Experimental Investigation and Performance Characterization of PCM Integrated Finned Tube Heat Exchanger for Building Heating and Cooling Applications

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ABSTRACT

Phase change material (PCM) based thermal energy storage (TES) technologies are promising for building heating and cooling applications. PCM based TES systems could enable flexibility of buildings' thermal demand, shave peak load, and provide energy savings to the end user. Although PCMs have large latent heat storage capacity, their low thermal conductivity values limit their charge and discharge rates and their overall efficiency. Herein we investigate the thermal performance of a PCM based heat exchanger that is designed to offset buildings' heating and cooling loads.

TES integrated with a thermally anisotropic building envelope (TABE) offers unique benefits by redirecting stored thermal energy from a building to a TES system using hydronic loops. In this work, we describe an experimental apparatus for two 5-gallon fin and tube heat exchanger systems integrated with a commercially available organic PCM that is subjected to heated and cooled boundaries. We investigated the thermal performance of the heat exchanger by varying the volumetric fluid flow rate and temperature difference of the PCM heat exchanger. Furthermore, we demonstrate the cyclic stability of the PCM heat exchanger system using the developed experimental apparatus over many cycles. The developed method and apparatus provide a means to investigate and characterize thermal storage systems at the gallon scale, which can help in the design of future energy storage systems optimized for cost and energy savings.

1. INTRODUCTION

The effort towards developing cost-effective energy storage in buildings has been a cornerstone in recent decades for the large-scale deployment of renewables and the broad decarbonization of the energy sector (Dowling et al. 2020; Ziegler et al. 2019). With approximately three-fourths of electricity consumed by buildings (EIA 2016), critical innovations in current building technologies are required to meet clean and sustainable energy goals. Thermal energy storage (TES) using phase change materials (PCMs) offers unique benefits in storing and releasing large amounts of energy from their latent heat of phase transition at a near-constant temperature. TES technologies based on PCMs can help alleviate peak energy demand in buildings, and provide flexibility in the delivery of hot and cold by charging TES system during off-peak times and discharging energy when required, thus reducing grid congestion and greater penetration of renewable electricity in buildings (De Gracia &Cabeza 2015; Heier et al. 2015).

In the context of commonly used TES-based materials, PCMs with solid-liquid phase transition are generally employed because of their wide range of melting temperatures and minimal change in volume during each thermal cycle. Commonly used solid-liquid PCMs such as paraffin and inorganic salts have transition temperatures in the range of 10-200°C (Sharma et al. 2009). While PCMs have large energy storage capacity from their latent heat, most commonly used PCMs have relatively low thermal conductivities (~ 0.1 W/(m·K) for paraffin, ~ 10 W/(m·K) for low

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melting point metallic PCMs) (Sarbu &Dorca 2019), which reduces their ability to charge and discharge energy, thus reducing the overall storage efficiency and PCM thermal performance. Several strategies have been put forth to improve the PCM performance such as introducing additional thermal conductivity networks in the form of metals of different sizes (Hassan et al. 2022), using a composite model approach to integrate extended metal surfaces (Tamraparni et al. 2023) and using extended surfaces in the form of metallic fins and foams of varying geometry and sizes (Lin et al. 2018). Such strategies have shown improvements in PCM thermal performance, achieving an overall increase in the energy and power densities of the thermal storage system.

