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# Effect of heat transfer structures on thermoeconomic performance of solid thermal storage

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ABSTRACT

The performance of a regenerative solid TES (thermal energy storage) system with enhancement heat transfer structures is analyzed. Thermal energy is transferred from a hot heat transfer fluid to the storage unit core elements during charge, and from the core elements to the cold heat transfer fluid during discharge. Herein, concrete as the solid storage material, nitrate solar salt as the heat transfer fluid, and aluminum plates as the heat transfer structures are considered. The discharge process from uniform initial temperature is studied with different configurations (pure concrete and concrete enhanced by transfer structures), operation strategies (laminar versus turbulent flow regimes), and dimensions. The results show a significant decrease in the cost of the TES system when heat transfer structures are added, as well as higher discharge efficiency and lower discharge time period. The amount of solar salt needed for this configuration is also decreased by the use of the heat transfer structures and is five time less than that of a two-tank system.

## 1. Introduction

CSP (Concentrated Solar Power) offers a clean alternative to traditional electricity sources. However, electricity demand and irradiance curves do not always match [1]. This mismatch of demand and production is a concern with other RES (renewable energy sources) as well. Another key limitation of RES, and CSP in particular, is the low capacity factor, defined as the ratio of the actual output of a power plant over a period of time and its potential output if it had operated at full nominal capacity over that period [2]. Typical wind power capacity factors are 20–40% [2]. Hydro capacity factors may be in the range of 30–80% [2]. Photovoltaic capacity factors in Massachusetts are 12–15% [2]. In contrast, base-load thermal power plants may often be in the range of 70–90% [2]. The objective of TES (thermal energy storage) systems is to overcome these inherent disadvantages. Storage has been claimed to increase the capacity factor to 56.2% for parabolic trough technology, and 72.9% for power tower technology [3].

In general, there are three types of TES: thermo-chemical heat storage, latent heat storage, and sensible heat storage [4–6]. Among the sensible heat storage systems, several concepts have been proposed in the literature. Two-tank systems with molten salt mixtures [7,4,8,9] are among the most developed and tested concepts. Also, alternative designs such as thermocline and rafted thermocline [10,11], and virtual two-tank [12–15] have been investigated. Moreover, two main types of solid storage concepts without phase change studied in the literature are packed bed and tube heat exchanger-type TES system [4]. A series of articles analyzes the behavior of oil-pebble bed thermal storage system for a solar cooker computationally [16,17] and experimentally [18–20]. In Ref. [21], a regenerative thermal storage system with air as the heat transfer fluid and different core geometries and materials for the packed bed is analyzed. Ref. [22] analyzes the discharge process of a thermocline TES system using molten salt as the heat transfer fluid and rock as filler. Also for the tube heat exchanger type, several studies can be found in literature. In Ref. [23], a simulation tool for the analysis of the transient performance of the tube-type storage system with varying material properties and geometries is presented. Ref. [24] studies the performance of two new storage materials, high temperature concrete and castable ceramic, with oil as the heat transfer fluid and a tubular heat exchanger integrated into the storage system. Ref. [25] presents different strategies to improve storage performance, such as additional structures to enhance heat transfer, and modular storage integration and operation into the solar-thermal power plant concepts. Ref. [26] presents a TES system with solid as

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**Nomenclature**

*Latin letters*

| | |
|---|---|
| $\overline{C}$ | storage cost [$\$/\mathrm{kWh_t}$] |
| $\bar{c}$ | constant electricity price [\$] |
| $\bar{u}$ | average velocity [m/s] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $\dot{Q}_{\mathrm{output}}$ | heat transfer output [kW] |
| $A$ | area [$\mathrm{m^2}$] |
| $b$ | volume percentage of heat transfer structure added |
| $C$ | cost [\$] |
| $c_p$ | specific heat capacity [J/(kg·K)] |
| $D$ | storage block outer diameter [m] |
| $d$ | storage block tube diameter [m] |
| $f_d$ | Darcy friction factor based on the tube diameter $d$ |
| $h$ | convective heat transfer coefficient [W/(K·$\mathrm{m^2}$)] |
| $k$ | thermal conductivity [W/(K·m)] |
| $L$ | storage block length [m] |
| $N$ | number of plates as heat transfer structure added |
| $Nu_d$ | Nusselt number based on the tube diameter $d$ |
| $Q_{\mathrm{output}}$ | total thermal energy output [$\mathrm{MWh_t}$] |
| $r$ | cylindrical radial coordinate |
| $R_h$ | convective thermal resistance by unit length [(K·m)/W] |
| $R_r$ | conductive thermal resistance in the radial direction by unit length [(K·m)/W] |
| $R_z$ | conductive thermal resistance in the longitudinal direction by unit length [(K·m)/W] |
| $Re_d$ | Reynolds number based on the tube diameter $d$ |
| $T$ | temperature [K] |
| $t$ | time [s] |
| $T_c$ | lowest temperature of the thermal storage system [K] |
| $T_h$ | highest temperature of the thermal storage system [K] |
| $T_{in}$ | inlet temperature [K] |
| $u$ | velocity [m/s] |
| $u_{\mathrm{in}}$ | design average inlet velocity [m/s] |
| $U_{\mathrm{th}}$ | total thermal energy capacity [$\mathrm{MWh_t}$] |
| $z$ | cylindrical longitudinal coordinate |

