SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Thermal Energy Storage Materials, Media, and Systems

https://doi.org/10.52825/solarpaces.v3i.2309

Published: 25 Nov. 2025

Multicriteria Comparison of two Different-Nature Fillers for High Temperature Sensible Heat Storage

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Abstract. The most suitable materials for thermal energy storage should combine low cost, high thermal capacity, high charging and discharging velocities, compatibility with the plant components in which they are integrated and, long-term durability. The use of solids to fill packed beds where the heat enters and leaves through a heat transfer fluid (HTF), is a solution that provides satisfactory amounts of energy density at low cost. In this work, two solid materials of different nature were comparatively tested at device level with air as HTF and according to various criteria. Material A is manufactured from recycled waste and tailored to improve its thermal properties, while material B is a natural, cheap and highly available in nature (pebbles). Material B showed significant mechanical strength problems at temperatures above 500 °C. Material A, instead, withstood well temperatures up to 850 °C under operating conditions. The comparative KPI revealed that material B has a slightly higher thermal capacity and a 4% higher energy efficiency than material A. However, these results lost validity after the first-round experiment with material B, since a strong degradation was detected affecting its physical properties and hindering its ability to store heat.

Keywords: Thermal Energy Storage, Packed-Bed, Materials, Thermal Properties

1. Introduction

Sensible heat storage technologies are on the market since several years linked to the concentrating solar power sector [1]. They are based on the heating of a fluid and/or a solid material with notorious thermal capacity when excess thermal energy is available and cooling it in moments of demand. The main advantage of sensible heat over other types of energy storage is their high Time Readiness Level, consequence of its technology maturity, competitive cost and system integration experience.

In the sensible heat storage field, the use of solid materials to fill tanks where the heat is carried in and out by a heat transfer fluid (HTF), is a solution which provides satisfactory amounts of energy density at low cost [2]. The HTF can be air, offering additional advantages versus liquids, as its applicability at high temperatures, the direct heat transfer between the working fluid and the storage and the lack of concerns on safety and corrosiveness [3]. As an air-solid packed-bed (ASPB) can be employed at high temperatures (with a maximum limited by the thermal resistance of the solids), this technology can be coupled to both industrial processes demanding heat at high temperature and Brayton power cycles as the scheduled for the next generation concentrating solar power plants.

Regardless of the technology, a material suitable for thermal storage should combine low cost, and high thermal capacity or energy density [4]. Other required characteristics for thermal storage materials are high charging and discharging velocities, compatibility with the plant components which be integrated into and long-term durability. Most of the studied carried out so far selected natural fillers for thermal storage mainly due to the availability and low cost of such kind of materials. Typical examples of materials used as fillers in liquid and air thermal storage systems are sand [5], rocks of different composition and origin [6] or pebbles. However, only few of the published works have focused on temperatures above 700 °C, which is actually the most interesting potential of ASPB [7-9]. Whereas customizing synthetic materials to impart them specific properties is a more expensive alternative if compared to using natural raw, some efforts have been also devoted to process waste material to be valorized and used as fillers in storage tanks [10,11]. In this word, a material specifically tailored for thermal stored is tested as filler for high temperature sensible heat storage in an ASPB. The material is composed of metal oxides in variable proportion, with minimum percentages guaranteed for each one. Its performance in charge and discharge modes is compared to a natural filler, river pebbles, by means of their key performance indicators. Both materials are also compared from thermal and mechanical stability viewpoints.

2. Materials for thermal storage

Figure 1–left shows material A, supplied by a specific producer [11]. Figure 1– centre presents material B, which is natural pebbles purchased from a gardening shop. Figure 1– right depicts the main properties of both materials. Some properties and characteristics of the materials were provided by the suppliers. Additionally, density and porosity were determined in the laboratory with techniques to measure mass and volume and reported somewhere else [12].

Property	A (provider info.)	A (own info.)	B (provider info.)	B (own info.)
Composition	Al_2O_3 (min. 35%), ZrO_2 (max. 25%), SiO_2 (max. 40%), Fe_2O_3+TiO_2 (max. 5%), K_2O+Na_2O (max. 5%), CaO+MgO (max. 1%)	_	SiO_2 (min. 95%)	_
Bulk density (kg/m^3)	2700	2987	_	2770
Porosity	0.45-0.47	0.51	_	0.44
Packing density (kg/m^3)	1458	1464	_	1551
Specific heat (J/kg·K)	1024	1063	_	1109
Characteristic length (mm)	40	40	14-22	14-22

Figure 1. *Studied materials A (left) and B (middle). Materials properties (left).*

3. Experimental methodology

The experimental facility is composed of a tank of close on 0.1 m^3 in volume, a blower and an air heater. It can be operated in charge and discharge modes. For the first one, preheated air is blown into the tank through its top and extracted through the bottom after crossing and heating up the packed-bed. The configuration is changed for discharging the tank, so that the air at ambient temperature enters through the bottom and exits through the top, carrying heat out of the tank. For additional information and real photographs, the cited bibliography sources can be consulted [12-14].

