IMPROVED CHARACTERIZATION FOR PHASE-CHANGE THERMAL ENERGY STORAGE

Summary

The use of phase-change materials (PCMs) for thermal storage has the potential to provide high-energy-density thermal energy storage that can be delivered at nearly constant temperatures. The recent advent of commercial products using phase-change materials has spurred the development and refinement of test methods and standard procedures to evaluate the performance of these devices under repeatable conditions. In this study, a commercially available latent heat storage system was tested using a pre-existing test method designed to evaluate similar products. The test data were then analyzed to develop a universal performance model for the phase-change thermal storage systems, enabling their performance to be predicted across a range of operating conditions. The final model was validated against the experimental results.

Keywords: Phase-change material, latent heat thermal storage, thermal performance, modelling

1. Introduction

The physics of phase-change material (PCM) storage has been studied by many researchers (Ahmed et al., 2022; Hassan et al., 2016; Radouane, 2022; Teggar et al., 2021). The process involves the latent "heat of fusion" associated with a phase change between a solid and a liquid that occurs without a change in temperature. In a recent study (Harrison et al., 2022), a commercially available phase-change thermal storage system was tested in a laboratory setting in accordance with the general requirements of ASHRAE 94.1-2010 (ASHRAE Standards Committee, 2010) to characterize their operation and quantify its capacity. The unit consisted of a leakproof container filled with a salt hydrate with a nominal phase-change temperature of 58°C. The storage was charged by circulating hot liquid through its integral tube-and-sheet heat exchanger and discharged by circulating cool liquid through a separate discharge loop. The unit weighed 176 kg.

At present, there are no current test methods in force to rate or characterize the thermal performance of such devices under repeatable conditions. Recently, there has been increased demand for standard test and rating methods as jurisdictions move to increased electrification to reduce greenhouse gas emissions. This switch has motivated utilities to implement electrical and thermal storage into their electrical grids.

In addition, uniform characterization and simulation methods are required to enable system integrators, utilities, and government bodies to predict annual performance as a function of climate, usage patterns, load, and operation. This requires a methodology and process to utilize the outputs of the standardized ratings in performance simulations. This requires the development of a functional relationship for PCM storage that can be derived from test results obtained during standardized testing.

2. Test Results & Discussion

Tests were conducted in accordance with the general requirements of ASHRAE Standard 94.1-2010 for phase-change storage. An instrumented calorimeter rig was used for testing as described by Harrison et al., 2022. Power input or output to/from the storage was calculated as the product of the water mass flow rate, specific heat, and the temperature difference between the storage inlets and outlets during charging or discharging.

Figure 1 shows experimental values of energy stored versus the mean temperature of the inlet and outlet charge fluid. The mean temperature, however, depends on the input temperature, power level, and associated temperature difference across the unit. As a result, it is not possible to obtain a single performance graph for different flow rates and powers when data are plotted against the mean fluid temperature.

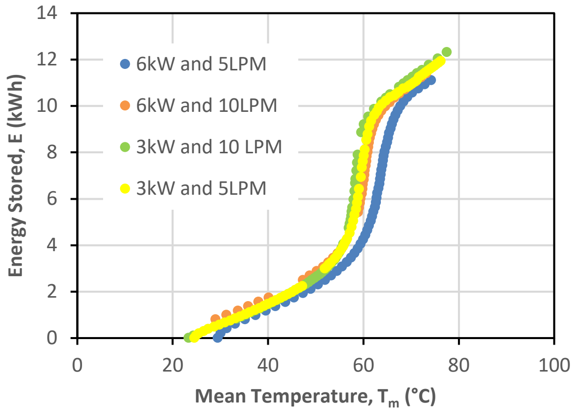

Fig. 1: Total Energy Stored versus Mean Temperature

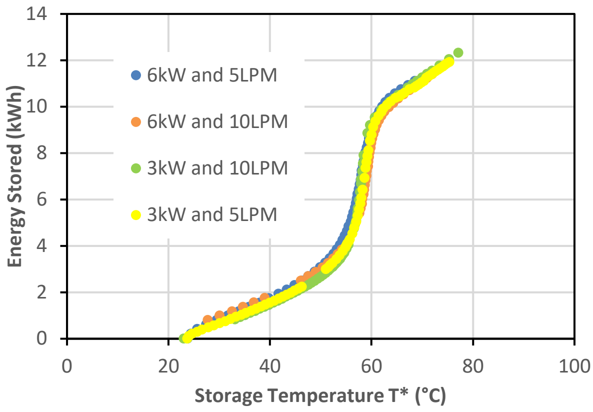

Fig. 2: Total Energy Stored vs Effective Storage Temperature

To minimize this effect, a non-dimensional Flow Factor, F_f, and a modified fluid temperature, T^* was introduced to represent the effective temperature of the storage unit, determined by conducting tests at a minimum of 2 flow rates. The flow factor depends on the fraction Power/Flowrate. T^* is calculated as:

$$T^* = T_{inlet} - F_f \cdot T_{inlet} = T_{inlet}\,(1 - F_f) \qquad \text{(eq. 1)}$$

After replacing T_m with T^*, the discrepancy mentioned above is significantly reduced (Fig. 2).

