EuroSun2026

A NOVEL DIFFUSER CONCEPT BASED ON A TPMS–PCM COMPOSITE FOR WATER TANKS

Summary

Water-based stratified thermal energy storage systems operating under solar-driven conditions are often exposed to oscillatory inlet temperatures, which can degrade stratification and reduce storage efficiency. This work proposes a novel PCM-enhanced inlet diffuser as a passive mitigation concept for sensible heat storage tanks. The diffuser embeds a porous metallic TPMS-based scaffold impregnated with phase change material, so that the incoming fluid exchanges heat with a latent-capable matrix before entering the storage volume. The concept was investigated numerically under transient oscillatory thermal forcing. Compared with a diffuser without porous insert, the TPMS+PCM configuration strongly smooths the transmitted thermal signal, reducing the equivalent outlet oscillation amplitude from 10 °C to about 1.72 °C. Results demonstrate the potential of PCM-enhanced TPMS-based diffusers as effective passive thermal buffers for sensible TES systems under non-uniform charging conditions.

Keywords: Thermal energy storage, phase change material, inlet diffuser, TPMS, thermal buffering

Field of application for the findings: Thermal Energy Storage, Solar Thermal Heat.

Addressed audience: Researchers, engineers, and industry professionals in solar thermal energy.

1. Introduction

Thermal Energy Storage (TES) systems play a key role in the integration of renewable energy sources, enabling more flexible and efficient thermal-energy management across many applications. Among them, stratified sensible heat storages are especially attractive for solar thermal plants and hybrid systems because they allow hot and cold regions to coexist within the same volume, thus improving storage density and cost-effectiveness (Han et al., 2009). In real operation, however, these systems are often subjected to non-steady inlet conditions due to fluctuating solar input and dynamic interaction with the user side (Karim et al., 2018). Such disturbances can degrade thermal stratification, promote mixing, and reduce both stored exergy and overall system performance (Chefiki and Boukraa, 2023).

Although inlet conditions are widely recognized as a key factor in stratified-storage performance (Karim et al., 2018), most previous studies have focused on steady or idealized boundary conditions, or on the effects of inlet velocity and turbulence (Lou et al., 2021). By contrast, dynamically fluctuating inlet conditions have received comparatively limited attention, despite their relevance in practical TES operation (Chang et al., 2022). In a previous study, it was shown that inlet-temperature oscillations can severely degrade the stratification of water-based sensible heat storage systems (Anacreonte et al., 2025). Similar sensitivity to non-uniform or oscillatory boundary conditions has also been reported for latent thermal energy storage systems (Li et al., 2020).

A possible passive mitigation route is to exploit the nearly isothermal heat exchange provided by phase change materials (PCMs), which are widely studied because of their high energy density and favourable thermal-regulation capability (Pielichowska and Pielichowski, 2014). However, pure PCMs suffer from low thermal conductivity and leakage issues, which limit their direct use (Li et al., 2012). For this reason, conductive porous supports have been extensively investigated, especially metal foams, which can significantly enhance effective heat transfer in composite PCM systems (Xu et al., 2017). More recently, attention has shifted toward Triply Periodic Minimal Surface (TPMS) architectures, which offer deterministic and tuneable pseudo-porous geometries (Gado, 2024). Overall, the recent literature demonstrates that TPMS-based porous supports can outperform traditional stochastic foams by providing a controllable and reproducible thermal response, tailored through geometric parameters (Qureshi et al., 2021).

Within this framework, the present study introduces a novel PCM-enhanced inlet diffuser concept for water-based sensible heat storage systems, conceived as a passive solution for retrofitting and optimization purposes. The proposed design is intended to mitigate the detrimental effects of non-uniform charging conditions, which are known to cause thermal inefficiencies, stratification degradation, and exergy losses in practical TES operation. The concept is investigated numerically under oscillatory thermal forcing representative of solar-driven operation, with the aim of assessing its capability to attenuate inlet temperature fluctuations and to clarify the thermo-fluid dynamic role of the embedded PCM-enhanced structure.

2. Conceptualization

The proposed concept is based on a PCM-enhanced porous insert integrated within the diffuser region of a water-based sensible heat storage system. As schematically shown in Fig. 1, the incoming fluid flows through a metallic I-WP TPMS-based scaffold whose porous domain is impregnated with phase change material. The selected TPMS geometry is described by its corresponding implicit surface equation.

In this way, the insert acts as a passive thermal buffer: the fluid exchanges heat with the PCM-enhanced matrix while crossing the diffuser, and the latent storage contribution helps mitigate inlet-temperature oscillations before the flow enters the storage volume. The thermophysical properties of both the PCM and the metallic scaffold were taken from Yang et al. (2024). The thermo-fluid dynamic response of the concept was investigated by means of a finite-element numerical model, previously validated against reference data available in the literature.