In previous work, a thermally anisotropic building envelope (TABE) was developed to improve the thermal management of a building envelope (Biswas et al. 2019). TABE redirects thermal energy to move in a preferential direction using a thermally conductive thin metal sheet in a building envelope through the use of hydronic loops connected to the conductive layers. During large temperature swings obtained from diurnal weather conditions such as solar irradiance in the winter and night sky cooling in the summer, the exterior surface of the TABE can be used to capture thermal energy when integrated with a TES system. In this paper, we describe an experimental apparatus for two 0.019 m3 (5-gal) fin and tube heat exchanger systems integrated with commercially available organic PCM, for potential integration with TABE for building envelope thermal management. Herein we describe the experimental testbed, which consists of a water-based fluid loop connected to a heater and a chiller to establish heated and cooled boundaries at the PCM integrated heat exchanger TES system. Using the temperature feedback from various locations inside the TES device, we provide a method to evaluate the state of charge (SOC) of the TES system obtained using energy balance across the system. Typical building peak loads for heating and cooling applications last for three to four hours and the average exterior surface temperature is at least 10°F higher or lower compared to indoor air temperature. Herein we seek to design a TES system that can utilize 75% of stored latent energy in three hours and 90% of stored latent energy in four hours at a temperature difference of 5.55°C (10°F) and also utilize 90% of TES tank volume with liquid phase PCM. Furthermore, we evaluate the cyclic stability for a commercial organic PCM at a gallon scale, which is a critical performance metric for the PCM, using the developed experimental testbed. The developed method and apparatus described in this study can be used for the future design of TES systems, providing a means to experimentally evaluate the performance at both materials and system levels for building thermal management applications.

2. SYSTEM DESCRIPTION

Figure 1(a) shows the designed fin and tube heat exchanger that are to be integrated with a PCM for potential application in building envelope thermal management. The fin tube heat exchanger has a height of 30.48 cm (12 in.), length of 22.86 cm (8 in.), and width of 22.86 cm (8 in.) was manufactured using commercially available materials. Heat exchanger components consist of copper tubes with 0.635 cm (0.25 in.) tube size and wall thickness of 0.076 cm (0.03 in.), 7.8 cm (3.07 in.) tube spacing, and aluminum fins with 0.2 mm (0.0078 in.) thickness and 1.5 cm (0.59 in.) fin spacing. Figure 1(b) shows the image of the experimental setup to characterize the performance of two 0.019 m3 (5-gal) TES systems with flow lines connected to a water heater and a chiller. Water as the heat transfer fluid was supplied to the inlet of the heat exchangers using a centrifugal type of pump, with differential proportional valves and a 3-way solenoid valve to control the flow rate and the flow direction to the heat exchanger respectively.

Temperature probes at the fluid inlet and outlet were installed on each tank to estimate the thermal storage capacity of the TES system. Additionally, temperature probes in the storage medium at various spatial locations were installed to investigate what the effects, if any, repeated cycling has on the stability of the PCM over time at a gallon scale, which is a critical performance metric for all TES systems incorporating PCMs. The uncertainty in measurement for the temperature sensors used in this study was ± 0.5°C. The uncertainty in measurement for the flow meters used in this study was ± 1% of the reading for a range of 0.2 – 2 GPM, using in situ gravimetric calibration method. In this study, the performance of the TES system was evaluated at a fluid flow rate of 1 GPM and subjected to a temperature difference of 5.55°C (10°F). The temperature difference in this study is defined as the difference between the inlet temperature of the TES system and the phase transition temperature of the PCM. Furthermore, we thermally cycle the TES system at a fluid flow rate of 2 GPM and a temperature difference of 16.66 (30°F) to evaluate the cyclic stability of the PCM used in this study.

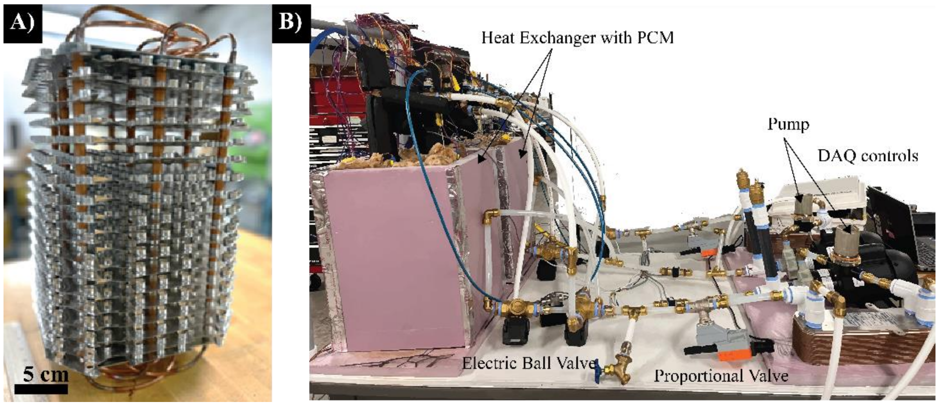

Figure 1: A) Image of fin and tube heat exchanger B) Image of the experimental testbed for characterizing the TES system.

