Future Cities and Environment

Experimental Study of PCM Cooling Storage System for Hot Climates

TECHNICAL ARTICLE

ubiquity press

MARIANA VELASCO-CARRASCO
OMAR RAMADAN
SAFFA RIFFAT

*Author affiliations can be found in the back matter of this article

ABSTRACT

In this work, the application of a PCM cooling system for hot climate applications is investigated. A novel design proposes the utilization of PCM panels to reduce the energy demand on an air-cooling system by absorbing a proportion of the thermal load. The system not only contemplates the application of the S27 PCM panels for indoor cooling but also considers a PCM-TES box to enhance the cooling performance. The experimental evaluation focused on two operating schedules, during daytime the environmental temperature was considered at 30°C, and at night-time, the temperature was reduced to 25°C. The results found an indoor average temperature difference of 1.8°C with the addition of the PCM panels. In terms of energy savings, the chiller energy consumption was positively impacted as the PCM reduced the operational time.

CORRESPONDING AUTHOR:

Mariana Velasco-Carrasco

Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, UK

mariana.velascocarrasco@nottingham.ac.uk

KEYWORDS:

cooling system; heat exchanger; phase change materials; thermal energy storage

TO CITE THIS ARTICLE:

Velasco-Carrasco, M, Ramadan, O and Riffat, S. 2022. Experimental Study of PCM Cooling Storage System for Hot Climates. *Future Cities and Environment,* 8(1): 4, 1–11. DOI: *https://doi.org/10.5334/fce.148*

1. INTRODUCTION

Worldwide the increase in energy demand required by the building sector has led to the adoption of smart strategies towards mitigating the effect of climate change and high-energy consumption. In this regard, energy efficient buildings are considered to consume less energy while maintaining or even improving the comfort conditions for their occupants. The implementation of energy efficient solutions is pivotal as the global energy demand is expected to increase by 50% in 2050 (Marin et al., 2016). Furthermore, the energy consumption for cooling is expected to increase sharply by 2050–by almost 150% globally, and by 300% to 600% in developing countries (Weinläder et al., 2017). For this reason, energy efficient buildings not only reduce the environmental impact but are also economically sustainable and resilient. This has created a growing concern within the Nigerian context, creating the first Building Energy Efficiency Guide (BEEG) in 2016, while the Nigerian Building Energy Efficiency Code (BEEC) was first launched in August 2017 (Ochedi & Taki, 2021).

Nigeria faces an acute shortage of housing stock with up to 16 million housing deficits. The construction sector is growing fast in Africa due to the increase in population, with a projection rate of 3.7% for urban dwellers (Micklethwait & Wooldridge, 2014). Previous housing units in Nigeria have not considered sustainable measures to reduce the energy demand and provide thermal comfort. For this reason, there is an urgent need to encourage the design of buildings that are responsive to the local microclimate, in order to mitigate the effect of climate change (Ochedi & Taki, 2021).

A novel design framework for energy efficient residential buildings in Nigeria is expected to produce thermal comfort and decrease energy consumption. In this regard, the application of thermal energy storage (TES) systems is a potential solution for the Nigerian climate. Thermal energy storage systems can create a balance between diurnal and nocturnal energy demand using latent heat thermal energy storage (Saffari et al., 2017). The integration of phase change materials (PCM) in building components is a method that can improve the energy efficiency of cooling systems, representing a high potential due to its high energy storing capacity (Elsanusi & Nsofor, 2020; Weinläder et al., 2017). The application of thermal storage represents great importance as it can assist with temperature fluctuations, resulting in a reduction in the heating and cooling demand (Panayiotou et al., 2016).

In general, phase change materials have been employed to enhance the building thermal mass, therefore resulting in better occupant comfort and energy savings. PCMs focus on latent heat storage by storing the heat, modifying the physical state of a substance from one state to another by melting or vaporization (solid to liquid or liquid to gas and vice versa). Ideally, the phase transition is being done at desired operating temperature range. Changes in the material phase can be classified into four states: solid–solid, solid–liquid, gas–solid and gas–liquid (Akeiber et al., 2016). There PCMs transitioning from solid–liquid phase change are mostly applied due to a variety of advantages, such as presenting a small volume change, compactness and easy handling (Zhang et al., 2016). ***Figure 1*** presents the latent and sensible heat storage variation with temperature in the solid-liquid state.