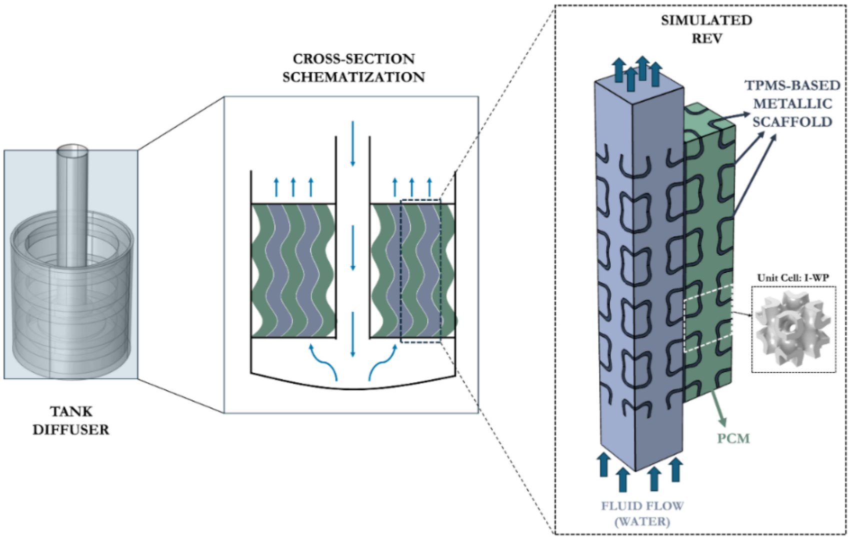

Fig. 1: Conceptual schematic of the proposed PCM-enhanced inlet diffuser. The insert consists of a TPMS-based metallic scaffold impregnated with PCM and placed within the diffuser region, so that the incoming fluid exchanges heat with the porous matrix before entering the storage tank.

3. Numerical results

To provide a first assessment of the proposed concept, transient numerical simulations were carried out under oscillatory inlet thermal forcing representative of non-uniform charging conditions. In the case shown in Fig. 2, the inlet fluid velocity was set to 0.02 m s^{-1} (corresponding to Re_{in}=25), while the inlet temperature was imposed as a sinusoidal function of time with mean value 55 °C, amplitude 10 °C, and an oscillation period (τ) in this case set to 300 seconds (5 minutes). Figure 2 compares the outlet temperature response of the diffuser equipped with the TPMS+PCM insert against the corresponding case without porous insert. The difference between the two responses is evident: while the reference diffuser transmits the imposed oscillation almost entirely, the PCM-enhanced insert strongly smooths the outlet signal, reducing both the oscillation amplitude and the short-term temperature variability. Quantitatively, the equivalent oscillation amplitude is reduced from 10 °C at the inlet to approximately 1.72 °C at the outlet, corresponding to an attenuation efficiency of 82.8%. This result demonstrates that the proposed concept can effectively operate as a passive thermal buffer, mitigating inlet-temperature fluctuations before the fluid enters the storage volume.

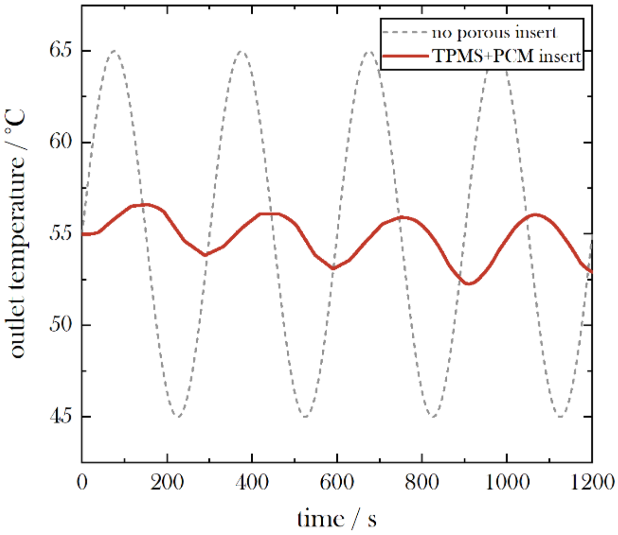

Fig. 2: Outlet temperature response of the diffuser under oscillatory inlet thermal forcing, with and without the pseudo-porous TPMS+PCM insert, for an inlet velocity of 0.02 m s^{-1} ($Re = 25$). The imposed inlet temperature oscillates sinusoidally around 55 °C with an amplitude of 10 °C.

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