A simplified flow setup of the experimental testbed is shown in Figure 2. In order to reduce the total test time for the thermal storage systems we employed two tanks that incorporate the same heat exchanger design to simultaneously heat and cool. For a heating cycle in the heat exchanger in tank 1, the heater was allowed to flow to the heat exchanger inlet via valve S4, exchanging heat with the PCM storage medium and returning to the heater through valve S2 and flow meter FM2. Simultaneously, a cooling cycle was achieved in the tank 2 heat exchanger, when water from the chiller was allowed to flow to the heat exchanger via valve S1 and back to the chiller through S3 and flow meter FM1. For a cooling cycle in the heat exchanger in Tank 1 and a heating cycle in Tank 2, the solenoid valves S1 to S4 are de-energized to redirect the flow from the chiller to Tank 1 and the water heater to Tank 2. The thermophysical properties of the PCM used in this study are shown in Table 1. The latent heat capacity and melting point of PCM were determined using Differential Scanning Calorimetry (DSC).

Table1: Thermophysical properties of PCM.

Material	**Thermal Conductivity W/m·K**	**Specific Heat J/g·°C**	**Latent Heat J/g**	**Melting Point °C**	**Density kg/m^3**	**Temperature Glide °C**
PCM	0.15 liquid, 0.25 solid	1.99 liquid, 1.84 solid	200	23	830 liquid, 910 solid	2

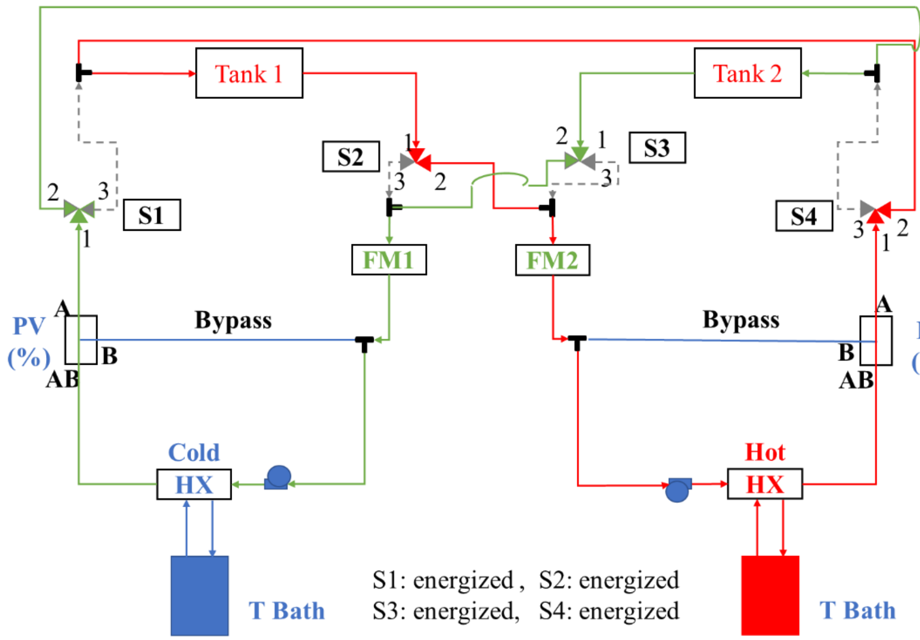

Figure 2: Simplified schematic of the experimental TES testbed. S1 to S4 represent electric actuator ball valves, FM1 and FM2 are the flow meters, PV represents the proportional valve, Tank 1 and Tank 2 are the TES systems that contain the PCM integrated heat exchangers. When the valve is activated, the chiller is allowed to flow to Tank 2 for a cooling cycle represented by the solid green line while for a heating cycle, the flow from the heater reaches Tank 1 as shown by the solid red line. The downstream of the heat exchanger for each tank goes through a flow meter and back to the heater or chiller for heating or cooling, respectively. To activate cooling for Tank 1 and heating for Tank 2 solenoid valves are de-energized as shown by the dotted gray lines.