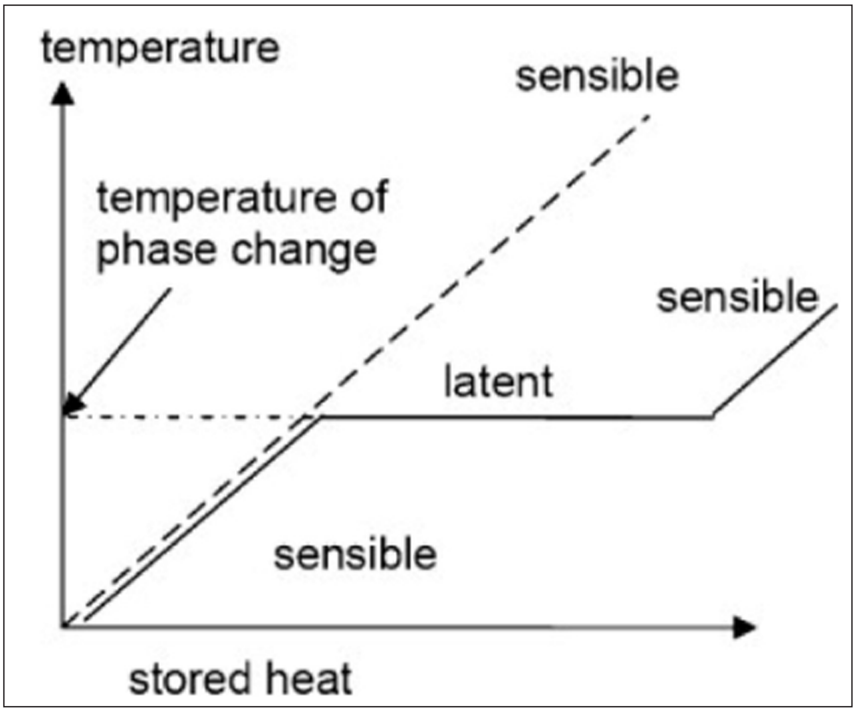

Figure 1 Latent and sensible heat storage variation with temperature (Mehling & Cabeza, 2008).

The PCM are commonly classified as organic, inorganic and eutectic. The commercially available PCMs, along with their classification, advantages and main drawbacks for building integration has been widely investigated (Akeiber et al., 2016; L. F. Cabeza et al., 2011; Jelle & Kalnæs, 2017). The main drawback of the PCM thermal performance is the low thermal conductivity and the lack of thermal stability in PCMs (Zhang et al., 2016). In addition, the melting temperature of the material should be less than the required operating temperature of the system (Liu et al., 2018). For building applications, the PCM melting temperature normally ranges from 20°C to 32°C (Panayiotou et al., 2016).

The PCMs are used to control the ambient temperatures aiming to archive thermal comfort, this can be applied to diverse components of a building (Mazzeo et al., 2017). Nevertheless, the success of the PCM would depend on several conditionings, the main elements that would determine the performance are the PCM melting temperature, the quantity, the encapsulation method, the location within the building structure, building design and orientation, the building energy load, the climate conditions, the energy demand, the selection of the equipment, utility rate policy, occupancy schedule, system control, and operational algorithms, among others.

In this regard, the encapsulation of the material is the most popular solution (L. F. Cabeza et al., 2011; Velasco-Carrasco et al., 2020a). This can be explained by the high potential of leaking during changing of the PCM phase to liquid. In addition, encapsulation can prevent the low viscous liquids from diffusing throughout the material (Akeiber et al., 2016). The application of PCMs as TES has been widely incorporated; however, few studies have experimentally evaluated the use of PCM as a storage medium in cooling systems (Moreno et al., 2014).

Jayalath et al. evaluated the thermal performance of PCMs in a residential house in Melbourne. Using TRNSYS the researchers compare the simulation results with experimental data published in the literature, finding that the PCM can delay the heat transfer and reduce the cooling and heating loads. The study concluded that the material achieved higher savings for cooling in comparison to the heating loads (Jayalath et al., 2016).

The integration of PCMs with air systems and heat exchangers has been another approach to boost performance. Talkeada et al. developed an experimental ventilation system that features direct heat exchange between ventilation air and granules containing a PCM, focusing on the potential of such systems for reducing ventilation load. The results concluded that the system could reduce up to 62.8% of ventilation load (Takeda et al., 2004). Mozafari et al. proposed a triplex-tube heat exchanger to improve the simultaneous storage and recovery processes using a dual-PCM configuration. The project utilized two PCMs with different melting temperatures, to increase the performance. The results demonstrated a performance improvement of 76.9% in energy storage and 32.9% for recovery (Mozafari et al., 2022).

