10.1063/5.0093521
Published by AIP Publishing. 978-0-7354-4195-8/$30.00

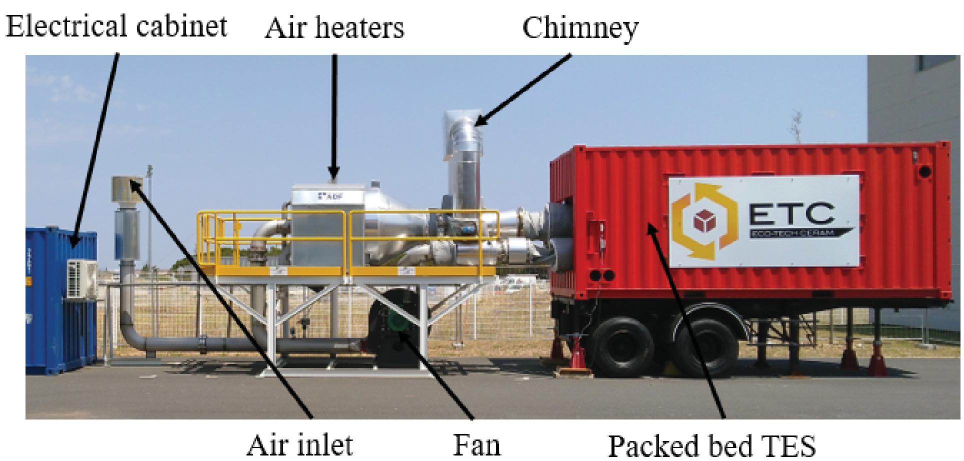

FIGURE 1. Commented photograph of the setup

Figure 2 presents the process flow diagram of the setup during the charge.

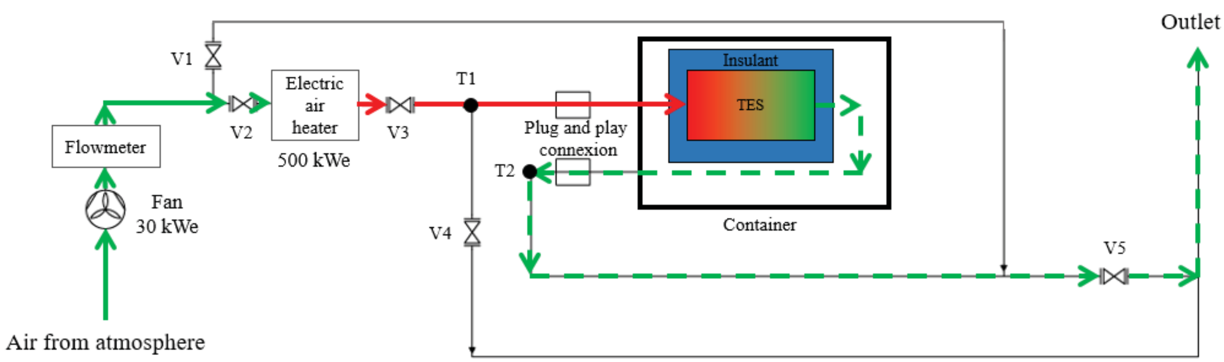

FIGURE 2. Process flow diagram during the charge

The hot air injected in the storage heats up the ceramic and creates a temperature gradient in the storage called thermocline. Figure 3 shows the positions of 33 K-thermocouples which enables to follow the gradient along the tank and to detect any flow heterogeneity. Section A, B and C are each equipped with 3 rows of 3 thermocouples, located at 150, 850 and 1550 mm from the top of the storage tank.

