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Development of phase state detection method for latent heat thermal energy storages

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Abstract

Industrial heating accounts for 74% of the total energy consumption within the industry and latent heat thermal energy storage systems using Phase Change Materials (PCMs) as storage medium, offers an efficient and CO2-netrual solution for the provision of steam in the temperature range from 150 – 350°C [1]. However, determining the stored thermal energy in these systems during partial charging and discharging is challenging, mainly because the phase transition occurs under quasi-isothermal conditions. This study investigates density-induced fill-level changes for a eutectic nitrate-salt (54 wt% KNO_3 – 46 wt% $NaNO_3$). Cylindrical storage equipped with a laser distance sensor and thermocouples was used to measure fill-level variations during phase change. The liquid fraction from fill-level measurements agreed well with the thermocouple-based rule calculation, with maximum and mean differences of 0.125 and 0.115.

Keywords: Latent Heat Thermal Energy Storage, State of Charge Measurement, Phase Change Material, Change of Density

1. Introduction

Nearly 50% of the total energy consumption is needed for heating and cooling [2]. Moreover, Eurostat (2023) reports that the share of renewables in heating and cooling in the EU rose from about 11.7 % in 2004 to around 23 % (2021), indicating a steady increase in demand met by renewable sources [3]. Despite this progress, there is still a significant reliance on non-renewable sources for heating and cooling, highlighting the need for more efficient and sustainable thermal energy storage solutions. One promising approach is latent heat thermal energy storage (LHTES) using Phase Change Materials (PCMs). PCMs can absorb and release between 4 to 10 times more heat than conventional sensible heat storage systems in a narrow temperature range, thanks to the isothermal nature of phase change [4]. This isothermal nature also comes with the challenge of determination of total thermal energy stored inside LHTES, especially in the case of partial charge and discharge. To overcome this problem there is a need for reliable and feasible detection of global liquid fraction, considering also applications at large scale. Several methods have been proposed to estimate the state of charge (SoC) of LHTES systems beyond temperature measurements. An ultrasound-based shrinkage method demonstrated global SoC detection by exploiting phase-dependent mechanical and acoustic properties of the PCM; however, it was validated only in laboratory-scale transparent container, and significant signal attenuation and uncertainty are expected in steel vessels [5]. Pressure-based SoC estimation uses volumetric expansion during melting in closed PCM storages, but its applicability is limited to airtight geometries and excludes open designs [6]. Direct level-based SoC measurement has been demonstrated for ice storage systems using liquid level sensors, providing a direct global signal; however, this approach has not yet been applied to high-temperature PCMs [7]. Widely used PCMs in large-scale systems, e.g. nitrate salts, exhibit significant variations in thermophysical properties during phase change. For example, the eutectic mixture of 54 wt% KNO_3 – 46 wt%

$NaNO_3$ experience a density decrease of approximately 5% upon melting from solid to liquid at 222°C, as shown in Figure 1, while thermal conductivity changes from approximately 0.435 W/mK in the solid state to 0.457 W/mK in the liquid state [8]. These property variations directly influence the feasibility and accuracy of liquid-fraction measurement methods. Consequently, the selection and development of a measurement technique should be PCM-specific.

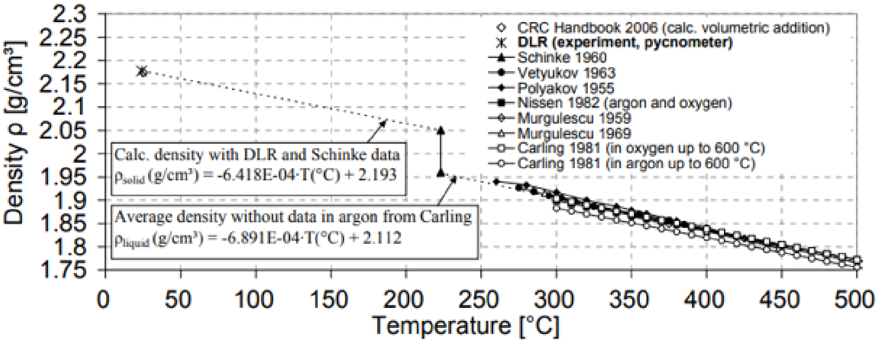

Figure 1. Change of density of eutectic mixture of 54 wt% KNO_3 – 46 wt% $NaNO_3$ over the phase change temperature [8]

To overcome these limitations, the present study investigates the use of density variation during phase change for liquid – fraction measurement in an open-top test rig geometry, which eliminates the need for pressure resistance design while enabling direct and continuous monitoring phase transition process.

2. Materials and Method

The cylindrical test rig and the placement of thermocouples inside the storage is shown in Figure 2. The base cylinder with a diameter of 150 mm is fully filled with the eutectic mixture. The cover of the storage consists of a riser with a smaller diameter of 40 mm to increase the measurement accuracy. The laser distance measurement sensor operates at a wavelength of 660 nm and has a measuring range of 50 to 350 mm. Its repeat accuracy varies between 2 and 30 µm, while the calculated combined measurement accuracy is 0.52 mm. Additionally, a floating object is placed on the top of the PCM to avoid incorrect measurements of distance because of the light-transmissive nature of nitrate salts in liquid phase. Four heaters with each 500 W of power are placed in the top lid to ensure that the PCM melts from the top to the bottom.