Santos et al. investigated a new PCM panel to integrate with an air heat exchanger system. The experimental investigation focused on the improvement in the melting and solidification process and increase thermal energy storage capacity. The researchers increased the PCM storage quantity by 30%, this expanding the melting and solidifying time by 86% and 38% respectively (Santos et al., 2019). Similarly, Elsanusi et al. investigated the arrangements of PCM plates inside the heat exchanger. The results identified the effects of conduction and natural convection heat transfer for different PCM arrangements in the heat exchanger. Finding a 15.5% reduction in the melting time with a serial arrangement. In addition, the study concluded that by having different PCMs the storage capacity by 25% (Elsanusi & Nsofor, 2020).

Riahi et al investigated a vapor-compression cooling system utilizing PCM is studied whereby the electricity consumption peak load is shifted. The system utilized the cooling energy to freeze or "discharge" the PCM during nighttime when the cooling load is minimally needed and uses the stored cooling energy during the peak load hours by melting or "charging" the PCM. The study concluded that the PCM increased the cooling load, reducing the electricity consumption at peak hours (Riahi et al., 2021).

Ceiling boards incorporated with PCMs for air conditioning systems play an effective role in indoor room temperature control. The University of South Australia developed a roof-integrated solar air heating storage system using a latent heat storage unit, in which an existing corrugated iron roof sheet is used as a solar collector. The system was able to store heat during the day and supply the heat at night or when sunshine is unavailable (Belusko et al., 2004). Weinläder, Klinker and Bavarian investigated the behavoiur of two configurations for PCM cooling ceilings, as presented in ***Figure 2***. The PCM panels were able to liquefy up to 55% more when the cooling pipes were installed at the bottom. The regeneration results reflect this different starting behaviour with typical solid fractions of PCM after regeneration of 90–100% for R112 (PCM on top) and 80–95% for R113 (PCM at the bottom (Weinläder et al., 2017).

The existing literature combines different approaches for the integration of PCM as a TES system. However, there are limited studies that experimentally investigate PCM cooling systems for hot climates such as the one presented in the Sub-African region. In this paper, the effect of the application of a PCM cooling

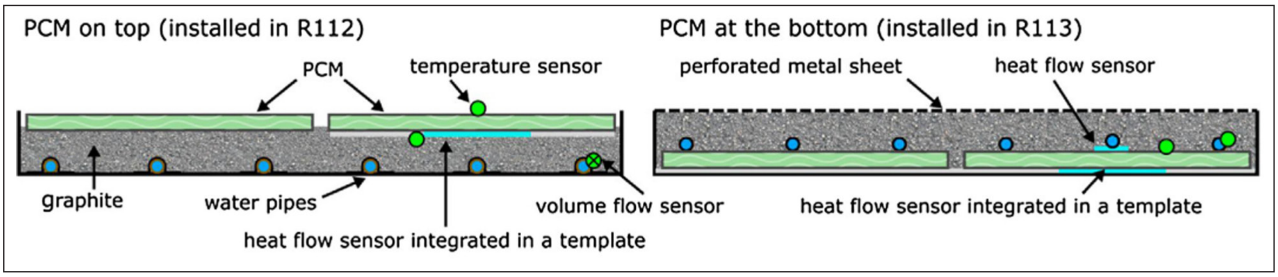

Figure 2 Sketch of the two PCM cooling ceiling systems configuration (Weinläder et al., 2017).

thermal behaviour based on a typical Nigerian climate temperature has been investigated to measure energy savings. The innovation of this work lies in the application of PCM-based TES storage, this is done by placing the material in series to the airflow before entering the air-cooling unit for dissipation; being the PCM discharge stage. The cooling is powered by a chiller unit and interconnected through a series of piping systems. The PCM is divided into a storage box and also applied as a radiating ceiling.