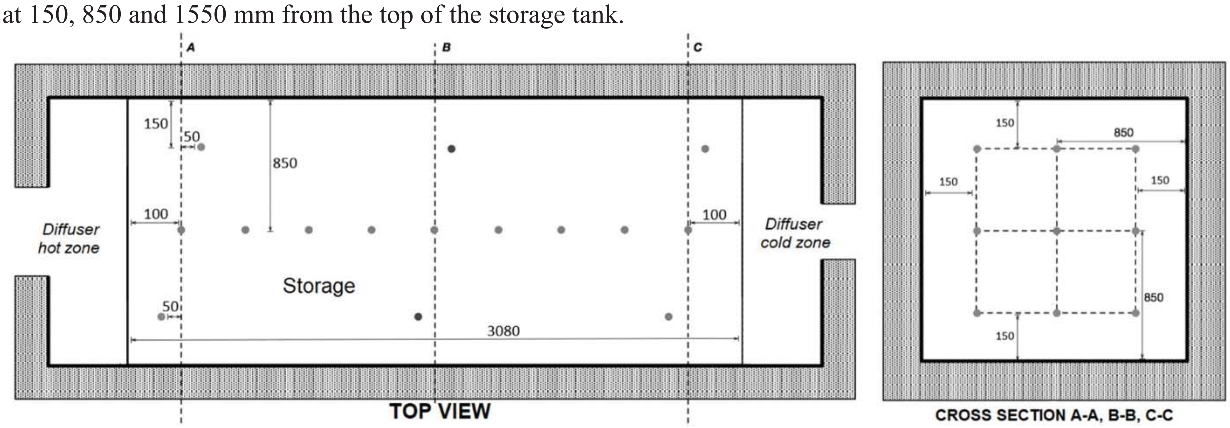

FIGURE 3. Instrumentation

PERFORMANCE INDICATORS

The charged energy, brought by the air heater, and the discharged energy are calculated using Equation 1, where *T* is the average temperature of the thermocouples from section A.

$$Q_{air-ch}(t) = \int_0^t \dot{m}(t) \left(\int_{Text}^{Tch(t)} c_{p\,air}(T)dT \right) dt \tag{1}$$

The yield is the ratio of energy discharged by the energy charged in the storage.

$$\gamma(t) = \frac{Q_{air-d}(t)}{Q_{air-ch}(t_{end-ch})} \tag{2}$$

NUMERICAL MODEL

The packed bed is modeled as a porous medium by a one-dimension model, which couples three energy equations: one for the fluid, one for the solid and one for the wall. The temperature of the alumina beads is assumed uniform, since the Biot number is calculated at 0.1. All correlations used for convection, conduction, radiation and effective conductivity are adapted from the work done by Esence *et al.*[4]. The model has been validated at 525°C and 2000 Nm3/h for charge and discharge[3].

$$\varepsilon\left(\rho c_p\right)_{air}\left(\frac{\partial T_{air}}{\partial t} + u\frac{\partial T_{air}}{\partial x}\right) = \frac{\partial}{\partial x}\left(k_{air-eff}\frac{\partial T_{air}}{\partial x}\right) + h_v\left(T_{bau} - T_{air}\right) + h_w\frac{A_{air\leftrightarrow w}}{(V_{air} + V_{bau})}(T_w - T_{air}) \tag{3}$$

$$(1-\varepsilon)\left(\rho c_p\right)_{bau}\frac{\partial T_{bau}}{\partial t} = \frac{\partial}{\partial x}\left(k_{bau-eff}\frac{\partial T_{bau}}{\partial x}\right) + h_v\left(T_{air} - T_{bau}\right) \tag{4}$$

$$\left(\rho c_p\right)_w\frac{\partial T_w}{\partial t} = \frac{\partial}{\partial x}\left(k_w\frac{\partial T_w}{\partial x}\right) + h_w\frac{A_{air\leftrightarrow w}}{V_w}(T_{air} - T_w) + h_{ext}\frac{A_{ext\leftrightarrow w}}{V_w}(T_{ext} - T_w) \tag{5}$$

RESULTS AND DICUSSIONS

Three charging scenarios are compared. The first scenario is a reference test, with a constant charging temperature and a constant flowrate. The second scenario is called "Solar". It takes into account power variation (increase and decrease) collected by the solar field during the day, with a flowrate variation at constant temperature. The third scenario called "Intermittency" investigates intermittency due to potential clouds: an idle phase is carried out between each charging phase until charge is completed.

The dimensionless temperature is defined commonly in the literature as follows:

$$\theta = \frac{T(t) - T_l}{T_h - T_l} \tag{6}$$

With T_l ambient temperature and T_h the charging temperature of the storage.

The charging temperature cut-off is the same for all tests to be compared. The cut-off temperature is set at 185°C, which corresponds to a cut-off threshold of 0.33, a technical limit due to the waste heat recovery application.

