EuroSun2026

EXPERIMENTAL VALIDATION OF A HYBRID SENSIBLE-LATENT PACKED-BED THERMAL ENERGY STORAGE AT TRL3 SCALE – FINDINGS FROM THE COOPERANT PROJECT

Summary

Hybrid thermal energy storage (TES) concepts that combine sensible solid-state materials with encapsulated phase-change materials (PCM) can increase volumetric storage capacity and improve temperature stability at high operating temperatures, which are required in next-generation concentrated solar power (CSP) systems. This contribution presents a laboratory-scale TRL3 packed-bed storage unit (40 L), developed as part of the Horizon Europe project COOPERANT, containing approximately 130 particles and tested under representative high-temperature air conditions relevant for air-based CSP operation.

The campaign compares a sensible configuration with hybrid setups featuring different PCM fractions. Both structured and unstructured packed-bed arrangements are investigated to evaluate the influence of bed morphology on heat transfer, pressure drop, and discharge behaviour. The objective is to assess the effects of latent integration and bed structuring on energy capacity and thermal performance.

The experimental methodology and evaluation framework are presented. Final performance results will be discussed at the conference.

Keywords: thermal energy storage, hybrid sensible-latent storage, packed bed, encapsulated PCM, high temperature, experimental validation, TRL3

Field of application for the findings: high-temperature CSP systems and industrial process heat above 700 °C

Addressed audience: TES researchers, high-temperature material developers, packed-bed designers, CSP system engineers

1. Introduction

The Horizon Europe project **COOPERANT** aims to develop and validate an advanced air-based CSP concept operating at elevated temperatures to improve overall system efficiency and enable new application fields. Raising operating temperatures in next-generation CSP systems increases cycle efficiency and broadens application potential, but it also imposes demanding requirements on thermal energy storage.

Purely sensible packed-bed systems are robust and cost-effective (Pelay et al., 2017), yet their energy density scales linearly with temperature difference. Latent storage using phase-change materials offers higher energy density and near-isothermal heat release (Pelay et al., 2017; Ong et al., 2019) but introduces challenges related to encapsulation, compatibility, and integration.

Hybrid TES concepts combine a high-temperature sensible matrix with embedded macro-encapsulated PCM. In such systems, the sensible structure ensures mechanical stability and convective heat transfer, while the PCM contributes latent heat and improved temperature control during discharge (Flueckiger and Garimella, 2014). Besides material selection, the geometrical arrangement of the storage medium inside the reactor influences thermocline behaviour, pressure drop, and effective heat transfer area (Nithyanandam et al., 2012). Structured and unstructured packed beds may therefore exhibit different operational characteristics.

Although modelling studies predict benefits in energy density and thermal management, experimental validation under representative high-temperature airflow conditions remains limited.

This work reports on a TRL3 experimental campaign designed to validate the hybrid concept at particle and packed-bed level, and to quantify performance differences between sensible-only and hybrid configurations as well as between structured and unstructured bed arrangements.

2. Experimental setup and methodology

2.1. Storage unit

The packed-bed reactor has a hexagonal geometry with a total internal storage volume of approximately 40 L. The bed is filled with around 130 solid-state particles manufactured from an extruded high-temperature formulation.

The extruded bodies consist primarily of slag as the main raw material, aluminium-oxide-containing components as functional secondary materials, an inorganic binder, and additives to improve plasticity and processability. The slag provides thermal storage capacity and high-temperature stability. Aluminium-oxide-containing materials enhance mechanical strength, chemical durability, and thermal conductivity. The inorganic binder, applicable as powder or aqueous solution, ensures particle cohesion, supports homogenisation during mixing, and guarantees dimensional stability during extrusion.

Each particle contains four internal channels. These channels either promote convective heat transfer and controlled airflow distribution or serve as integration cavities for PCM capsules.

For hybrid configurations, macro-encapsulated PCM is embedded within the four channels. The encapsulation concept is based on high-temperature-resistant metallic capsules designed to withstand repeated melting and solidification cycles in the 700–900 °C range. Following an extensive evaluation including material compatibility and cycling tests of different PCM and encapsulation combinations, the PCM H885 supplied by PCM Products was selected for integration.

The storage is operated with electrically heated air to reproduce representative boundary conditions of advanced air-based CSP systems.

2.2. Test Campaign

The experimental campaign is designed to systematically evaluate the influence of PCM integration and bed configuration on storage performance. Both structured particle arrangements and unstructured packed-bed configurations are investigated to identify possible differences in thermocline development, heat transfer behaviour, and pressure drop.

The test programme consists of two main stages.

a. **Sensible reference operation**
   In this configuration, the storage contains no PCM. These tests establish the baseline behaviour of the system, including heat capacity, thermocline propagation, pressure drop, and discharge characteristics under defined boundary conditions.
b. **Hybrid configurations with increasing fractions of PCM-integrated particles**
   All operating conditions such as inlet temperature and mass flow rate are kept constant to ensure direct comparability with the sensible reference case. This step allows isolation of the latent contribution to overall performance.

The evaluation focuses on the following performance indicators:

- Effective volumetric energy density
- Discharge duration above a defined outlet temperature threshold
- Outlet temperature stability and thermocline shape
- Pressure drop across the packed bed
- Repeatability over multiple cycles

This structured approach enables a consistent comparison between sensible-only and hybrid configurations as well as between structured and unstructured bed arrangements.

3. Expected impact and discussion framework

The experimental campaign addresses the following research questions:

- To what extent does latent integration increase effective volumetric storage capacity within the same temperature window?
- How does PCM fraction influence discharge temperature stability?
- How do structured and unstructured packed beds differ in terms of heat transfer characteristics and pressure drop?
- Does PCM integration significantly alter airflow distribution within the bed?
- How robust is the hybrid particle concept under repeated thermal cycling?

The results will provide validated performance data at TRL3 scale. These data will serve as input for calibration of reduced-order packed-bed models and support subsequent scale-up towards higher TRL demonstrations.

4. Conclusions

A 40 L laboratory-scale packed-bed storage containing approximately 130 particles has been developed to experimentally validate a hybrid sensible-latent TES concept under high-temperature air operation. The campaign systematically compares sensible-only and hybrid configurations with varying PCM fractions and analyses both structured and unstructured packed-bed arrangements.

The contribution presents experimental design, test strategy, and performance evaluation framework. Quantitative results and comparative performance analysis will be presented at the conference.

5. Acknowledgement

COOPERANT project is funded by the European Union under the Grant Agreement Nº 101172882. This work was supported by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract Nº 2400402.

5. References

Flueckiger, S.M., Garimella, S.V., 2014. Latent heat augmentation of thermocline energy storage for concentrating solar power – A system-level assessment. Applied Energy. 116, 278–287.

Nithyanandam, K., Pitchumani, R., Mathur, A., 2012. Analysis of a latent thermocline energy storage system for concentrating solar power plants. Proceedings of the ASME 2012 6th International Conference on Energy Sustainability, ES2012, collocated with the ASME 2012 10th International Conference on Fuel Cell Science, Engineering and Technology, Parts A and B. 519–528.

Ong, T.C., Graham, E., Will, G., Steinberg, T.A., 2019. High-temperature phase change material selection for concentrating solar power tower applications. Advanced Sustainable Systems. 3(2), 1–11.

Pelay, U., Luo, L., Fan, Y., Stitou, D., Rood, M., 2017. Thermal energy storage systems for concentrated solar power plants. Renewable and Sustainable Energy Reviews. 79, 82–100.