2. METHODOLOGY

The cold accumulated by the PCM panels is calculated according to the cooling capacity of each time step, as shown in Eq. (1) and Eq. (2). The temperature difference is measured by the chiller water temperature where $T_{HTF,in}$ is the inlet (€), $T_{HTF,out}$ is the outlet (°C), cp is the specific heat capacity (kJ/kg K), $\dot{m}$ is the mass flow rate (kg/s), $\dot{Q}$ is the cooling capacity (kW), Δt is the time step (h), and E is the cold storage (kWh). The discharge efficiency (ε) is defined as the cold supplied (E_d)/cold stored (E_c) ratio, as presented in Eq. (3).

$$\dot{Q} = \dot{m} \cdot cp \cdot (T_{HTFin} - T_{HTFout}) \qquad \text{Eq. (1)}$$

$$E = \int_0^t \dot{Q} \cdot \Delta t \qquad \text{Eq. (2)}$$

$$\varepsilon = \frac{E_d}{E_c}. \qquad \text{Eq. (3)}$$

The main aim of the test is to examine the effect of the PCM panels, on reducing the load on the chiller (vapour compression) and assess the impact, in terms of energy savings. In addition, the PCM behaviour is studied, during the daytime test, in terms of temperature variation, and for the overnight cooling.

To simulate the environmental conditions suitable for the tropical weather in Nigeria the environmental chamber temperature was set at 30°C for daytime simulation, having a 20% relative humidity (RH). The heater mat inside the testing box was activated, increasing the testing box temperature. The chiller unit and air-cooling channel components are initiated, with airflow then extracted and cooled in the air-water heat exchanger. All components are then left to run until an equilibrium is established. This is monitored forthe 8–12-hour daytime period. On completion, all systems are then switched to the night-time simulation phase. For the night-time simulation, the environmental chamber temperature was switched to 25°C and the RH was maintained. The heater power was decreased by 75%, representing the lower load that occurs in the building during night hours. The components are monitored for an 8–12-hour night period.

Sufficient energy must be stored, for this reason, the PCM has been selected at 27°C, surpassing the ambient temperature conditions. This will boost the system performance in terms of energy saving and at the same time will allow the successful regeneration of the material in a 24-hour cycle.

2.1 MATERIAL SELECTION

The encapsulation material was filled with S27, a salt hydrate from the PlusICE family developed by PCM Products Ltd ©. The material thermal properties are described in ***Table 1***, having a melting point of 27°C. The capsule container consists of a rectangular container with a length of 24 cm × 49 cm, with a weight of 3.5 kg and a net weight of 2.68 kg as shown in ***Figure 3***. In total, 12 panels were used having a net PCM weight of 32.16 kg.

2.2 EXPERIMENTAL SETUP

The study describes a set of experiments performed in the Environmental Climatic Chamber in the Marmot Laboratory, at the University of Nottingham. The experiment rig consists of a testing box, a PCM storage box, a chiller unit, a heat exchanger, a room heater, a fan, a pump and the measurement equipment as described in ***Figure 4***. Inside the environmental chamber, an insulated box was used to monitor the temperature variation. The testing box has 1 m^3 and was covered by insulation material with a 10 cm thickness. The radiant ceiling was

Melting point (°C)	27
Density (kg/m^3)	1530
Thermal conductivity [W/(m·K)]	0.54
Heat capacity (J/kgK)	2.2

Table 1 Thermal properties of S27.

