EuroSun2026

Development, Characterization and Storage Performance of a Paraffin-Based PCM Emulsion

Summary

Phase change material (PCM) emulsions and PCM slurries are promising candidates for compact thermal energy storage (TES) in the low temperature range, especially in heating and cooling applications where narrow operating temperature windows and high cycling stability are required. This work presents the development of a paraffin-in-water PCM emulsion based on Parafol 18 97 (Sasol), its characterization in the laboratory, its upscaling to cubic meter scale, and its experimental evaluation in a 500 L storage tank with a focus on thermocline behavior and effective storage capacity.

Keywords: PCM-storage, PCM-Slurry, PCM-Emulsion, PCM-Dispersion, Stratification, Thermocline

Field of application for the findings: Thermal Energy Storage

Addressed audience: Researchers

1. Introduction

PCM slurries and emulsions combine sensible and latent heat storage within a pumpable heat transfer fluid. Typical systems employ paraffinic or fatty acid either microencapsulated or emulsified, dispersed in an aqueous carrier. In contrast to macro encapsulated PCM systems, slurries allow direct circulation through heat exchangers, offering high effective heat transfer coefficients and flexible integration into existing hydraulic circuits. However, they introduce challenges regarding rheology, long term dispersion stability, and the reliable characterization of their storage behavior under realistic operating conditions.

Shaikh et al., 2011; Giro Paloma et al., 2016; Cabeza, 2015 for example highlight that for PCM-based TES materials, key design parameters include: (i) the effective latent and sensible enthalpy in the operating temperature window, (ii) viscosity as a function of temperature, shear rate and cycling, and (iii) the ability to maintain stable microstructure and phase fraction over thousands of charge/discharge cycles. For PCM slurries and emulsions in particular, additional issues arise from density and viscosity gradients across the phase change range, which can affect both hydrodynamics and thermal stratification in storage tanks.

Regarding storage measurements, the performance of TES systems is often evaluated in terms of (i) total stored and recoverable energy, (ii) thermocline thickness and its temporal evolution, and (iii) round trip efficiency and exergy preservation. While there is a substantial body of work on stratified water tanks and tanks containing macro encapsulated PCM modules, systematic experimental studies on pilot scale or large scale tanks directly filled with PCM slurries or emulsions are still comparatively limited. Haobin (2022) observed e.g. a similar stratification for a storage filled with water or with a PCM-Emulsion. They also report about a storage density which was PCM- emulsion 1.6 to 1.7 times higher than using water. Recent TES literature emphasizes that accurate characterization of stratification requires dense temperature measurements or advanced reconstruction methods (Miró et al., 2016; Gasia et al., 2017). However, in practical systems the number of sensors is often small due to cost and integration constraints. This motivates the development of simplified, yet robust analysis approaches that exploit available hydraulic and temperature data to reconstruct thermocline evolution and effective storage capacity in PCM slurry and emulsion systems, as pursued in the present work.

2. Materials, Emulsion Development and Laboratory Characterization

A paraffin-based PCM emulsion was developed in the laboratory at a 5 L scale using Parafol 18 97 (Sasol) as the dispersed PCM phase. The initial formulation contained 35 wt.% PCM in an aqueous continuous phase stabilized with suitable surfactants. The emulsion was prepared using high shear mixing followed by high pressure homogenization and characterized with respect to particle size distribution, thermal properties and rheology.

Differential scanning calorimetry (DSC) showed a phase change interval between approximately 20 °C and 28 °C, which is well suited for low temperature heating and cooling applications (e.g. pre heating and cooling in air conditioning, machinery cooling). Over this temperature range, the emulsion exhibited an effective enthalpy change of about 80 kJ/kg, combining both latent and sensible contributions.

Rheological measurements revealed that the emulsion behaves nearly Newtonian within the relevant shear rate range, with a dynamic viscosity between approximately 10 and 40 mPa·s, depending on temperature and PCM phase state. Long term stability was investigated using a dedicated cycling test rig, in which the emulsion was subjected to 10,000 controlled freezing/melting cycles. Over this period, no critical degradation of enthalpy or catastrophic phase separation was observed, indicating that the formulation is robust under laboratory conditions at the 5 L scale.

3. Upscaling to Cubic Meter Scale and Stability Optimization

Encouraged by the laboratory results, the emulsion was transferred to industrial production by the project partner Hansen & Rosenthal GmbH & Co. KG and upscaled to cubic meter scale. However, the change in composition, combined with different mixing equipment and hydrodynamics at large scale, resulted in pronounced deviations from the lab-scale behavior.

After upscaling, the viscosity of the emulsion was approximately twice as high as in the laboratory formulation, and the dispersion stability was significantly reduced. These observations highlight the strong sensitivity of PCM emulsions to both composition and process conditions during manufacturing: energy input, shear history and mixing time at large scale can markedly influence not only droplet size distributions but also rheology and stability.