*Acronyms*

| | |
|---|---|
| CSP | concentrated Solar Power |
| CSPonD | concentrated Solar Power on Demand |
| CTE | coefficient of thermal expansion |
| HTF | heat transfer fluid |
| RES | renewable Energy Sources |
| TES | thermal energy storage |

*Greek letters*

| | |
|---|---|
| $\alpha$ | thermal diffusivity [$\mathrm{m^2/s}$] |
| $\delta$ | thickness [m] |
| $\varepsilon$ | ratio of the tube cross sectional area to the total block cross sectional area |
| $\eta$ | efficiency |
| $\mu$ | dynamic viscosity [kg/(m·s)] |
| $\rho$ | density [$\mathrm{kg/m^3}$] |
| $\tau$ | time period [s] |
| $\theta$ | non-dimensional temperature |

*Subscripts*

| | |
|---|---|
| aluminum | aluminum |
| block | single storage block |
| bulk | bulk fluid |
| charge | charge process of the TES system |
| concrete | high temperature concrete |
| discharge | discharge process of the TES system |
| pipe | pipe material |
| plate | plate shape |
| pump | pumping of the HTF |
| salt | nitrate solar salt |
| surface | lateral surface |

the storage material and different gas as the heat transfer fluid. In Ref. [27], a similarity analysis of efficiencies of TES systems is presented in order to generalize the study of regenerative thermal storage systems. Therein, analysis of a packed bed configuration of solid filler material, and of thermal storage material with tubes embedded in it where the HTF (heat transfer fluid) flows is performed. In the latter case, the storage material considered is liquid, solid, or a mixture of the two.

This article is focused on the design of a regenerative thermal storage system. The regenerator configuration is a matrix solid material with an embedded tube heat exchanger (Fig. 1). The operation in these systems is the following: during charge, thermal energy is transferred from the HTF to the storage system. At discharge, thermal energy is transferred from the storage system to the HTF, heating up the latter. High-temperature concrete as the solid storage material is studied. Its ease of handling, low cost, and high availability of raw material (blast furnace cement as a binder system, temperature resistant gravel and sand as aggregates, and a small amount of polyethylene fibers [28]) are its main advantages over liquid sensible storage systems. A significant disadvantage is its relatively low thermal conductivity, which makes the charge and discharge processes heat-transfer limited. That is, for two hypothetical materials with the same volumetric capacity $\rho c_p$, the one with lower thermal conductivity needs more tube heat exchanger structures for the same effective storage capacity and heat transfer output. This results in higher cost, since these heat exchange structures account for a significant share of the system capital cost [23]. Thus, the charge/discharge duration is a critical feature of the system. It is related to the entire cycle, which also accounts for the time the storage is idle. In solar-thermal power plants the entire cycle duration typically is 24 h [15,29], and the charge and discharge processes are of similar length [15,23–25]. Herein, a daily time scale with 24-h operation cycles is considered, with a charge/discharge time of the thermal storage system lower than 12 h.

To overcome the aforementioned heat transfer limitation, structures to enhance heat transfer have been proposed: fins [25],

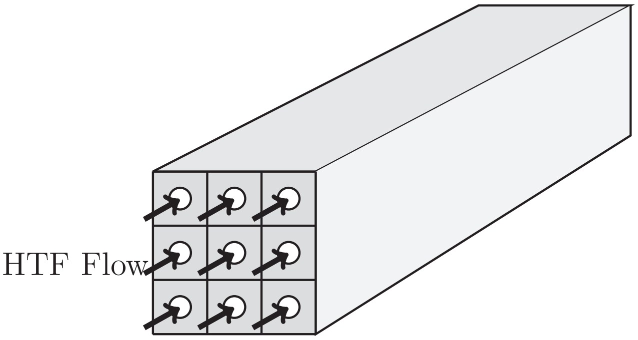

**Fig. 1.** Schematic of a solid thermal storage system with an embedded tube heat exchanger.