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Evaluation of thermal stratification of an air-based thermocline TES with low-cost filler material

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Abstract

In the present work, a computational fluid dynamics (CFD) approach was followed to evaluate the extent of thermal stratification of an industrial-scale thermal energy storage (TES) system, based on a packed bed of river pebbles The TES is integrated into a reference concentrating solar power plant which uses air as heat transfer fluid. The transient evolution of thermal stratification was qualitatively evaluated according to the dimensionless MIX number based on the so-called moment of energy, or height-weighted energy, into the packed bed. The resulting stratification efficiency ranges between 0 and 1 with the theoretical threshold values given by the moment of energy of fully mixed and ideally stratified TES respectively. The 30 consecutive cycles analyzed were characterized by 12 hours of charging followed by 12 hours of discharging. The results obtained showed that the TES system reached a stable working condition after 20-22 cycles with an average stratification efficiency of about 0.95. The CFD simulations were performed with Fluent 14.5 code from ANSYS.

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Keywords: thermal stratification; packed bed; thermal energy storage (TES); MIX number; effective thermal conductivity (ETC); computational fluid dynamics (CFD); concentrating solar power (CSP).

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1. Introduction

Single-tank, or thermocline, thermal energy storage (TES) systems can be considered as a valuable alternative to the most common two-tank solution normally exploited in conventional concentrating solar power (CSP) plants. Thermal energy is stored, in the form of sensible heat, in a packed bed of low-cost filling material contained into the tank. The thermocline TES is charged from top and discharged from the bottom exploiting the buoyancy of the heat transfer fluid (HTF) for establishing and maintaining a thermocline zone which separates the hot and the cold regions within the tank. This thermal stratification is among the key factors that can sensibly affect the performance of the TES system: the thinner the thermocline, the higher the thermodynamic quality of the energy stored. However, at the beginning of the operation, i.e. when the TES is subjected to the first charge and discharge phases, the thickness of the thermocline zone varies sharply reaching a stable working condition after some cycles.

The present study aims at evaluating, by means of a computational fluid dynamics (CFD) approach, the extent of thermal stratification of an industrial-scale TES system, based on a packed bed of river pebbles subjected to a total of 30 consecutive cycles.

2. Evaluation of thermal stratification

The definition of a proper approach for determining thermal stratification in thermocline TES, water tanks especially, has been the subject of several studies [1-3]. As a result, dimensional and dimensionless quantities have been proposed for predicting and evaluating the extent of thermal stratification. Most of them require, as input parameter, the energy or the temperature distribution into the tank. For this reason, it might be difficult to gather these information from experimental tests unless a large number of thermocouples would be equipped into the tank increasing however the complexity of data management. This drawback can be easily tackled exploiting a CFD-based approach which allows to obtain the temperature distribution at any point in the computational domain. Therefore, the temperature profiles, as a function of the storage tank height, were exploited as graphical representation of thermal stratification at different times.

The MIX number, developed by Davidson et al. [4] and lately modified by Andersen et al. [5], was also exploited to characterize the extent of thermal stratification in greater detail. The MIX number is based on the so-called moment of energy given by both the energy stored and the temperature distribution into the storage tank. The moment of energy is given by the summation of the energy stored in the packed bed, virtually divided into an arbitrary number of horizontal layers, weighted by the vertical distance from the base of the tank to the center of the *n-th* layer under consideration. Therefore, the higher the energy is stored into the tank the larger the moment of energy.

The temperature profiles, obtained with the CFD simulation, are used to calculate the moment of energy of the real TES. Two theoretical TES configurations, ideally stratified TES and fully-mixed TES, are then derived on the basis of the amount of energy stored into the real TES. The ideally stratified TES is characterized by the fact of having two adiabatically-separated regions, at high and low temperature, into the packed bed; conversely, the whole packed bed of the fully-mixed TES is at average temperature. The MIX number is then derived combining the moment of energy of the real TES (M_{exp}) with those of ideally stratified TES (M_{str}) and fully mixed TES (M_{mix}) respectively as follows:

$$MIX = \frac{M_{str} - M_{\mathrm{exp}}}{M_{str} - M_{mix}} \tag{1}$$

The resulting stratification efficiency, ranging from 0 to 1 where 1 indicates the moment of energy of an ideally stratified TES, is given by:

$$\eta_{MIX} = 1 - MIX \tag{2}$$

3. Industrial-scale TES

The single-tank TES system under investigation was designed to fulfill the round-the-clock energy requirement of a reference 80 MW_e CSP plant which uses air as HTF. The latter is fed through the storage at 650°C; whereas, after the power block heat exchangers, the HTF temperature is reduced down to 270°C. On the basis of the reference operating temperatures, a packed bed of natural rocks, 3-4 cm average particles diameter, was exploited as low-cost filler material. The pebbles are contained into a concrete vessel, buried into the ground, with a truncated-cone shape in order to minimize the effect of thermal ratcheting on the lateral walls.

During the charge phase, the HTF at high temperature flows downward through the packed bed delivering its thermal energy to the gravel. Conversely, during the discharge phase, the energy stored can be recovered by reversing the air-flow direction with the HTF coming from the heat exchangers of the power block. Hence, 650°C and 270°C were assumed as reference charging and discharging temperatures respectively. With the given CSP plant dimensions, and considering the case of largest available DNI (in the month of June), calculations showed that a total of 7 TES units, 25.7 m and 21.7 m the upper and the lower diameter respectively and 9.5 m packed bed height, are required to hold the whole volume of about 30,000 m^3 of rocks [6]. The thermal capacity of each TES unit, defined as the total energy stored in the packed bed when charged from ambient temperature to isothermal conditions at the inlet air flow temperature of 650°C, is about 1 GWh_{th}. The air mass flow rate through each TES unit is about 89.6 kg/sec for both the charging and discharging.

4. CFD model

Left-hand side of Fig. 1 shows the CAD model of one of the seven units. The computational domain considered for the analysis is a quarter of the whole geometry. It was discretized with a grid of almost 1,150,000 hexahedral elements. Right-hand side of Fig. 1 shows the main boundary conditions applied to the model.

Navier-Stokes, energy, turbulent kinetic energy and turbulent dissipation rate transport equations were numerically solved with the finite volume method (FVM) approach [7] by means of Fluent 14.5 code from ANSYS. The realizable k -ε model [8], with standard wall functions [9], was selected to account for turbulence effects.

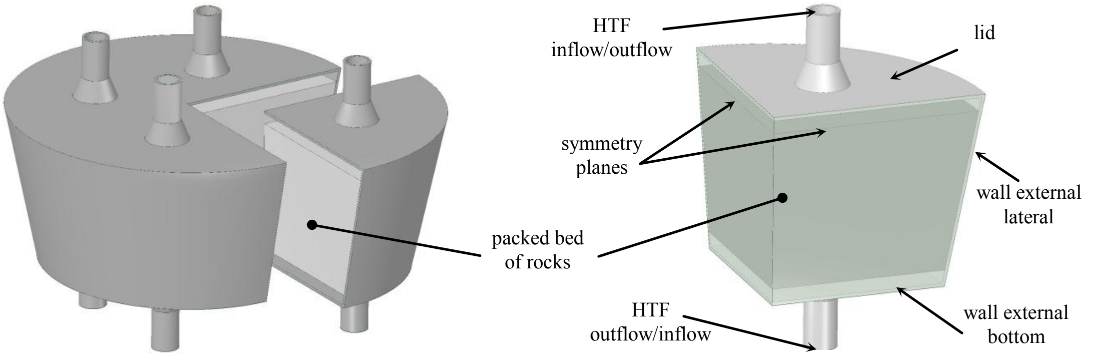

Fig. 1. Schematic CAD model of a single TES unit (l.h.s.) and main boundary conditions applied to the computational domain considered (r.h.s.).

Thermal energy losses by means of conduction through the ground and convection/radiation from the lid towards the environment were accounted for. The environment temperature was assumed equal to 35°C and 20°C during charging and discharging respectively. The layers of concrete and insulating materials were numerically modelled, by means of the shell-conduction approach [10], with a material of equivalent thermo-physical properties.