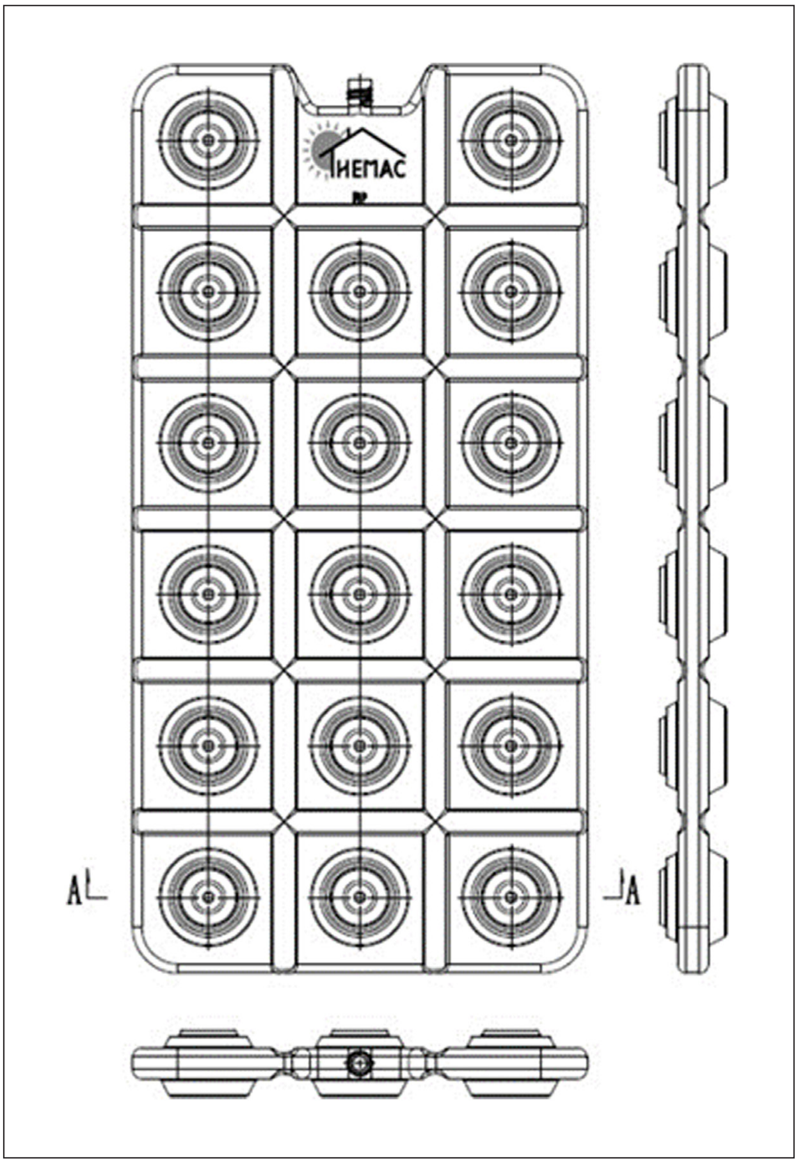

Figure 3 Encapsulation container.

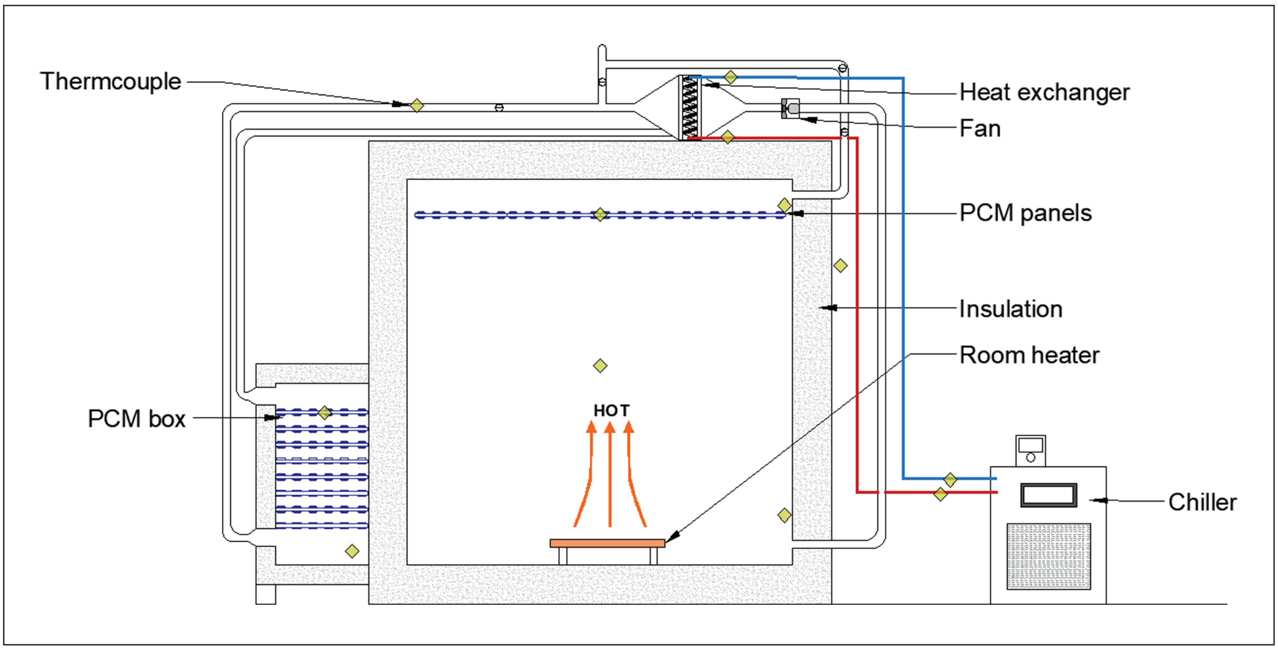

Figure 4 Schematic setup of the panel rig.

composed of 4 PCM panels placed on top of the testing box. In addition, 8 PCM panels were allocated in a control box adjacent to the environmental chamber and were connected to the heat exchanger unit, where the cooling occurs (***Figure 5***). The chiller unit (Grant LTC4) had a temperature range between (–30 to 100°C) and for this experiment was set at 5°C (***Figure 6***). The environmental chamber temperature was set at 30°C representing the daytime temperature and 25°C for the night-time and the RH was maintained at 20%.