3. EXPERIMENTAL CHARACTERIZATION

3.1 Method

During the heating cycle, water from the heater was allowed to flow to the heat exchanger inlet tank 2, exchanging heat with the PCM storage medium and returning to the heater via the valve S3 and flow meter FM2 as shown in Figure 2 (when the valves are de-energized). Figure 3(a) shows the inlet and outlet temperature recorded from the tank 2 during a heating cycle. From the temperature recordings at the inlet and outlet of the heat exchanger, the rate of heat transfer across the heat exchanger measured in Watts (W) can be calculated using,

$$\dot{Q} = \dot{m}c_p(T_{in} - T_{out}) \tag{1}$$

where $\dot{m}$ is the mass flow rate measured from the mass flow meter (kg/s), c_p is the specific heat of water (J/g °C), and T_{in} and T_{out} are the inlet and outlet temperatures (°C), respectively. Using equation (1), the heat rate for a heating cycle in tank 2 TES system is shown in Figure 3(b). Similarly, valves are energized to enable a cooling cycle in tank 2 as shown in Figure 2. The resultant temperature from the inlet and outlet for a cooling cycle is shown in Figure 3(b) with the heat rate evaluated using the equation as shown in Figure 3(d).

In order to evaluate the total thermal energy stored by the system,

$$Q_{total} = \int_0^t \dot{m}c_p(\dot{T}_{in} - \dot{T}_{out})dt \tag{2}$$

where Q_{total} is the total thermal energy stored without considering the losses from ambient in Joules, $\dot{Q}$ is the heat transfer rate (W) and t is the total time (in seconds). Furthermore, we employed Newton's law of cooling to estimate heat losses in the system, where the system was cooled to ambient temperature conditions.

