Solar World Congress 2025

LESSONS LEARNED FROM A 1-YEAR TESTING OF A COPPER SLAG PACKED BED THERMAL ENERGY STORAGE WITH RADIAL-FLOW TOPOLOGY

Summary

This study reports the experimental testing of a radial-flow packed-bed thermal energy storage (TES) system using Chilean copper slag as storage material. This system is proposed as an affordable solution to integrate renewable electricity in Power-to-Heat applications. Key challenges emerged over a year of operation: heater failures due to external conditions, significant thermal inertia from the steel structure, difficulties in characterizing the system's pressure drop, and temperature measurements due to the filler material's irregular shape. These findings highlight critical design and operational considerations for future TES scale-up.

Keywords: Thermal Energy Storage, Packed-bed, Experimental testing

1. Introduction

Thermal Energy Storage (TES) systems play a critical role in mitigating the mismatch between thermal energy generation and demand profiles. Although TES is often regarded primarily as a backup for solar thermal systems, its application extends to a broader range of renewable heat-supply technologies. For instance, due to the extensive deployment of variable renewable energy (VRE) systems, the occurrence of curtailment of renewable electricity has increased significantly. In this context, there is a growing interest within the scientific community in the development of cost-effective solutions to harness such electricity surplus through Power-to-Heat strategies.

The present work describes the insights gained from a 1-year testing of a TES system designed to store energy by transforming electricity into heat. The system comprises a packed bed TES unit that employs Chilean copper slags, a by-product of copper smelting, as a storage medium. The material is confined in a concentric cylinder tank, especially engineered to facilitate radial flow of the heat transfer fluid (HTF), thereby inducing a thermal gradient within the solid matrix. Previous studies had demonstrated that radial-flow systems reduce pressure and thermal losses (Calderón-Vásquez & Cardemil, 2024). Furthermore, the thermophysical properties of copper slag allow operation at temperatures up to 800 °C, enabling high energy densities, which contribute to reducing the TES design volume (Segovia et al. 2025). Despite these advantages, the operation of the system revealed several challenges that must be addressed to ensure a scalable and practical solution.

2. Materials and methods

The experimental test-rig was designed and built to investigate the performance of a radial-flow packed bed TES system during charge, discharge, and stand-by processes. The system consists of four main components: (1) The heat source comprises an electric heater (EH) of 35 kW of nominal heating capacity. The EH is connected to a fan and, as a whole, provides hot air during the charging process. (2) The piping system is built from 4-inch diameter pipes, fittings, and valves. The latter allows air flow control to study charge, discharge, and stand-by configurations in the test bench. Additionally, a secondary fan is employed to supply ambient-temperature air during the discharge phase. This is achieved through a bypass system designed to circumvent the primary heat source. (3) The storage tank is a cylinder of 0.2 m³ of internal capacity. Cylindrical meshes are arranged concentrically to form an annulus of 363 mm. The space is filled with copper slags as received from the foundry, with an apparent diameter of 1 inch. (4) The instrumentation includes thermocouples to measure the tank's inlet and outlet air temperature; thermocouple (TC) trees developed to collect data from radial and axial temperature distribution in the storage medium, a differential pressure sensor to measure pressure drop along the storage tank, and a hot-wire anemometer to quantify the inlet mass flow rate.

During the charging process (denoted with red lines in Fig. 1), the EH supplies hot air to the TES. It enters from the inner pipe, conveys thermal energy to the copper slags, and exits the tank at the external mesh. The cold air is collected in an outlet pipe and exhausts the environment. To discharge the stored thermal energy, the valve that enables the heated air to enter the piping network is closed and redirected to an exhaust pipe to cool the resistive elements in the electric heater (see orange line in Fig. 1). The other valves in the piping systems are re-configured to discharge mode (blue lines in Fig. 1), and the second fan is activated. In this process, room-temperature air enters the tank from the outer layers, recovers the heat stored in the solids, and exits the system at the inner pipe. For the stand-by process, all the test rig valves are closed without activating the EH or the second fan.

The interaction of all the described components enables the system's operation at the laboratory scale, controlling the charge, discharge, and stand-by periods manually. The monitored variables that define the start and end of each period are temperature and process time, which are locally recorded in a data acquisition system.

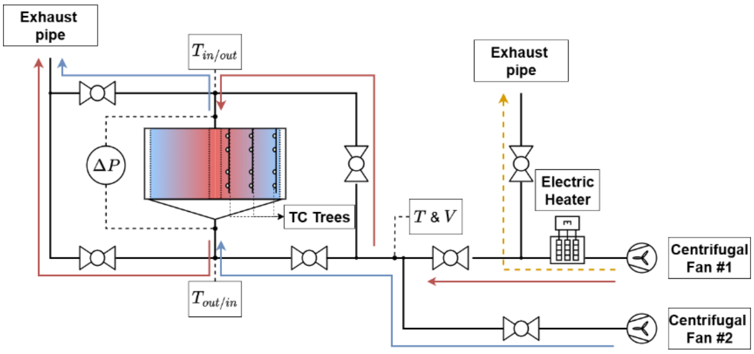

Fig. 1: Scheme of the experimental setup

3. Results

Considering the experimental campaign, several insights were gained regarding the challenges in operating a radial-flow packed-bed TES system, using an industrial byproduct as a storage medium. These are described in this section.