Simulated Solar Power

The Solar test consisted in increasing the charging power from 115 to 320 kWth, to simulate the energy collected by the solar field during the day, with a flowrate variation at constant temperature of 500°C. The charging power can be seen on Figure 3 along the charging time, which lasted 7.2h. The reference test was carried out at 340 kWth, at

525°C and 0.57 kg.s^{-1}. The charging power of the reference test immediately raises to 340 kWth and is maintained constant along the test until the cutoff temperature is reached at 6.3h. The charging time is therefore 7.5% longer for the simulated Solar Power, because the power was lower during the first 2.5h.

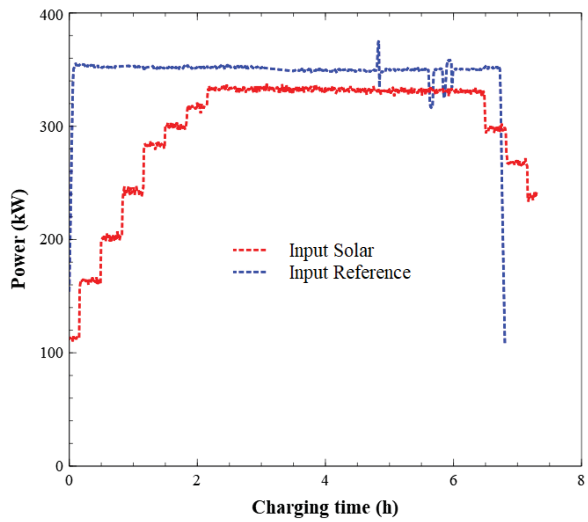

FIGURE 4. Charging power

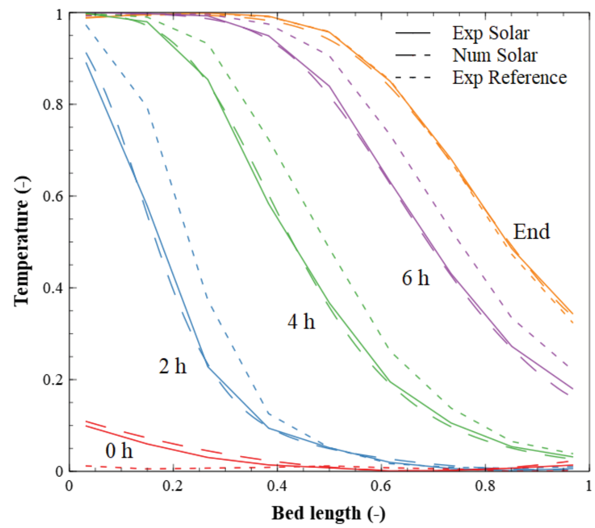

FIGURE 5. Temperature profiles

The temperature profiles are plotted against the bed length every 2h until the end of the charge. A gap can be observed for Reference and simulated Solar curves in Figure 4 at 2, 4 and 6 hours of test. This gap is due to the difference in charging power. However, these two curves are superposed at the end of the charge, which indicates that the input power had no influence on the final temperature profiles. The model was able to predict accurately the temperature profiles of the simulated Solar test.

The discharged was carried out with an air flowrate of 0.65 kg.s^{-1}. The yield has been plotted for the reference, simulated Solar and model during the discharge, against the discharged temperature, to show how the heat quality is affected by the storage process (Figure 5).