A data logger (DT85), was used to monitor the data from the thermocouples placed at different locations in the rig. The thermocouples used were K-type thermocouples, with a standard deviation of ±0.3°C. The data logger was set to log the data every 30 seconds for the daytime and night-time test, while it was set to log

Figure 5 (**a**) Testing box, (**b**) PCM box.

Figure 6 (**c**) Heat exchanger, (**d**) Chiller unit.

the data every 30 mins for the overnight PCM cooling test. A water flow meter was integrated to display the mass flow rate of water, while a hot wire anemometer was utilised to log the airspeed before the heat exchanger. An energy meter was connected to the chiller, pumps and fan to indicate the energy consumed by these components throughout the test. A room heater was placed inside the testing box, representing the room's internal gain with a maximum capacity of 60 watts.

3. RESULTS

The thermal performance was assessed with respect to the testing box indoor temperature, based on the temperature difference created by the integration of the PCM panels inside the testing chamber as well as in the PCM box storage. The temperature comparison of the system using PCM and bypassing the PCM was monitored, demonstrating the effectiveness in terms of energy savings.

Figure 7 presents the testing results of the testing box, using two heating cycles and reaching a maximum temperature of 39°C, reaching the melting point of the PCM. The results exhibit that the S27 panels reduce the cooling time, reaching a lower temperature of 25°C faster. In terms of the chiller performance, the reduction in the operational time was of 12 minutes in comparison to the box without the PCM panels. In terms of energy saving, this represents a reduction from 1.8 kWh to 1.7 kWh as shown in ***Figure 8***.

Figure 9 presents the impact of the 12 PCM panels on the chiller load. The PCM provides a reduction in the ambient temperature, comparing the heat exchanger and the chiller inlet and outlet. The reduction in the heat exchanger air inlet temperature demonstrates the successful heat absorption from the PCM panels, having an average temperature difference of 1.8°C with a maximum temperature difference of 3°C.

Figure 10 presents the average temperature inside the insulated box comparing the temperature loss with and without PCM storage. Having the PCM panels reduced the temperature faster; therefore, reducing the chiller to operational time and ultimately diminishing the energy requirement. The energy consumption measured by the energy meter is presented in ***Figure 11***, where a reduction of 0.15 kWh is presented by using 12 PCM panels.

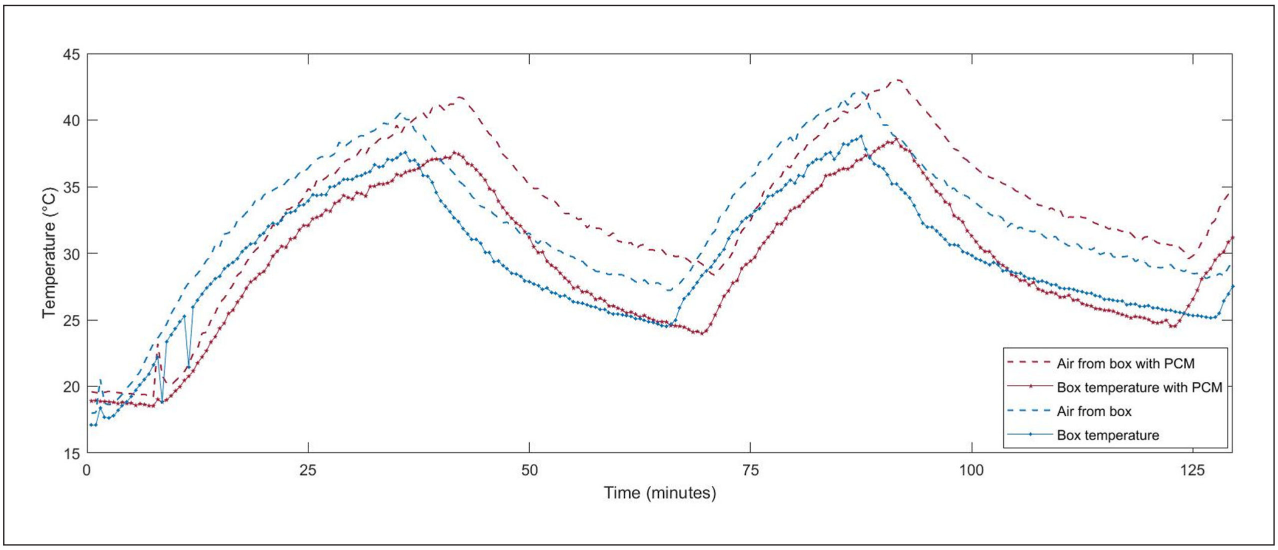

Figure 7 Testing box temperature comparison with and without PCM panels.