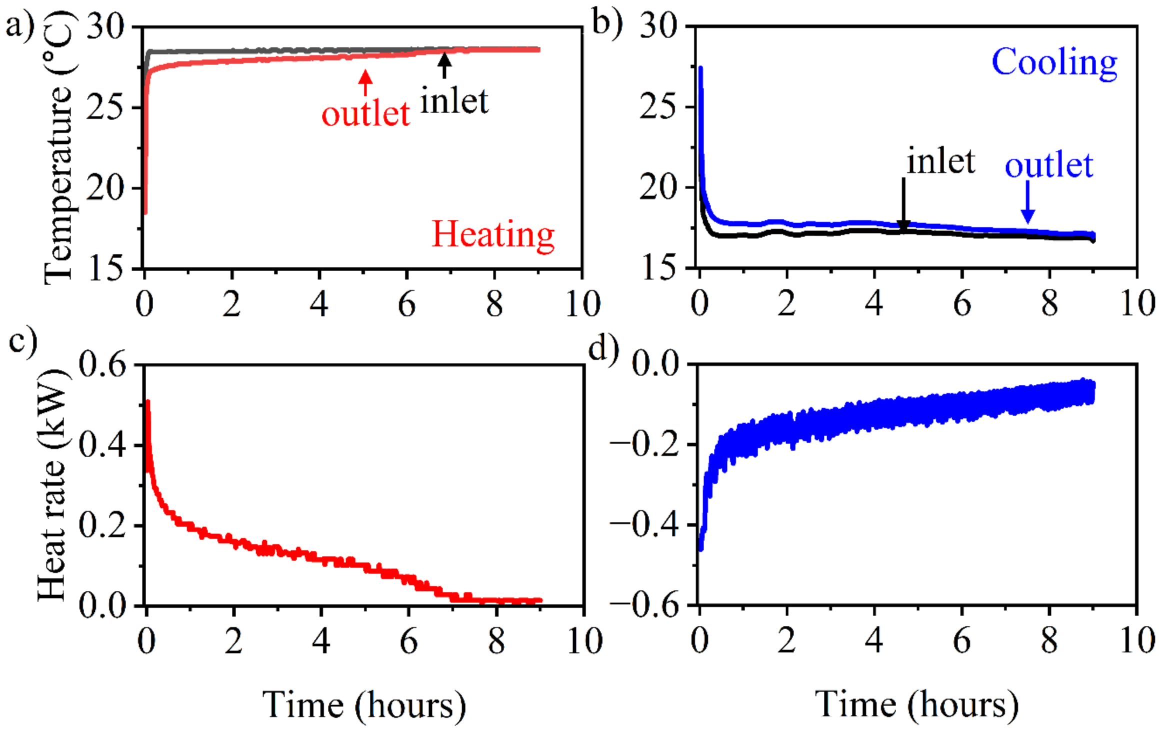

Figure 3: a) water inlet and outlet temperatures from tank 2 with PCM during heating, b) tank 2 water inlet and outlet temperatures during cooling, c) heat transfer rate calculated while heating, and d) heat transfer rate calculated while cooling for tank 2.

The corrected total energy stored by the TES system is,

$$Q_{total,corrected} = \int_0^t \dot{Q}dt - \dot{Q}_{loss}dt \tag{3}$$

where $Q_{total,corrected}$ is the total energy stored for the TES system after correction in Joules, $and\ \dot{Q}_{loss}$ is the heat loss from the system to ambient measured in Watts (W). Estimation of loss for the TES system can be found in a recent study (Tamraparni et al. 2024).

3.2 Estimation of State of Charge

The stored latent energy or SOC as a function of time is an important parameter in characterizing the TES system. In order to quantify the melt fraction of the PCM, we used the temperature sensors inside the PCM storage medium and recorded the transient temperature response of the PCM as shown in Figure 4(a) for a heating cycle and Figure 4(b) for a cooling cycle. The gray band in the phase change temperature region represents the temperature glide from Table 1. As the rate of heat transfer in the storage medium varies spatially, PCM locations close to the heat exchanger coil and fins undergo melting faster as shown by the solid green lines in Figure 4(a) and PCM locations away from the fins have longer melting times as shown by red dotted lines.

In order to estimate the thermal SOC for the system considering only the latent heat, we decouple the energy stored by the thermal mass of the heat exchanger and the specific heat of the PCM. SOC can be evaluated using,

$$SOC = \frac{Q_{total,corrected} - Q_{HX} - Q_{PCM,specific}}{m_{PCM} h_{fg}} \tag{4}$$

$$Q_{HX} = \int_0^t m_{hx} c_{p,HX} dT dt \tag{5}$$

$$Q_{PCM,specific} = \int_0^t m_{PCM} c_{p,HX} dT_{PCM} dt \tag{6}$$

where Q_{HX} is the total energy stored by the heat exchanger thermal mass in Joules, $Q_{PCM,specific}$ is the specific heat energy stored up to the PCM transition temperature (in Joules), and m_{PCM} is the mass of PCM in the TES tank measured in kilogram (kg), h_{fg} is the latent energy storage capacity of the PCM (J/kg). In equation (5) m_{hx} represents the measured mass of the heat exchanger (2.45 kg), $c_{p,HX}$ is the specific heat of the heat exchanger (0.8 kJ/kg·K) and dT_{pcm} is defined as the temperature difference measured between PCM temperature and the transition temperature (Celsius) of the PCM.