3.1. Heating element maintenance

The electric heating unit experienced two failures during the experimental campaign. The first was caused by moisture accumulation on the resistive elements due to prolonged inactivity. As the system remained in an indoor workshop, the moisture content in the surrounding air was not controlled. The second failure was triggered by a power outage that affected the whole country. This event abruptly stopped a charging period, causing the resistance's lack of cooling. During the repairing process in this second failure, it was noted that one of the electric resistances was damaged due to the sudden outage, as observed on Fig. 2.

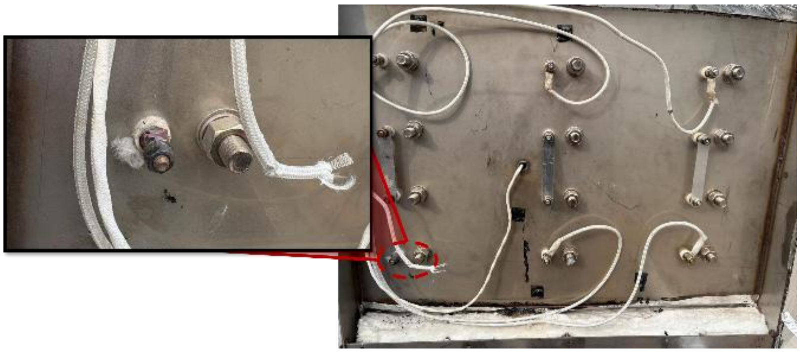

Fig. 2: Wiring of electric resistances in the heater and the damaged elements

3.2. Thermal capacitance of the steel structure

The thermal inertia of the steel piping and tank is comparable in magnitude to the copper slag within the storage system. Consequently, part of the thermal energy supplied is transferred to the steel structure. The initial heating of the system must be accounted for in the TES thermal analysis and control strategy. Fig. 3 demonstrated this capacitance effect comparing the electric heater’s outlet temperature and the TES inlet temperature during a charging process at 220 °C. At the beginning of the charging process, there was a considerable difference in the heating rates during the initial heating periods. After reaching the target temperature, the difference between the two variables remained up to 20 °C.

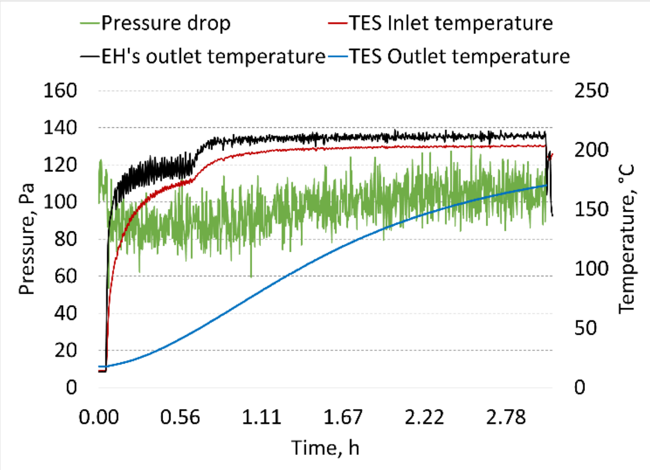

Fig. 3: Transient operation of pressure and temperature during the charging process at 220 °C

3.3. Pressure drop measurements

Measuring the pressure drop attributed solely to the porous medium is a current challenge. The recorded data showed significant noise, as depicted in Fig. 3. This noise is attributed to the positioning of the pressure sensors. Furthermore, the complex storage geometry and the lack of suitable instrumentation limited the precision of the measurements. Those conditions led to the implementation of experimental campaigns with the empty system. Comparing these measurements, the effect of the porous medium should be isolated to improve the characterization of the pressure drop in the radial-flow topology.

3.4. Implementation of thermocouple trees

Thermocouple trees effectively capture the spatial temperature distribution within the tank, providing insights into thermal gradients in multiple directions. However, the irregular shape of the "as-received" copper slag contributes to channeling that affects flow distribution. This feature led to unexpected temperature readings in certain storage zones. Improving the packing procedure or pre-processing the storage material could mitigate these effects in future experiments.

4. Conclusions

The experimental operation of the TES system revealed key operational considerations: The heating elements require proper maintenance to avoid failures due to external conditions; the steel structure's thermal inertia significantly affects energy distribution and must be accounted for. Regarding measurements, better instrumentation should be employed for pressure drop characterization, whereas temperature distribution is affected by the filler material's irregular shape. These findings should be considered for upscaling this technology in integrated energy systems.

5. References

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