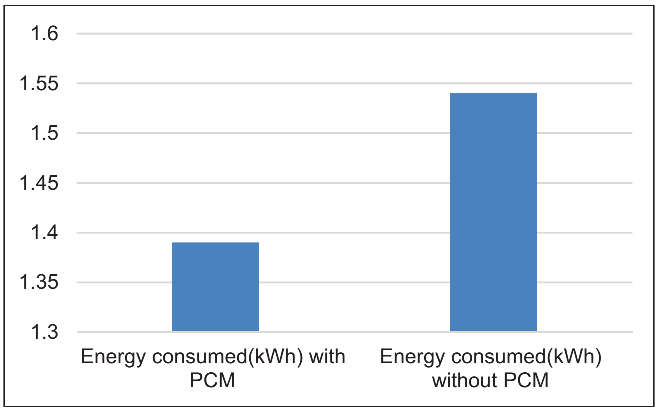

Figure 8 Energy consumption comparison with and without PCM panels for heating period.

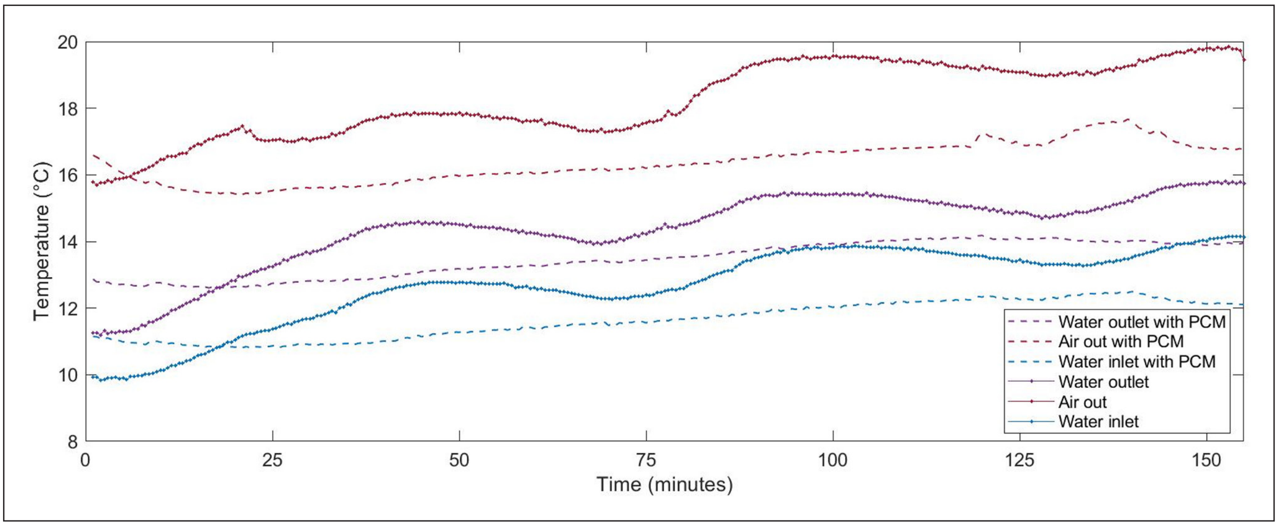

Figure 9 System temperature comparison with and without PCM panels.