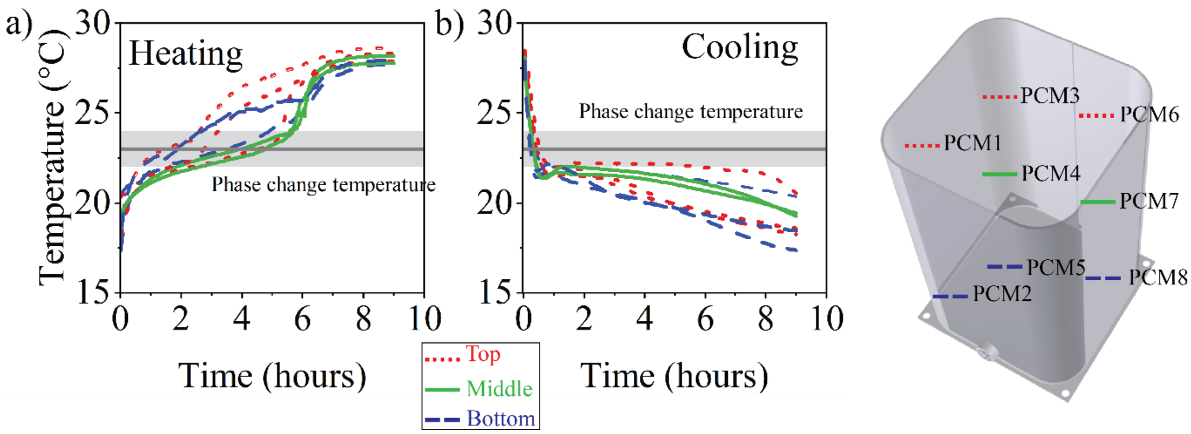

Figure 4: a) Temperature vs time plot for PCM storage media during the heating cycle and b) during cooling at various spatial locations inside the TES tank. The top, middle, and bottom represent the height along the TES tank measured from the bottom surface of the tank. The above temperatures were recorded for a TES system at a fluid flow of 1 GPM and a temperature differential of 5.55°C (10°F) measured from the phase transition temperature of the PCM.

Figure 5 shows the calculated SOC using equations (4-6) for the TES system at a fluid flow rate of 1 GPM. Here, we observe that the system utilizes 75% of stored latent energy in 2.8 hours and 90% of stored latent energy in 3.8 hours meeting the desired performance metrics in reducing building peak loads while heating. Similarly, for cooling, the system meets the performance objectives with rates of charging of 75% stored energy in 2.4 hours and 90% stored energy in 3 hours.

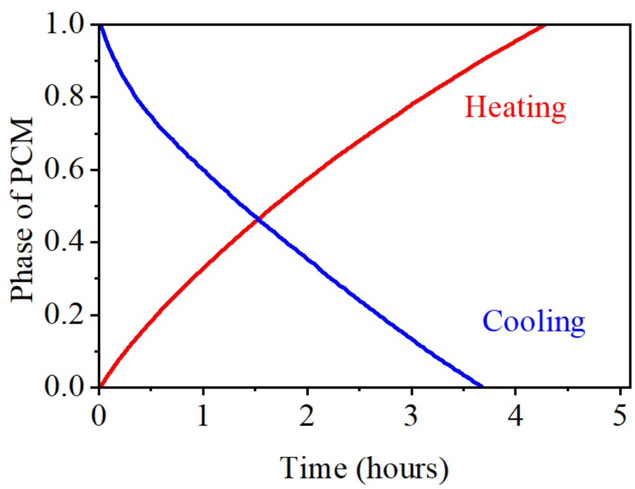

Figure 5: Phase of PCM evaluated as a function of time for heating and cooling of the tank 2 PCM with heat exchanger at 1GPM.

3.3 Demonstration of cyclic stability of PCM in fin and tube heat exchangers

Long-term cyclic stability is an important performance metric of PCMs for TES applications. The apparatus for repeated thermal cycling can be performed based on sample volume, which is a) Differential Scanning Calorimetry (small scale), b) Temperature History (medium scale), or c) system level validation techniques (large scale). Previous studies have shown that small volume characterization of PCMs is not representative of real-scale engineering applications (Anand et al. 2021; Ferrer et al. 2015). Using the developed TES testbed, herein we perform repeated thermal cycling at a temperature differential of 16.66°C (30°F) and 2 GPM fluid flow rate for the PCMs integrated with heat exchangers in tank 1 and tank 2. Figure 6 shows the preliminary data recorded for ten continuous heating and cooling overlaid for Tank 1 and Tank 2. The results from the temperature response show that the PCM shows little to no signs of degradation and the initial and final transition points between the tanks differ, possibly due to the movement of temperature sensors in the tank. In the future, we will continue testing with a large number of cycles and integrate different classes of PCMs to assess their long-term performance.