In order to evaluate the effect of start-up on thermal stratification, at the beginning of the time-dependent CFD simulation, namely at time t = 0 sec, the TES system unit was considered in thermal equilibrium with the environment with a dead-state temperature of 17°C.

The rock-bed was treated as a continuum and hence it was modelled exploiting the porous media approach [11]. Local thermal equilibrium (LTE model) between the solid matrix and the fluid phase was assumed; therefore, a single conservation equation of energy is solved to model the heat transfer through the porous medium.

An effective thermal conductivity (ETC), based upon the Kunii & Smith's model [12, 13], was considered to account for all the non-convective heat transfer mechanisms occurring into the packed bed. The ETC was implemented into the CFD code by means of a purpose-built user defined function (UDF), i.e. a C-language routine properly written to be linked to the CFD solver. Thermal radiation heat transfer was accounted for by the ETC itself and hence none radiation model was activated for the computation. A quadratic void-fraction distribution was also implemented in order to replicate the different particles arrangement, numerically and experimentally observed [14, 15], in the axial direction of the packed bed.

Air was treated as incompressible ideal gas with temperature-dependent thermo-physical properties assigned as piecewise linear interpolations of tabulated data. Conversely, the thermal properties of the solid materials (rocks and concretes) were experimentally measured, and extrapolated afterwards, to cover a wider temperature range [15]. The extrapolated values were then assigned to the relative materials as piecewise linear profiles.

5. Evaluation of stratification efficiency

With the aim of characterizing the stratification efficiency of the industrial-scale TES system proposed, a UDF was developed and implemented into Fluent. Once executed, the UDF allows to perform a loop over all the computational cells of the packed bed in order to collect information such as temperature, volume and absolute position of each cell.

Based upon an arbitrary number of divisions, the packed bed is virtually divided in the axial direction into a multilayer zone of constant thickness. All the cells information are automatically stored into the proper layer according to the axial position of each cell. The temperature of each layer is then computed by means of a volume-averaging technique. The resulting array, containing the temperature and the volume of each layer, is automatically exported and post-processed. The gathered values were exploited to compute the total amount of energy available, along with the temperature distribution into the packed bed, during the process.

6. Results and discussion

The 30 consecutive cycles analyzed were characterized by 12 hours at most of charging followed by 12 hours of discharging with an air mass flow rate, through each TES unit, of 89.6 kg/sec for both the phases. However, especially for the first cycles, a discharge phase of 12 hours would have led to a too low HTF outlet temperature. Because of that, besides the temporal constraint, the discharge phase was considered completed once the HTF outlet temperature from the TES was equal to 600°C. With this further constraint, the only discharge phase with a duration sensibly lower than 12 hours was the first one lasting for about 10 hours. The second discharge showed a duration of about 11 hours and 30 minutes and, from the fifth discharge phase on, the TES was able to provide an HTF outlet temperature higher than 600°C for the 12 hours.

The resulting temperature profiles are presented in terms of temperature distribution, of the TES system, at different time spans. Non-dimensional quantities were exploited to describe the results obtained; non-dimensional position and temperature of unity indicate the upper surface, and the highest temperature respectively, of the packed bed. Non-dimensional position is obtained by dividing the dimensional axial position with respect to the total packed bed height; while, non-dimensional temperature is given by the ratio of the resulting temperature, of the layer under investigation, minus the minimum temperature of the packed bed, at the instant of time considered, divided by the difference between the maximum and the minimum temperature of the packed bed at the same instant of time. Figure 2 shows the result obtained in terms of temperature distribution into the packed bed as a function of the axial position. Left-hand side of Fig. 2 focuses on the temperature distribution at the end of some of all the charge phases analyzed; conversely, in the r.h.s. of Fig. 2, the end of the corresponding discharge phases is reported. An important consideration that can be drawn is that, during the initial cycles, the TES undergoes a sharp variation of thermal stratification. This is due to the fact that, at the beginning of the CFD simulation the TES system was assumed to be in its dead-state; the effect of having both the charging and discharging temperatures different from that of the initialization led to the creation of two separate thermocline zones into the packed bed. This phenomenon was already observed in a previous study [6] in which 15 consecutive cycles only where analyzed. The additional cycles simulated here allowed to confirm that the double thermocline effect disappears towards the end of the 30 cycles analyzed.

