MULTISCALE MODELING OF HYBRID SENSIBLE-LATENT PACKED-BED THERMAL ENERGY STORAGE FOR HIGH-TEMPERATURE CSP - FINDINGS FROM THE COOPERANT PROJECT

Summary

Dispatchable, high-temperature concentrated solar power (CSP) concepts require thermal energy storage (TES) solutions that can operate close to 1000 °C with acceptable pressure drop, thermal losses, and long-term durability. Hybrid sensible-latent packed-bed TES can increase energy density and improve temperature management, but design choices (particle geometry, PCM fraction, packing arrangement) create strong coupled trade-offs between heat transfer, pressure losses, manufacturability, and cost. This work presents a multiscale modelling workflow to screen and rank hybrid TES concepts from particle/block level to packed-bed unit level, and to generate reduced-order inputs for subsequent system simulation and control design.

Keywords: hybrid thermal energy storage, packed bed, phase change material, high temperature, multiscale modelling, effective properties, CSP, air heat transfer fluid

Field of application for the findings: high-temperature CSP-TES (tower/OVR concepts), high-temperature industrial process heat and solar fuels enabling technologies.

Addressed audience: TES/CSP researchers and engineers, modelling and digital-twin developers; designers of high-temperature storage components and demonstrators.

1. Introduction

Next-generation CSP concepts targeting high receiver outlet temperatures (≈800-1000 °C) enable more efficient power cycles (e.g., air Brayton and supercritical CO_2) and broaden the scope of solar-driven industrial heat and fuels. Achieving dispatchability at these temperatures requires TES concepts that combine high energy density, robust containment, and efficient heat transfer under air as HTF.

Hybrid TES concepts that combine a high-temperature sensible matrix with encapsulated phase-change materials (PCM) offer two key benefits: (i) increased storage density through latent heat and (ii) improved temperature management by exploiting phase-change plateaus and/or cascading temperature levels. However, hybrid packed-beds introduce design complexity: the same measures that increase heat transfer surface (smaller particles, higher PCM fraction, complex geometries) can increase pressure drop, cost, and manufacturing risk. As a result, reliable design requires a modelling workflow that (a) explores the design space systematically and (b) produces consistent effective properties for higher-level TES and plant simulations.

This extended abstract focuses on the modelling workflow developed for a hybrid TES concept at material/block and packed-bed scales, and on the first quantitative screening results used to support early design and materials selection within the framework of results from Horizon Europe project COOPERANT.

2. Multiscale modeling workflow

The modelling strategy is organized in two complementary blocks: SIM 1A (block + packed-bed screening): fast parametric screening of candidate hybrid particle/block concepts and their packed-bed arrangements to compute performance indicators (energy density, effective heat-transfer surface density, indicative costs) and SIM 1B (particle-level CFD): higher-fidelity transient simulations to derive aggregated effective properties (effective thermal conductivity, heat-transfer coefficients, pressure-drop behavior) required by reduced-order packed-bed models.

2.1 SIM 1A - block-level parametric screening and packed-bed analysis

The hybrid particle/block design space is explored by combining sensible matrix candidates, PCM candidates, and capsule shell concepts within admissible temperature windows and manufacturing constraints. The parametric study covers 9 particle cross-sections, 4 length-to-diameter ratios, 10 PCM candidates, 3 sensible matrix candidates and 2 encapsulation materials.

For each PCM-matrix-shell combination, block-level calculations provide volumetric and gravimetric energy density (based on a defined temperature window), effective surface density proxies, indicative material and capsule costs.

To translate block properties into unit-level indicators, representative packed-beds are generated and analyzed in two main configurations, random packings via three-dimensional rigid-body simulations, ordered packings via two-dimensional packing algorithms followed by three-dimensional rendering.

Packed-bed geometries are post-processed into surface meshes where exposed and unused surfaces are distinguished to compute effective heat-transfer surface area (as opposed to purely geometric surface area). Combined with block-level properties, this yields packed-bed unit indicators such as volumetric energy density, effective surface density, packing density, and total storage cost.

2.2 SIM 1B - particle-level CFD for aggregated effective properties

SIM 1B builds on the most promising concepts identified by SIM 1A and targets the derivation of aggregated effective properties suitable for reduced-order packed-bed modelling. Representative capsule and small-assembly geometries are defined in alignment with planned experimental configurations. The CFD workflow is intended to quantify transient heat transfer (conduction, convection and radiation contributions where relevant), effective thermal conductivity, convective heat-transfer behavior, and pressure losses in hybrid particles/assemblies under representative operating conditions.

The SIM 1B outputs are used to populate system-level models with physically grounded closure parameters (e.g., void fraction, convective transfer coefficients, Biot-number-consistent heat transfer behavior), enabling efficient simulation of charging/discharging dynamics without explicitly resolving phase change in every capsule at full bed scale.

3. Preliminary results and design implications

Table 1 summarizes a reference hybrid concept selected for the next validation iteration in the screening workflow. The concept combines a high-temperature PCM candidate with a sensible matrix and a metallic capsule shell, yielding a block-level volumetric energy density of $\approx 231\ \mathrm{kWh\ m^{-3}}$ for the stated temperature window.

Table 1 Example block-level properties of a screened hybrid concept (SIM 1A).

Parameter	Value
PCM (candidate)	sulphate-based molten salt, PCT ≈885 °C
Sensible matrix (candidate)	extrudable high-temperature sensible matrix
Block height	65 mm
Capsule shell thickness	2.5 mm
Temperature window	Thot = 985 °C, Tref = 785 °C
Capsules per block	4
PCM volume fraction	21.3 %
Sensible matrix volume fraction	62.1 %
Encapsulation volume fraction	16.6 %
Block-level volumetric energy density	231.245 kWh m^{-3}

At packed-bed unit level (40 L reference cases), the screening shows a packing density varies strongly with arrangement and container (≈0.46-0.71), effective surface density around ≈40-51 $m^2\,m^{-3}$ and a volumetric energy density spanning ≈106-164 kWh m^{-3} for the analyzed configurations.

These results highlight two design-relevant insights: Geometry/packing can dominate performance metrics at unit level (surface density and effective energy density) even when block-level properties are fixed. Cost indicators are highly sensitive to capsule design and fraction, motivating early integration of manufacturability and cost constraints in concept ranking.

4. Conclusions and outlook

A multiscale modelling workflow for high-temperature hybrid sensible-latent packed-bed TES has been established to support early concept ranking and materials selection for a CSP-TES demonstrator. The approach combines fast parametric screening (block + packed-bed) with higher-fidelity particle-level CFD intended to deliver aggregated effective properties for reduced-order packed-bed models.

Next steps focus on refining screening inputs as additional material characterization data become available, completing SIM 1B to derive effective heat-transfer and pressure-drop closures, and integrating the resulting reduced-order TES representations into system-level simulations and monitoring/control design for upcoming validation activities.

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