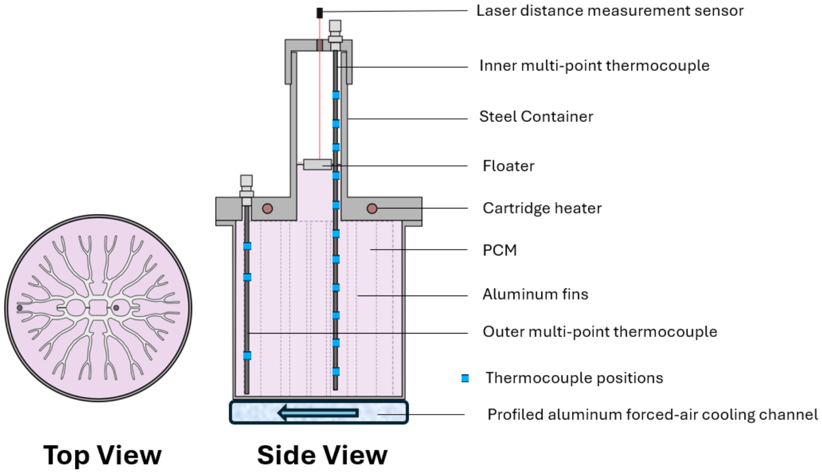

Figure 2. Schematic top and side view of the cylindrical steel test rig

For the discharge, an air channel is placed below the storage dissipating the heat by forced convection. To test different charging and discharging rates heater set temperatures of 250 −290 °C and volumetric air flow rates of 3 −30 $\frac{m^3}{h}$ are tested.
Validation of the fill-level measurement was performed using a thermocouple-based reference method. The PCM volume was subdivided into discrete sub-volumes, each instrumented with a centrally positioned thermocouple. The measured temperature was interpreted as the volumetric average, with complete phase transition assumed when T ≥ Tm (liquid) or T < Tm (solid). To ensure one-dimensional vertical heat transfer, heating and cooling were applied from the top and bottom surfaces, respectively, promoting vertical propagation of the solid-liquid interface. This configuration enabled direct comparison between thermocouple-derived and density-based liquid-fraction measurements.

3. Results and Discussion

The measured PCM fill levels were converted into volume, and then corresponding density value from the literature applied to calculate the total liquid fraction.
Figure 3 shows the comparison of two different references for the identification of liquid fraction where blue line (LF_ρ) represents the fill-level based measurement and the orange (LF_T) representing the thermocouple-based reference method.

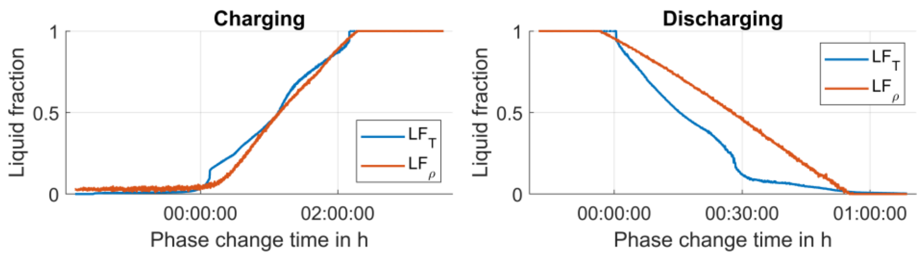

Figure 3. Liquid Fraction by fill level measurement vs. thermocouple-based rule calculation

Additional comparison can be shown in Figure 4, where density values reported by Bauer et al. are compared with the fill-level-based calculated density during charging and discharging.

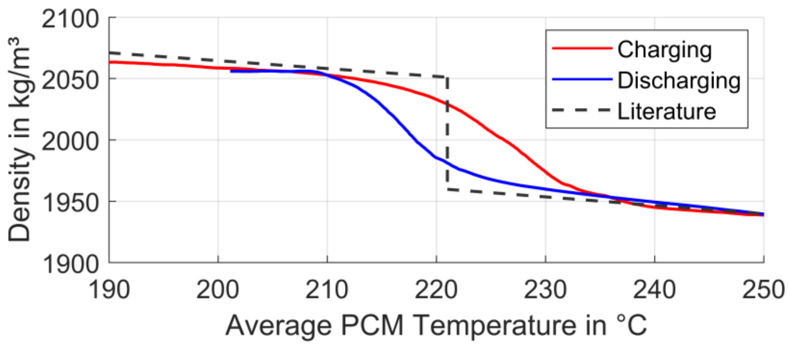

Figure 4. Comparison of measured density with the literature for charging vs. discharging

The step in measured density at the melting point corresponds well with the reported value in literature [8]. The maximum absolute difference and the mean difference between the two reference liquid fraction values correspond to 0.125 and 0.115 for charging cycle, respectively. Moreover, the change of density due to sensible heating above the melting point is also reflected well by the data. The deviations between the experimental results and literature values are attributed primarily to spatial averaging effects of the thermocouples, which measure temperatures representative of finite PCM sub-volumes rather than strictly local values.

4. Conclusions

A fill-level–based liquid-fraction measurement method was tested in an open-top test rig using a eutectic KNO_3–$NaNO_3$ mixture with a melting temperature of 222 °C, which served as PCM in this study. The open design, allowed the molten PCM to move freely, so the need for pressure resistance container was eliminated. The eutectic mixture of KNO_3–$NaNO_3$ showed a clear density change during phase transition, following the values reported by Bauer et al., enabling reliable level measurements.

The liquid fraction derived from fill-level data agreed well with thermocouple-based method and the calculated variation of the density using the density values from [8]. This confirms that the method is practical for estimating liquid fraction during the melting and solidification process of the eutectic mixture of KNO_3–$NaNO_3$, and can support future work on determining stored thermal energy during partial charging and discharging, in LHTES systems. Further studies need to be done to validate this methos for large scale applications.

5. Acknowledgements

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