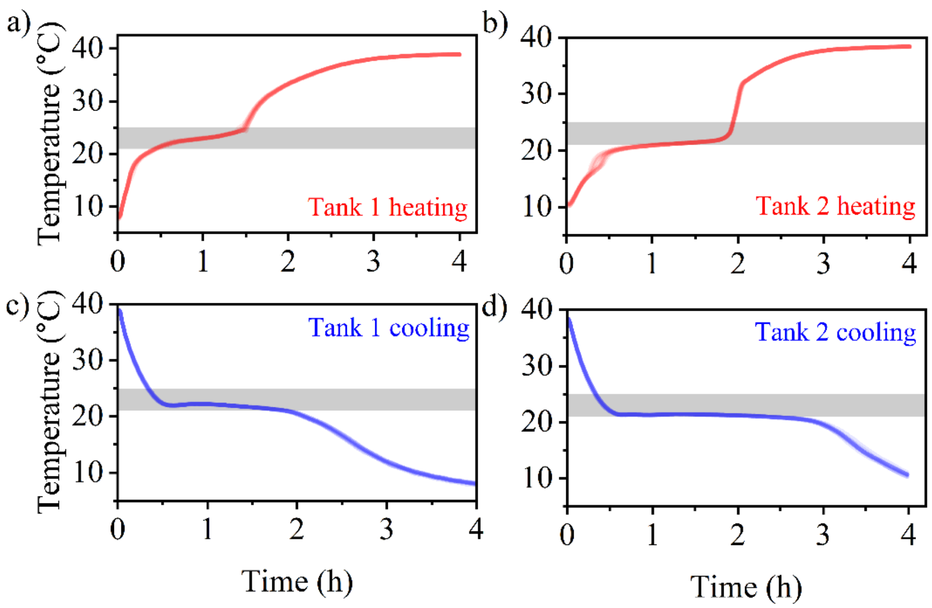

Figure 6: Plots of temperature as a function of time for a) heating in tank 1, b) heating in tank 2, c) cooling in tank 1, and d) cooling in tank 2. 10 cycles of PCM temperature from the center location have been overlaid to show the cyclic stability of the PCM measured under a temperature differential of 16.66°C (30°F) and 2 GPM fluid flow rate. The gray horizontal band represents the phase change transition temperature region of the PCM.

CONCLUSION

In this paper, we developed and demonstrated the experimental characterization of two 0.019 m3 (5-gal) thermal storage systems, which incorporate fin and tube heat exchangers integrated with a solid-to-liquid phase change material for thermal management in buildings. The results for the TES system showed that the system utilizes 75% of stored latent energy in 2.8 hours and 90% of stored latent energy in 3.8 hours meeting the desired performance metrics in reducing building peak loads while discharging. Similarly, for charging, the system meets the performance objectives with rates of charging of 75% stored energy in 2.4 hours and 90% stored energy in 3 hours, meeting the desired performance characteristics. Additionally, the developed thermal storage system testbed allows repeated thermal cycling to assess the long-term performance of the PCM in large-scale quantities (5 gal). Preliminary results for the PCM under thermal cycling performed at a temperature differential of 16.66°C (30°F) and 2 GPM fluid flow rate showed little to no signs of significant degradation. The experimental apparatus and developed methodology described in this study can help in designing future thermal storage materials and systems in buildings, characterized for performance at both system and materials level at gallon scale.

NOMENCLATURE

c_p	=	specific heat capacity, J/g-°C
h_{fg}	=	latent heat capacity, kJ/kg
m	=	mass, kg
$\dot{m}$	=	mass flow rate, kg/s
Q	=	total energy stored, J
T	=	temperature, °C
t	=	time, s
U	=	overall heat transfer coefficient, W/m^2·K

Subscripts

HX	=	heat exchanger
PCM	=	phase change material
in	=	inlet
out	=	outlet
total	=	total energy stored

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