Figure 3 shows the the temperature contours of the TES system at the end of some consecutive charge phases. The result obtained in terms of transient evolution of thermal stratification is reported in Fig. 4 and Fig. 5. The graphs of Fig. 4 shows the instantaneous values of stratification efficiency (eq. 2), computed every two hours of simulation, for some of the charging (l.h.s.) and the discharging (r.h.s.) analyzed. Conversely, Fig. 5 summarizes the previous results indicating the average value of the six stratification efficiency computed for each phase. The blue markers represent the average stratification efficiency of the charge phases while the red ones correspond to that of the discharge phases. Concerning the charging, the results reported in the l.h.s. of Fig. 4 and Fig. 5 indicate that the TES behaves almost as an ideally stratified TES during the first charging loosing rapidly the stratification within the initial cycles. The minimum value of stratification efficiency, of about 0.73 on average, is achieved with the 4th cycle; from that point on the stratification efficiency increases. A different behaviour is observable for the discharge phases; in this case, the stratification efficiency was minimum during the 1st discharge phase increasing constantly during consecutive phases until reaching a maximum value of 0.95 at the 20th discharging.

The difference between the average stratification efficiency of the charge and discharge phases reduces with consecutive cycles, disappearing towards the 19th cycle where the two thermocline zones merge with each other into a single one. From this point forward, the stratification efficiency slightly decreases until reaching a stable condition of about 0.93.

Considering that a single cycle corresponds to one day, the transient behaviour of the TES system is in the order of one month. Pre-charging the TES system, i.e. charging for a certain time the storage before the beginning of the cyclic operation might be a valuable solution to reduce the long time required to achieve a stable condition.

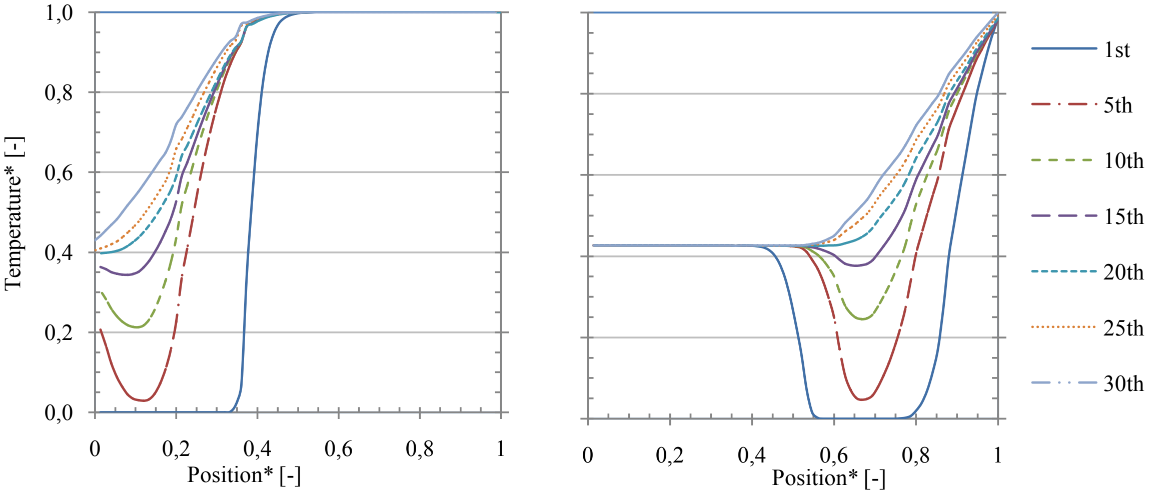

Fig. 2: Non-dimensional temperature as a function of packed bed height at the end of some charge (l.h.s.) and discharge (r.h.s.) phases

