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CFD modeling and experimental validation of a high-temperature pilot-scale combined sensible/latent thermal energy storage

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Abstract

The present study aims at modeling, by means of computational fluid dynamics (CFD) simulations, the thermo-fluid dynamics behavior of a thermocline combined sensible/latent heat storage. A simplified 2D axisymmetric numerical model was developed and time-dependent CFD simulations were performed. The channeling effect was accounted for by modeling an exponential decay of the void fraction in the radial direction of the packed bed. The results of the CFD simulation were satisfactorily validated with experimental data gathered from a pilot-scale thermal energy storage (TES). The CFD simulations were performed with Fluent 15.0 code from ANSYS.

Introduction

The development of reliable and cost-effective TES systems is among the main technical challenges to realize the long-term energy policy (Energy Strategy 2050) developed by the Federal Council. In the field of high-temperature TES, packed beds with low-cost filler material can be considered as representative solution for sensible heat storage and even the most suitable for air-based systems such as advanced adiabatic compressed air energy storage (AA-CAES). However, an intrinsic drawback of this solution is the decrease of the heat transfer fluid (HTF) outlet temperature, towards the end of the discharge phase. This drawback can be avoided if a latent TES, based on phase change material (PCM), is exploited instead. However, the high cost of the PCM is among the limiting factors on its integration into an AA-CAES plant. For this reason, the idea of adding a small amount of PCM on top of the packed bed was proposed with the aim of mitigating the HTF temperature decrease during discharging limiting, at the same time, the increment of the overall TES system cost.

TES prototype

A 42.3 kWh_{th} combined TES pilot-scale prototype (Fig. 1) has been built and tested. A packed bed of gravel, 32 mm average diameter, was exploited as sensible heat storage. Because of its melting temperature range suitable for AA-CAES technology, the $AlSi_{12}$ alloy was selected as proper PCM material. It was encapsulated in steel tubes, 18 mm external diameter, positioned on top of the packed bed. Pebbles and encapsulated PCM were located into a well-insulated 1.68 m high cylindrical stainless steel tank, 0.4 m external diameter, resulting in a total height of 1.27 m and 0.09 m of the former and the latter respectively. The prototype is equipped with several thermocouples (TCs), along with a mass flow meter, to monitor the temperature and the HTF mass flow rate evolution during tests. Air was exploited as HTF. During charging, hot air is fed through the TES from top delivering its thermal energy to the PCM and rocks leaving then the system from the bottom. Conversely, during discharging, the energy stored is recovered by reversing the air-flow direction with the HTF entering the TES from the bottom and leaving it from top.