Both materials were subjected to a set of charge and discharge experiments with a set point temperature that varies from 500 °C to the maximum reachable depending on the appearance of limiting factors, regarding whatever the material or the set-up components. Different airflow rates were also imposed always in the range of the facility operation (50-80 kg/h).

Three KPIs have been calculated and are reported here: maximum stored energy in charge, recovered energy in discharge and energy efficiency. Equations 1, 2 and 3 have been employed to calculate each one.

$$E_{stored} = (m_{filler} C_{p,filler} + m_{dev} C_{p,dev}) \int_{T(i)}^{T(t)} dT \quad (1)$$

$$\chi_{Er} = \frac{\dot{m} Cp_{air} \int_0^t (T_{air,out} - T_{amb}) dt}{E_{stored}} \quad (2)$$

$$\eta_{storage} = \frac{\dot{m} Cp_{air} \int_0^t (T_{air,out} - T_{amb}) dt}{E_{power}} \quad (3)$$

4. Results

A comparison of the temperature distribution measured during the testing of each material is presented in Figure 2. Heat transfer between air and solid is more efficient in case of material A. It can be inferred from the fact that the upper layer of material A rapidly reaches the set point temperature, once the inlet air has been achieved it. This does not happen for material B, which remains entirely at lower temperature that the inlet air. The thermal capacity of filler B is slightly higher than that of filler A. Temperature curves suggest that filler B requires a little more time to be fully charged, what implies, obviating differences in thermal losses and assuming a constant supply power, more stored energy.