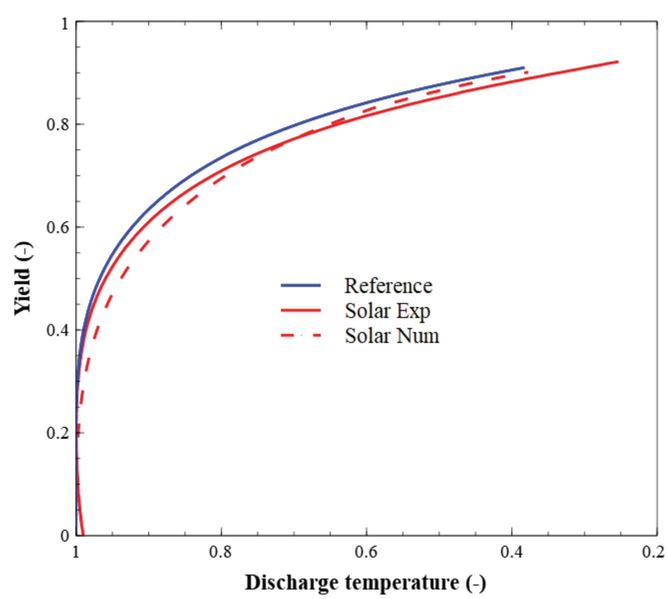

FIGURE 6. Yield comparison between solar test and reference

The packed bed is able to discharge 35% of its energy at constant temperature. The solar experimental discharge temperature seems to go increase from 0.98 to 1 since natural convection occurs during idle phase between charge and discharge. The discharge temperature starts to decrease after 35% of yield. The yield reaches 70% at a cutoff temperature of 0.8, usual for solar application, and up to 89% at a cutoff temperature of 0.4. At this last cutoff temperature, the discharging performance is only 3% lower for the simulated Solar compared to the Reference, revealing a minor effect of the power input variation on the packed-bed performance. So, the model is also able to handle power variation.

Intermittencies

In this scenario, the impact of intermittencies due to possible clouds on the packed-bed performances is investigated. The storage tank is charged with a flowrate of 0.57 $kg.s^{-1}$ at 500°C for 1h, followed by a 1h stand-by. This cycle is repeated until the cutoff temperature of 0.33 (185°C) is reached. The temperature profiles are plotted for both Intermittency and Reference test on Figure 6.

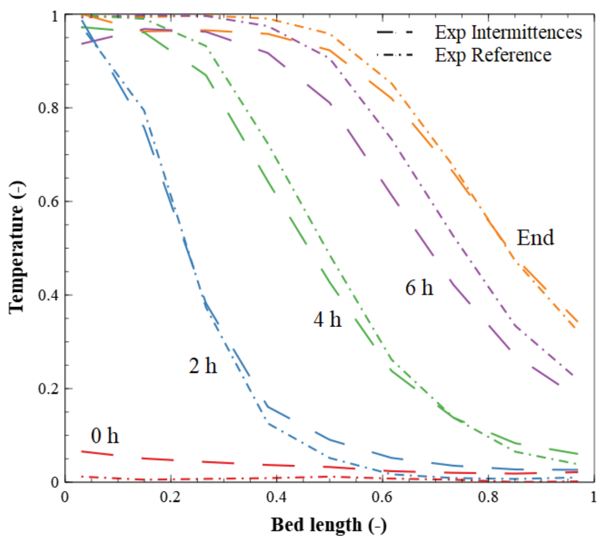

FIGURE 7. Charging power

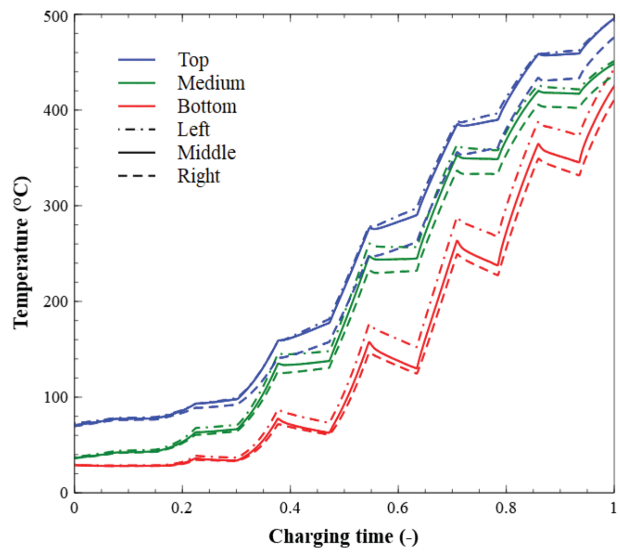

FIGURE 8. Temperature profiles

The gap between Intermittency and Reference increases along the charge. It can be explained by the heat losses on the hot side of the storage caused by a natural convection during the stand-by phases, as the temperature only reached 0.96 (480°C). At the end of the charge, a slightly lower stratification can be observed.

However, the stand-by phases double the charging time. Since the experiment is carried out on a horizontal packed bed, radial heterogeneities are present. The temperature of the 9 thermocouples located in cross-section B (Figure 3) are plotted against the charging time on Figure 8. During stand-by phases, the temperature increases for the top thermocouples, is constant for the centered thermocouples, and decreases for those set at the bottom. The phenomenon is caused by the natural convection. However, all thermocouples are between 400°C and 500°C at the end of the charge, showing a relative homogeneous temperature of the section B at the end of the charging step.