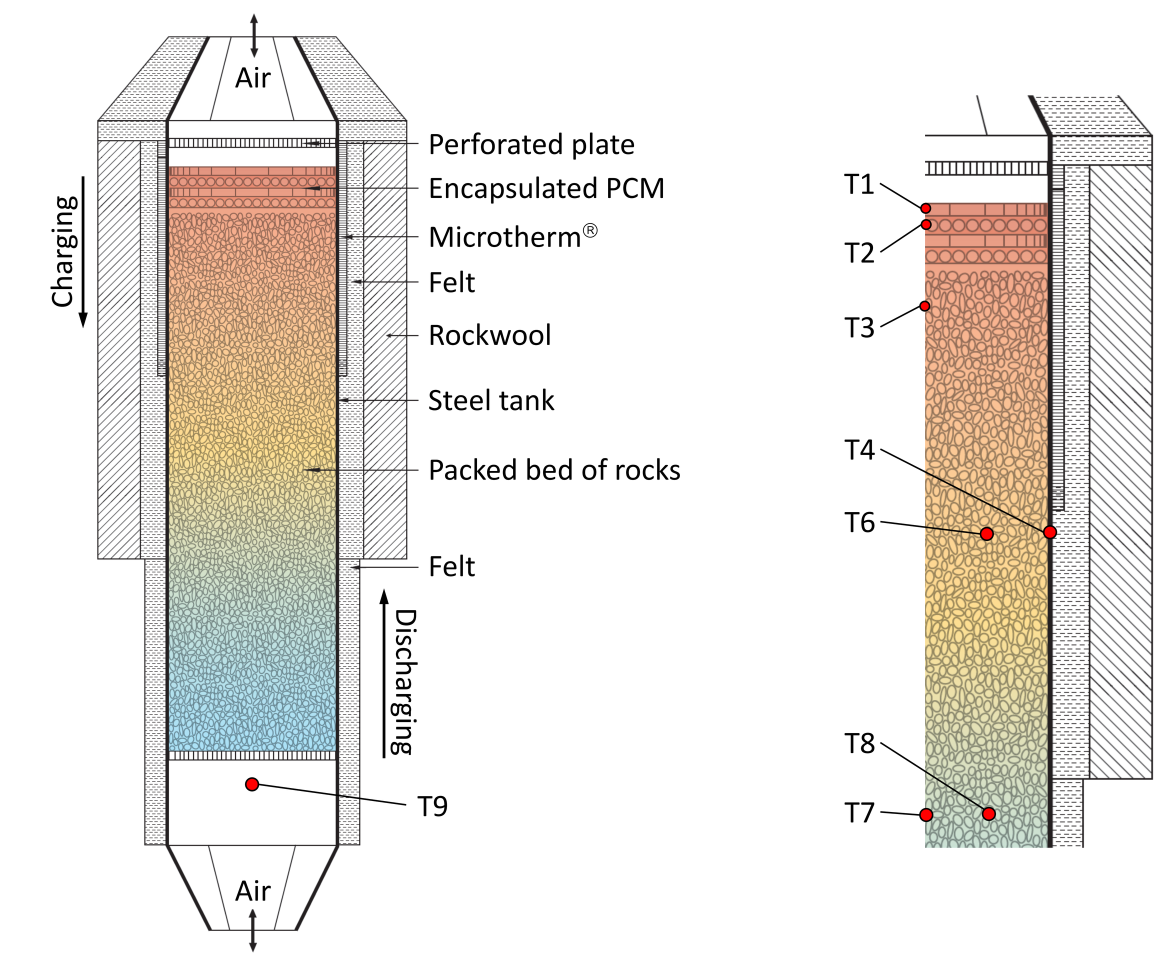

Fig. 1: Schematic of the pilot-scale combined TES (l.h.s.) and TCs position (r.h.s.).

Void fraction distribution and heat transfer in packed beds

Since the characteristic vessel-to-particle diameter ratio of the pilot-scale TES is lower than the threshold value of 25, the void fraction variation in the radial direction of the packed bed must be taken into account. This phenomenon, known as wall-effect or channeling, leads to an increased void fraction close to the wall and hence to a non-uniform HTF velocity distribution over the cross-section influencing the heat and mass transfer in the packed bed.

From the heat transfer standpoint, an effective thermal conductivity (ETC) model was exploited to account for all the non-convective heat transfer mechanisms (conductive-driven and radiative-driven) occurring into the packed bed.