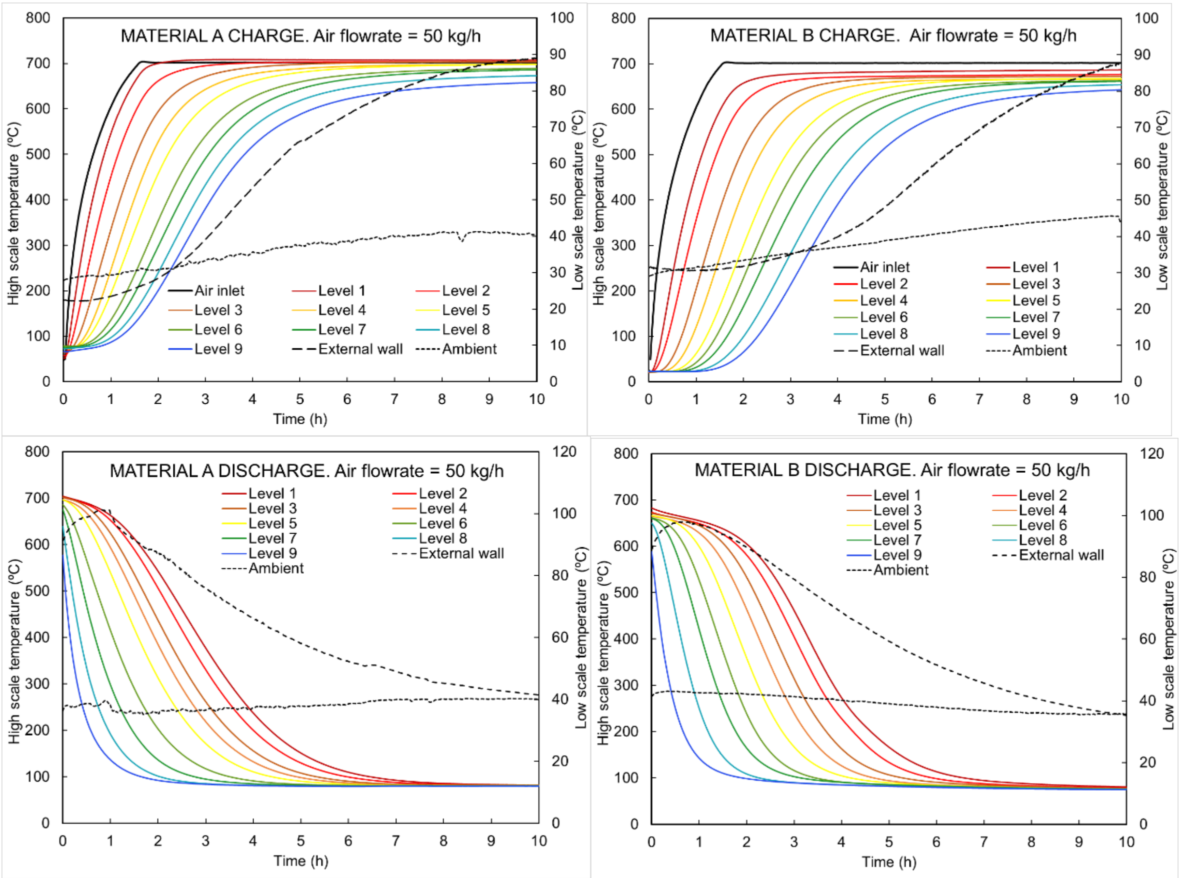

Figure 2. *Four representative cases of experimental testing including both materials A and B and charge and discharge experiments.*

The performance of both materials regarding to the capacity and ability of store energy under operating conditions corresponding to Figure 2 shows small differences. After 10 h of charging, material A stores around 61 % of its capacity and material B stores around 55 %.

The recovered energy corresponds to the fraction of energy recovered in a certain discharge to which had been stored during a previous charge. For the cases represented in Figure 2, it reaches 50% for material A and 58 % for material B after 10 hours of discharge. However, this result is inaccurate because the facility itself stores a large part of the supplied energy ($m_{dev}C_{p,dev}$) [12]. The same happens with thermal efficiency calculated according Equation 3. Obtained values are 29 % for material A and 33 % for material B, although they should be higher in larger-scale device where the contribution of the tank and conductions in the storage of energy is not so relevant.

Beyond the KPI, whose accuraty is interfered by the thermal capacity of the device, the main finding of this word is regarding the material degradation. Figure 3 shows some photographs of the materials after being subjected to a certain number of experiments. Material B did not change its appearance after a charge to 500 °C and further discharge. However, the picture in left of Figure 3 corresponds to the material B when it was checked after been charged to 700 °C and then discharged. As observed, from the top layer of the packed-bed to a depth exceeding 20 cm, the pebbles were partially crushed implying a relevant transformation in their physical properties. It was also observed that successive cycles of charge and discharge enlarged the depth of degraded material. This indicates that this material is not able to perform a packed-bed for thermal storage at temperatures up to 700 °C. The degradation occurring in the material is incompatible with its use for thermal energy storage, as the physical properties are continuously changing over the charge-discharge cycles.

***Figure 3**. Left: material B after 1 charge-discharge cycle at set-point temperature 500°C and 4 cycles at 700 °C. Center and right: material A after several cycles at 700, 750, 800 and 850 °C. Picture on the center shows the upper of the storage tank and picture in the left.*

Other works sign the higher decreasing in particle diameter and porosity occurs at the bottom due to the own weight of the packed bed and the displacement of the lower particles to the lower part of the tank [15]. In this case, the degradation starts and is more pronounced at the top, probably as a combination of higher temperatures and erosion caused by the air jet.

The main issues with the changes occurred in material B are the deterioration of its physical properties. Beyond causing an unacceptable pressure drop, especially in the upper levels of the tank, the material drastically losses its mechanical stability so that, it continues been cracked from one cycle to the next.

5. Conclusions

The comparison of two materials as fillers for thermal storage in packed bed has been intended by replicating the same type of charge-discharge experiments with both materials. Strictly regarding thermal performance, it can be concluded that material A showed a more efficient heat transfer during charge and discharge cycles and material B exhibited slightly better energy efficiency. However, material B, which consists in natural river pebbles, did not allow to increase the maximum charge temperature up to 700 °C and it showed important problems of mechanical resistance at this threshold, particularly at the top of the the tank. Material A, instead, with artificial origin, withstood well temperatures until 850 °C under operating conditions. This finding is critical when materials are pick off for high temperature thermal storage applications.

Author contributions

E. Alonso: conceptualization, data curation, formal analysis, investigation, methodology, writing-original draft.

E. Rojas: investigation, funding acquisition, formal analysis, writing-review&editing.

A. Ávila-Marín: writing-review&editing.

M. Rodríguez: writing-review&editing.

R.Bayón: writing-review&editing.

Competing interests

The authors declare that they have no competing interests.

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