The experimental results could not be compared to numerical ones because of the stand-by phase. Indeed, the radial heterogeneities makes the one-dimension model irrelevant, and would require a two-dimension or three-dimension model. Even with a three-dimension model, it would still be a complex task to estimate natural convection coefficients since it would depend on the whole packed-bed behavior.

The packed-bed was discharged with an air flowrate of 0.65 $kg.s^{-1}$. The yield is plotted against the discharge temperature on Figure 8 to measure how the quality of the heat is affected by the storage process.

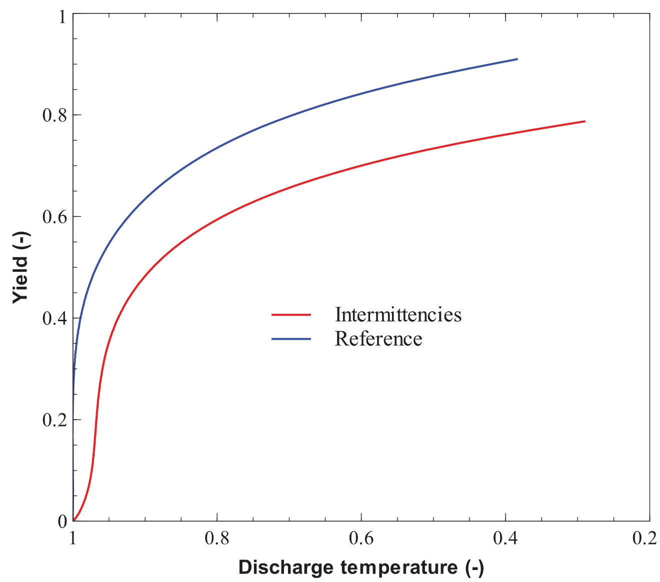

FIGURE 9. Yield comparison between solar test and reference

The packed bed yield seems strongly affected by intermittencies. First, the storage is not able to discharge the heat at the charging temperature. The discharge temperature immediately decreases at 0.96 because of the heat losses during the stand-by phase. A perfectly sealed valve would have been needed to lower heat losses. The packed-bed was able to discharge about 30% of its energy at a temperature of 0.96 before the discharge temperature starts to decrease due to the thermocline extraction. At a cutoff temperature of 0.8, the Intermittency yield is reduced by 13% compared to the Reference. The yield reduction is likely to come from a lower axial and radial stratification. However, 1h of stand-by every 1h of charge seems to be one of the worst case scenario to charge a packed bed compared to performances on usual conditions.

CONCLUSION

Tests investigating the impact of solar source on thermocline thermal storage were carried out on a novel industrial pilot of 28-tons (1.9 MWhth at 525°C). First, the solar power variation along the day was simulated. Power variation has a minor impact on the packed-bed performance, with a 3% decrease at the yield at 0.8 cutoff temperature. Numerical results match the experiment, proving the model to properly handle power variation. Second, intermittencies due to possible clouds were investigated. The stand-by phases had a major impact, reducing the yield by 13% at 0.8 cutoff temperature, due to heat losses and both axial and radial stratification. Numerical tools to model stand-by phases on horizontal units are still to be developed and validated.

ACKNOWLEDGMENTS

This project has received funding from the program "investissement d'avenir" (investments for the future) of the "Agence Nationale de la Recherche" (National Agency for Research) of the French state under award number" ANR-10-LBX-22-01-SOLSTICE, and from BPI France from the World Innovation Competition Phase 2 for the Eco-Stock® project. The authors would like to thank Yoann Le Blevennec for his help in the study.

REFERENCES

1. Angelini, G., Lucchini, A. & Manzolini, G. Comparison of thermocline molten salt storage performances to commercial two-tank configuration. *Energy Procedia* **49**, 694–704 (2013).
2. Lopez Ferber, N. *et al.* Flexibility and robustness of a high-temperature air/ceramic thermocline heat storage pilot. *J. Energy Storage* **21**, 393–404 (2019).

3. Touzo, A. *et al.* Experimental and numerical analysis of a packed-bed thermal energy storage system designed to recover high temperature waste heat : an industrial scale up. *J. Energy Storage* **32**, 101894 (2020).
4. Esence, T., Bruch, A., Molina, S., Stutz, B. & Fourmigué, J. F. A review on experience feedback and numerical modeling of packed-bed thermal energy storage systems. *Sol. Energy* **153**, 628–654 (2017).