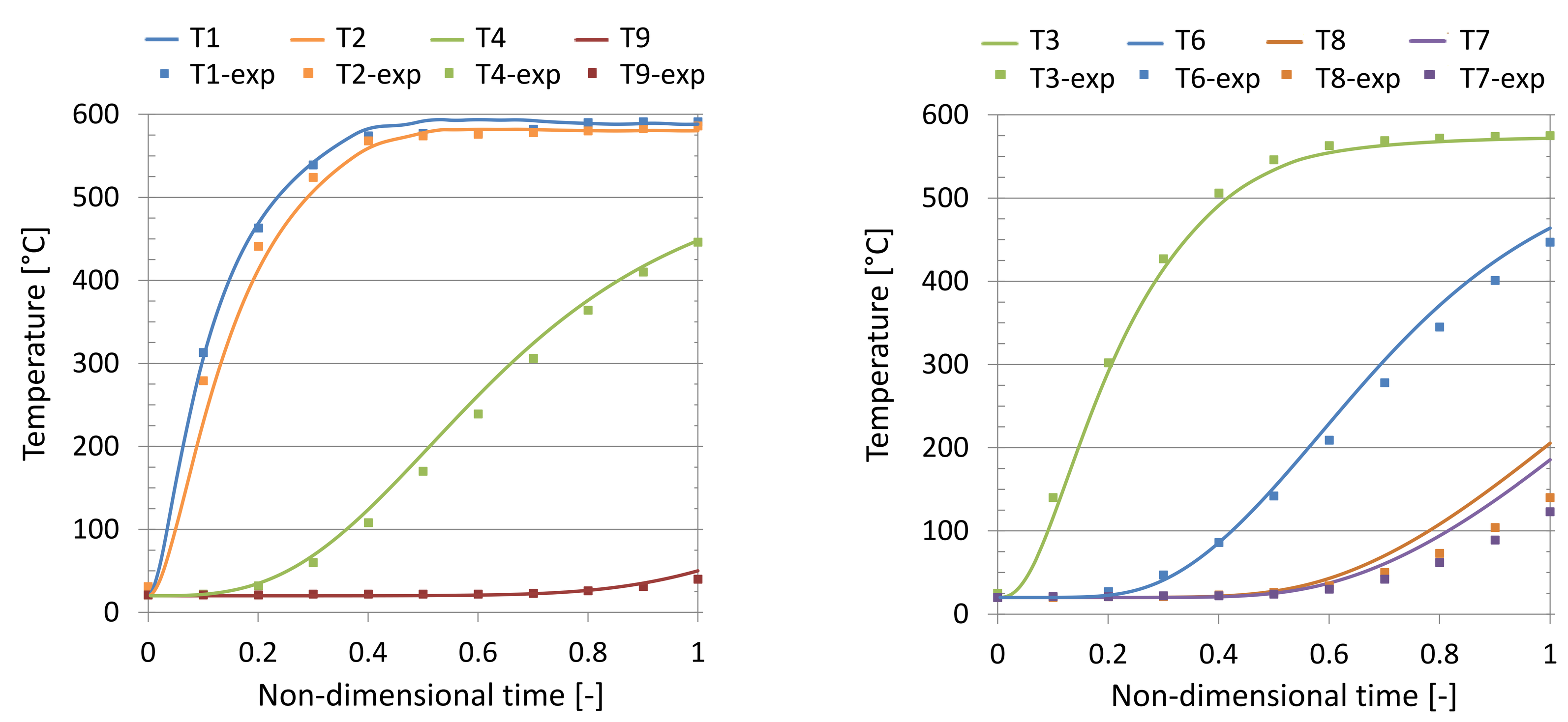

Fig. 2: Comparison between CFD simulation results (solid lines) and experimental data (markers).

CFD simulation results and conclusions

The packed bed of rocks and the PCM layers were modeled exploiting the porous media approach under the assumption of local thermal non-equilibrium (LTNE). The PCM phase transition was modeled as sensible process, i.e. non-explicit phase change tracking, with an increased material heat capacity. Figure 2 shows the validation of the CFD model developed with experimental data. A good agreement between CFD results (solid lines) and experimental data (markers) was obtained for all the TCs. Nevertheless, further efforts are still required to improve the model accuracy concerning the lowest two TCs (T7 and T8) in the packed bed. Figure 3 shows the temperature distribution into the TES prototype during the reference charging test; the importance of channeling on the heat transfer into the packed bed can be easily noticed by the resulting thermal gradients in the radial direction.