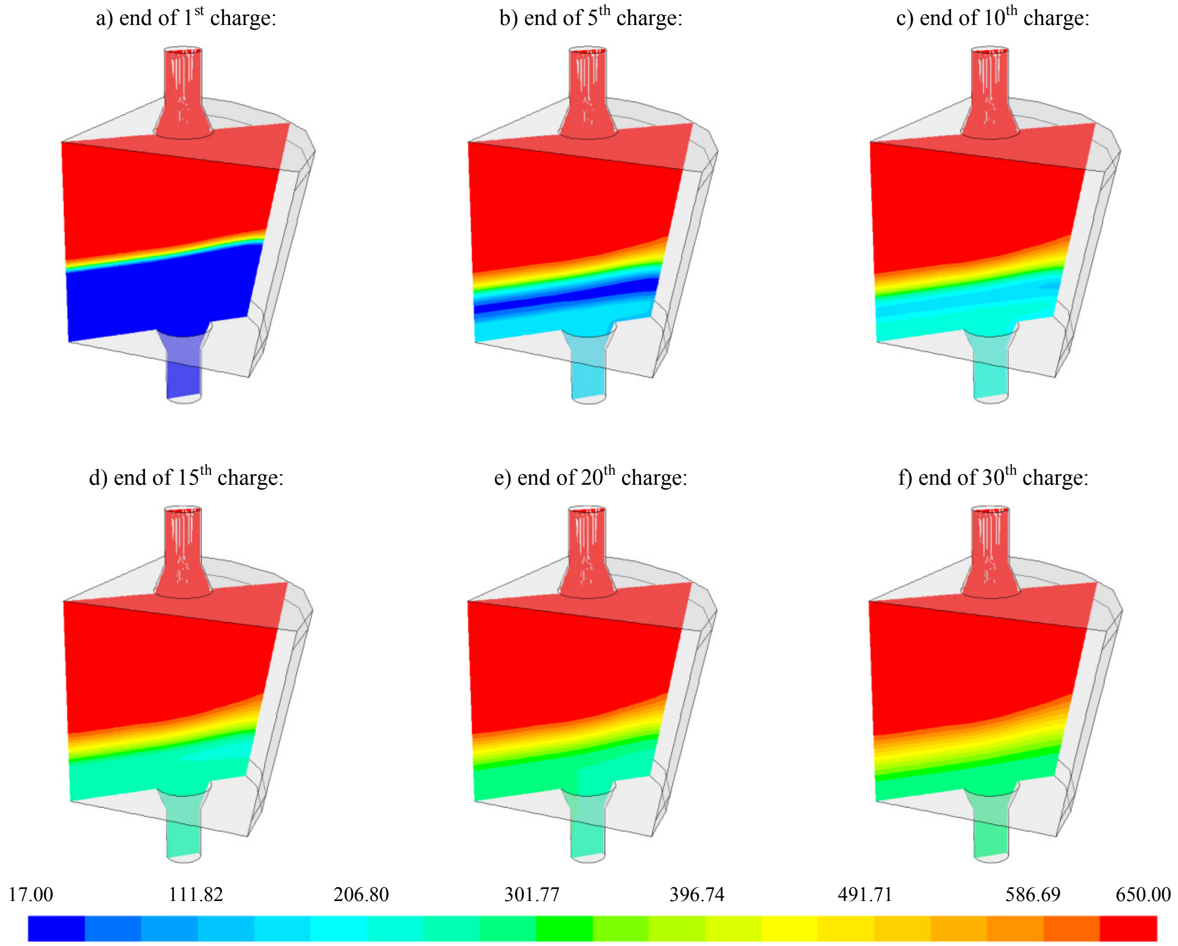
a) end of 1st charge:
b) end of 5th charge:
c) end of 10th charge:
d) end of 15th charge:
e) end of 20th charge:
f) end of 30th charge:

Fig. 3: Temperature contours of the TES system at the end of several consecutive charge phases. Temperature values are [°C].