3. Generalized Performance Characterization for PCM Storage

It is desirable to have a universal "black box" model that can describe the performance of a PCM storage based on experimental data. The model should be general and applicable to a wide range of PCM materials and operational modes. The following equation was found to best fit the complex shape of the PCM heating/cooling experimental data shown in Fig. 2.

$$E = E_0 + c \cdot T^* + \frac{a}{1+e^{b(T_{pc}-T^*)}} + [\Delta c(T^* - T_{liq})] \cdot I(T^* > T_{liq}) \qquad \text{(eq. 2)}$$

This equation can be broken down into four terms:

- E_0: the energy stored at 0°C in theory.
- $c \cdot T^*$: describes the curve in the solid sensible heating section (before phase change).
- $\frac{a}{1+e^{b(T_0-T^*)}}$: responsible for the S-shape curvature, or the phase change (latent heating) section
- $[\Delta c(T^* - T_{liq})] \cdot I(T^* > T_{liq})$: added in after the material finishes its phase change to describe the curve in the liquid sensible heating section. $I(T^* > T_{liq})$ is an indicator function with $I = 1\ if\,(T^* > T_{liq})$ and $I = 0\ if\ (T^* < T_{liq})$.

where: E: energy stored by the storage.
T_{pc}: representative temperature at phase change.
T_{liq}: temperature at the end of phase change, or at the start of the liquid phase
$a, b, c, \Delta c$: fitting constants.

For the case shown in Fig. 3, based on tests conducted on the storage, *Tpc* was identified as 58°C, and T_{liq} as 60°C (representing the neck of the curve marking the transition from the phase-change region to the liquid region).

The remaining terms of the general equation were then identified by regression analysis of the measured data (Table 1).

Since the proposed equation contains both linear functions (for the sensible heating sections) and the logistic function (for the phase change section), a non-linear regression analysis was used.

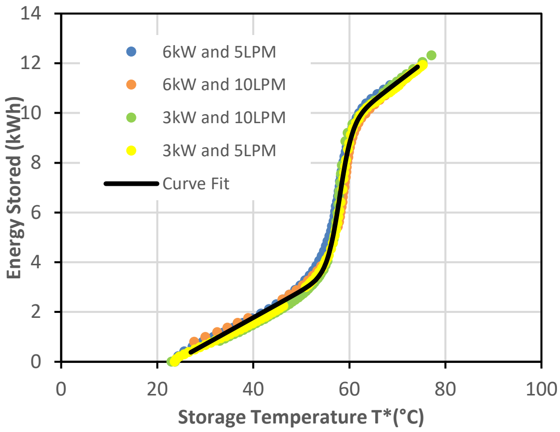

Fig.3: Curve Fit versus Data Points for the Storage Performance

Tab. 1: Regression results for the Energy vs Storage Temperature curve fit equation

E_0	**-2.52**
a	5.86
b	0.78
c	0.107
Δc	0.040

4. Conclusion

As a result of the analysis described in this report, a piecewise function comprising linear and nonlinear elements was identified and found to accurately characterize the results of a standard test protocol for PCM storage. The correlations produced excellent results when the predicted performance was compared with the measured results. In the future, these models and test procedures should be validated on a variety of devices, and their accuracy compared with monitored results.

5. References

S.F. Ahmed, Rafa, Mehnaz, B. Ahmed, 2022. Integration of phase change materials in improving the performance of heating, cooling, and clean energy storage systems: An overview. Journal of Cleaner Production 364:132639.

Hassan, Laghari, Rashid, 2016. Micro-Encapsulated Phase Change Materials: A Review of Encapsulation, Safety and Thermal Characteristics. MDPI, Sustainability, Volume 8.

Radouane, 2022. A Comprehensive Review of Composite Phase Change Materials (cPCMs) for Thermal Management Applications, Including Manufacturing Processes, Performance, and Applications. MDPI, Energies, Volume 15.

Teggar, Arıcı, Mert, Ajarostaghi, 2021. A comprehensive review of micro/nano enhanced phase change materials. Journal of Thermal Analysis and Calorimetry, Springer Science, p. 3989-4016.

S. Harrison1, R. Indranil, K. Nguyen, 2024. Experimental Evaluation of a Phase-change Thermal Storage, ENERSTOCK 2024, International Conference on Energy Storage, June 5–7, 2024, Lyon, France.

ASHRAE 94.1-2010, 2010. Method Of Testing Active Latent-Heat Storage Devices Based on Thermal Performance. 1791 Tullie Circle NE, Atlanta, GA 30329.