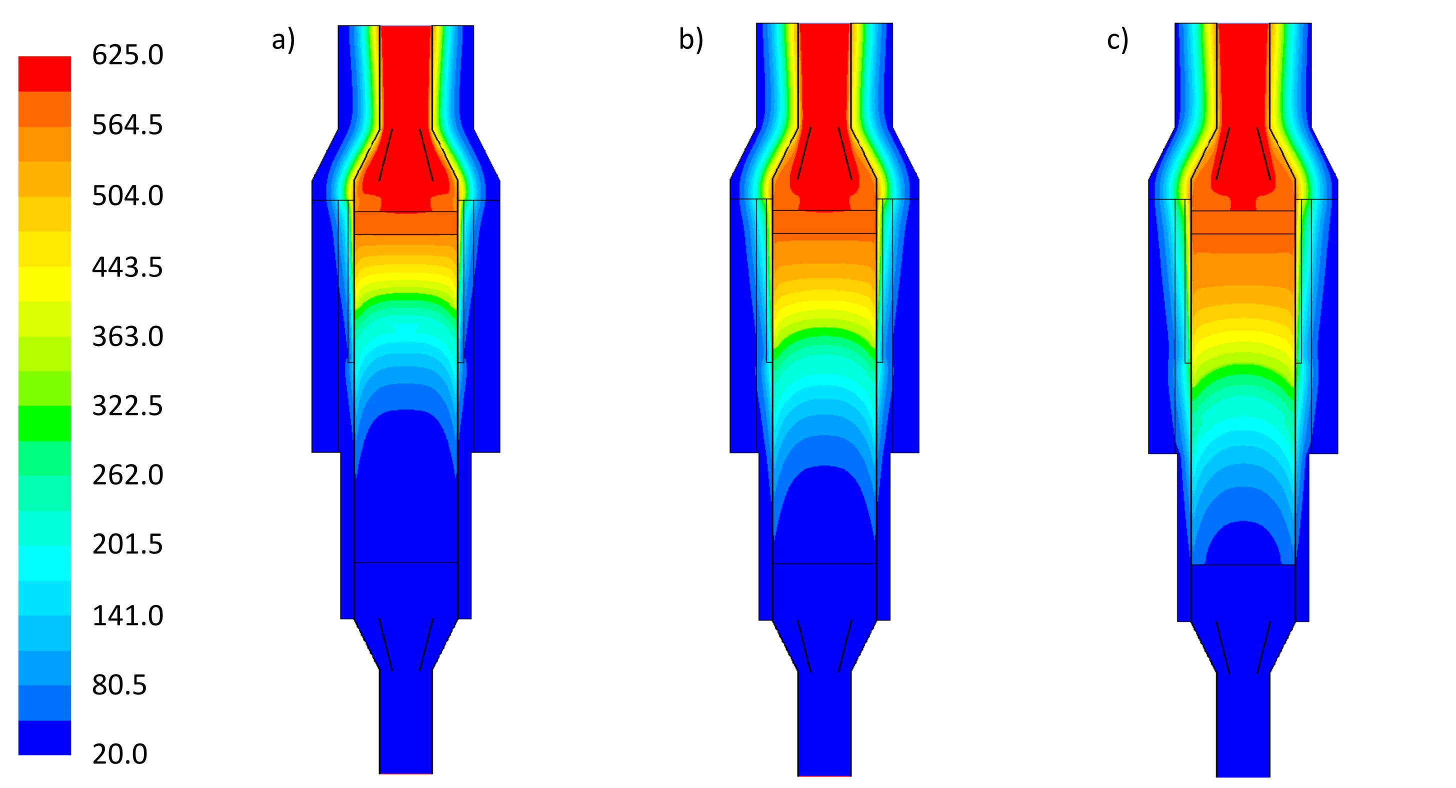

Fig. 3: Temperature distribution after the reference charging of: a) 1.67 h; b) 2.22 h; c) 2.78 h. Temperature values are in [°C].

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