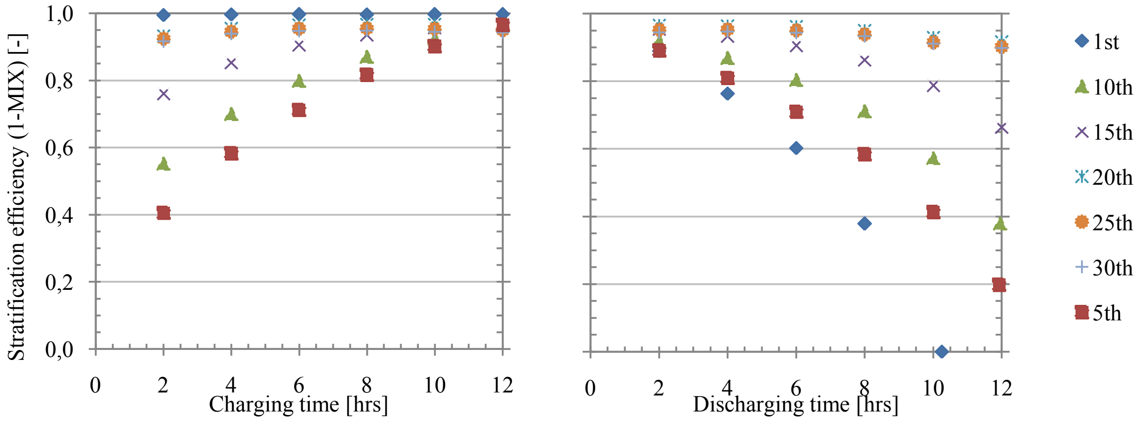

Fig. 4: Instantaneous stratification efficiency for consecutive charging (l.h.s.) and discharging (r.h.s.).

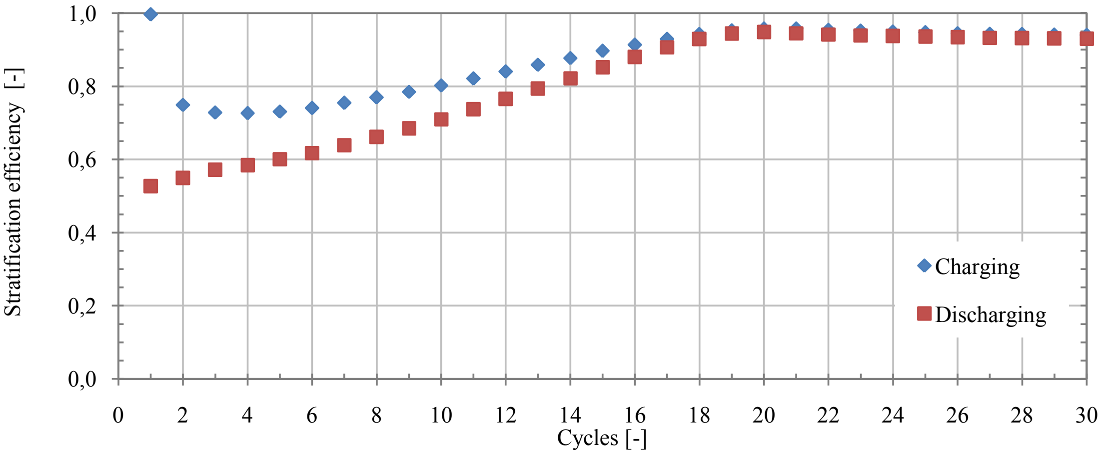

Fig. 5: Average transient stratification efficiency for consecutive charge/discharge cycles.

7. Conclusions

The thermo-fluid dynamics behaviour of a single-tank TES system, with gravel as low-cost filler material, was obtained by means of accurate time-dependent 3D CFD simulations. The system was analyzed, under 30 consecutive cycles of charge and discharge phases in order to evaluate the effect of the initial cycles on the thermal stratification. A stratification efficiency index, based on the so-called moment of energy, was exploited to characterize the extent of thermal stratification into the packed bed. The latter showed a strong variation lasting for 20-22 cycles. A stable thermal stratification into the packed bed was achieved towards the end of the 30 cycles analyzed. The long transient behavior is the result of the two thermocline zones, observed into the packed bed for the first 19-20 cycles, given by the start-up of the TES. Pre-charging the TES system before the first cycle might be a valuable solution to sensibly reduce the long time required to achieve a stable thermal stratification.

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