To mitigate these issues and especially the increased viscosity, the PCM mass fraction was reduced from 35 wt.% to about 32 wt.% and the process parameters were adjusted. This modification improved the stability substantially while maintaining a high storage capacity. The resulting emulsion still exhibited a higher viscosity than the original 35 wt.% lab formulation but remained within an acceptable range for pumping and heat exchange in the addressed demonstration system. Thermal analysis confirmed that the effective enthalpy in the 20–28 °C range remained with 70 kJ kg^{-1} K^{-1} also on an acceptable level.

4. Thermocline Measurements and Storage Capacity in a 500 L Tank

The optimized 32 wt.% PCM emulsion was filled in a 500 L vertical cylindrical storage tank to investigate its stratification behavior, thermocline formation and effective storage capacity under realistic charging conditions. The tank was equipped with five temperature sensors along the vertical axis, representing a practical instrumentation level rather than a dense research-grade sensor grid.

To characterize the thermocline despite the limited number of sensors, a dynamic evaluation method was developed. For each charging experiment, the volumetric flow rate at the inlet (here: 250 L/h) was measured. From the known radius and cross-sectional area of the tank, the average vertical flow velocity within the tank was estimated. As the thermocline passed each sensor, the recorded temperature changed from the initial to the final storage temperature over a characteristic transition time. Multiplying this transition time by the estimated vertical velocity yielded an effective local thermocline thickness for each sensor position. By repeating this analysis over time, the evolution of the thermocline thickness along the tank height could be reconstructed.

The measurements showed that, during charging at 250 L/h, the thermocline initially formed as a relatively sharp interface near the top of the tank, with a thickness of about 140 mm (~10% of the storage´s total height). As the thermocline propagated downward, it broadened, reaching approximately 240 mm near the bottom. The broadening is attributed to a combination of axial dispersion and residual mixing. Despite this increase in thickness, the stratification quality achieved is comparable to typical values reported for water-based stratified tanks under similar hydraulic conditions, demonstrating that PCM emulsions can sustain reasonably sharp thermoclines.

5. Quantitative Assessment of Storage Capacity and Comparison with Water

In the 500 L tank filled with the PCM emulsion, the experimentally determined storage capacities are 10 kWh for a temperature range of 20–30 °C and about 7.6 kWh for a temperature range of 21–28 °C.

For a fair comparison, the theoretical storage capacity of a 500 L water tank over the same temperature ranges can be estimated from sensible heat in the same temperature ranges with 5.8 kWh and 4.1 kWh. However, stratified water tanks do not fully exploit this theoretical capacity due to thermocline formation and mixing losses. Experimental studies on water-based thermocline tanks (e.g. Agyenim et al., 2010; Gasia et al., 2017) typically report effective reductions of 10–25 % in usable ΔT, depending on flow conditions and thermocline thickness (often 0.1–0.3 m). Applying a representative 15–20 % reduction to the ideal values yields realistic water capacities in the order of 4.6–5.0 kWh (20 -30 °C) in 500 L and 3.3–3.5 kWh (21 – 28 °C) in 500 L.

Compared to these realistic water values, the PCM emulsion in the same tank and operating windows provides approximately a factor of 1.8–2.3 higher stored energy. This gain reflects the contribution of latent heat within the phase change interval, while the achieved thermocline quality remains comparable to that in conventional water tanks.

6. Conclusions

The study demonstrates the successful development and upscaling of a paraffin-based PCM emulsion with a phase-change interval between 20 and 28 °C and an effective enthalpy change of about 80 kJ/kg in this range. Laboratory tests at 5 L scale confirmed high cycling stability over 10,000 thermal cycles, and robust dispersion stability. Upscaling to cubic meter scale highlighted the sensitivity of viscosity and stability to PCM content and production conditions; reducing the PCM fraction from 35 wt.% to about 32 wt.% was essential to balance storage capacity, pumpability, and long-term stability.

In a 500 L storage tank, the optimized emulsion formed thermoclines with thicknesses increasing from ~140 mm at the top to ~240 mm at the bottom during charging at 250 L/h, which is comparable to stratification performance in water tanks. The measured storage capacities of approximately 10 kWh (20–30 °C) and 7.6 kWh (21–28 °C) significantly exceed those of a realistic water tank operated over the same temperature intervals, by roughly a factor of two. These results underline the potential of PCM emulsions as advanced storage media for low temperature TES systems.

7. References

Shaikh, S. et al. (2011). Review on phase change material (PCM) slurries. Energy Conversion and Management, 52(1), 290–307.

Dincer, I., Rosen, M. A. (2011). Thermal Energy Storage: Systems and Applications (2nd ed.). Wiley.

Cabeza, L. F. (Ed.). (2015). Advances in Thermal Energy Storage Systems: Methods and Applications. Woodhead Publishing.

Giro Paloma et al. (2016). Types, methods, techniques, and applications for microencapsulated phase change materials (MPCM): A review. Renewable and Sustainable Energy Reviews, 53, 1059–1075.

Miró, L.et al. (2016). Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. Renewable and Sustainable Energy Reviews, 51, 847–855.

Gasia, J. et al. (2017). Experimental evaluation of a lab-scale thermocline storage tank filled with PCM–water slurries and water. Applied Energy, 190, 720–731.

Haobin, L. et al. (2022). Towards idealized thermal stratification in a novel phase change emulsion storage tank. Applied Energy, 310