Parametric and optimization analysis of a packed bed thermal energy storage system

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1. Introduction

In addition to a better exploitation of the available solar resources in concentrated solar power (CSP) plants, thermal energy storage (TES) solutions lead to an optimum energetic production strategy together with the subsequent decrease of the final cost of the produced electricity. This optimization of the energetic resources through the deployment of cost effective TES systems is in agreement with the main roadmaps which determine the potential evolution in the next decades of the CSP production. The accomplishment of these objectives implies an important cost reduction of the CSP technologies implemented on current production plants, such as the double molten salt tank TES systems. In this line, solid packed bed arrangements have been proposed in the last years as a successful cost effective TES system with high thermal performance [1, 2]. The increasing number of scientific publications analyzing the mentioned TES system for CSP, waste heat recovery or adiabatic compressed air energy storage (ACAES) applications demonstrates the large capabilities of this concept. This configuration provides a highly efficient TES with a minimized overall cost, as low cost solid materials can be implemented as storage materials in this single tank storage solution. As an example, natural rocks, sand or ceramic industrial wastes have been proposed as solid TES materials for this application. Although a noticeable research effort has been done on the analysis of the driving mechanisms of this storage system, the commercial implementation maturity of this technology still presents important improvement challenges in real scale applications.

Following the research work performed in our laboratories [3], in this work, the use of steel slag as low cost solid material is proposed together with air as heat transfer fluid (HTF). This material selection presents a double interest. On one hand, the cost effectiveness of the TES system is guaranteed, as the solid material is a waste from the steel industry and the HTF is air. On the other hand, these materials permit to remove the current operation temperature range limitation, constrained to the solar salt range between 280-565 °C. In addition to the viability analysis of the selected packed bed configuration for TES, the main objective of this work is to provide a complete design guideline of a generic packed bed storage system, showing all the potential optimization gap of this technology. The performed parametric analysis includes a detailed study of the impact of the main design parameters such as the tank geometry (cylindrical or conical), aspect ratio, solid particle size and mass flow rate/velocity of the HTF. Additionally, the influence of the heat management of the storage is also analyzed, showing a great importance in order to maximize the thermal performance and dispatchability of the stored energy. The impact of these parameters on the stored energy, quality of the released heat and the overall efficiency is discussed. To assess all the mentioned parametric analysis computational fluid dynamic (CFD) calculations have been performed.

2. Methodology

To maintain the generality of the results, a benchmark case study was pre-selected, with a full compatibility to a new generation CSP production frame. As a reference, the volume of the TES unit was fixed to 3 m³, corresponding to a maximum storage capacity of around 1 MWh. The selected HTF was air up to a maximum temperature of 700 °C, whereas the TES material is the aforesaid steel slag [3].
In order to guarantee the accuracy of the presented results, prior to the calculations, the implemented model was validated using the experimental results published by Zanganeh et al. [2]. This allowed performing precise calculations to determine a general optimization process of packed bed storage units as a function of a wide variety of design parameters.

All the presented optimization work not only permits to determine a successful design procedure of TES systems of this nature, but also identifies the optimized operation conditions of the storage unit. In this work the flexibility of the investigated system is also discussed, as it opens the possibility of a stationary or transient storage operation, depending on the governing conditions. As an example of this parametric analysis, in Fig. 1, it is presented the total energy as a function of the solid pebble size and fluid flow rate for a fixed tank aspect ratio of two. The temperature difference between the fluid and the solid media close to the tank outlet during discharge operation is also shown for two pebble size at a fixed fluid flow rate.

3. Conclusions

Even if the packed bed TES technology was introduced in the CSP field in the last years, its full deployment in commercial CSP plants presents a clear improvement potential. In order to overcome the under-development of this storage technology, this work shows the great capabilities of packed bed storage units after a successful design and operational parametric optimization procedure. The obtained results show that a correct design of this type of facilities for heat storage allow to increase around 50 % the storage capacity reaching an overall efficiency higher than 90 %. The design guideline obtained as a result of this work could open new objectives and applications for the packed bed storage technology as it represents a cost effective and highly performing storage alternative.

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