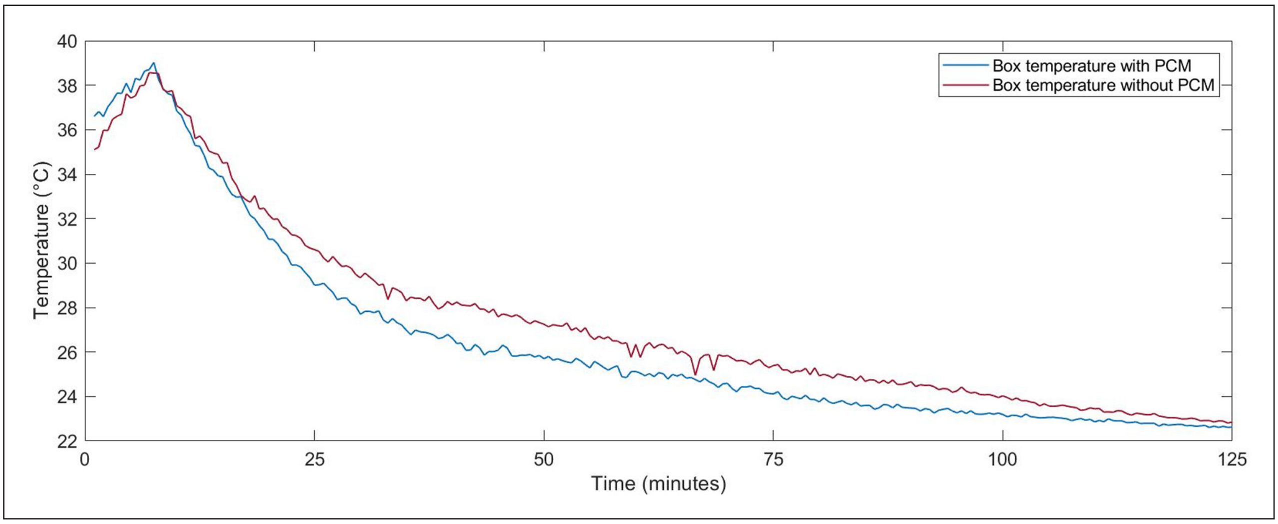

Figure 10 Testing box temperature loss comparison with and without PCM panels.

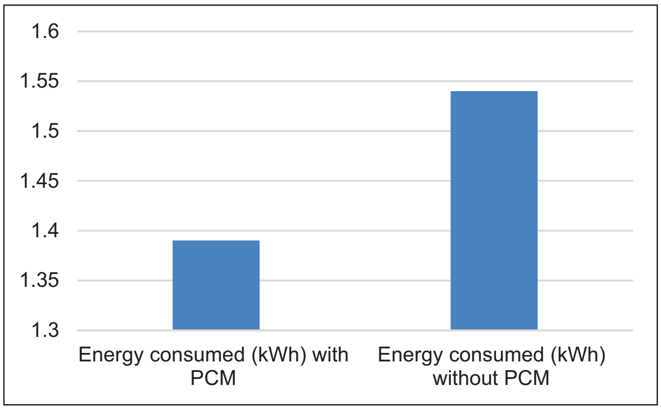

Figure 11 Energy consumption comparison with and without PCM panels for cooling period.

4. DISCUSSION AND CONCLUSIONS

PCMs have been identified as a powerful alternative to conventional cooling systems. This research aims to experimentally assess the application of PCM panels as a storage system coupled with an air-cooling system to effectively reduce the energy consumption of buildings by absorbing a portion of the thermal load. This innovative system is supported by the application of a heat exchanger, assisting with the cooling performance. The experiment evaluation has been set under hot climate applications, using the Northern region in Nigeria as a reference.

The investigation focused on the application of S27 salt hydrates panels as a latent heat storage unit for space cooling and monitoring the thermal response of TES to the temperature step function and energy reduction on the chiller unit. The following conclusion was derived from the study:

- The system had two operating schedules, during daytime the environmental temperature was considered at 30°C, and at night-time, the temperature was reduced to 25°C. The S27 PCM panels effectively melt and regenerate during the testing cycle. The average temperature difference presented by the PCM panels was found at 1.8°C.
- The experimental results of the energy rate control demonstrated the impact of the PCM panels to procure cooling and exhibited the potential energy savings, represented by the diminishing energy demand on the chiller unit. During the heating phase, an energy reduction of 0.10 kWh was presented with the addition of 12 PCM panels, for the cooling phase a 0.15 kWh reduction was accomplished.

Review studies have identified comparable energy savings for cool storage applications. Riffat et al. found a temperature reduction of 2 to 2.5°C by using a chilled ceiling coupled with a driven vapour-compression cooling system (Riffat et al., 2022). Velasco et al found a room temperature difference up to 1.5°C with the addition of S23 PCM panels (Velasco-Carrasco et al., 2020b). Nagano et al. found that temperature reduction of 1.5–2.1°C by using a granular PCM (Nagano et al., 2006). In this regard, the temperature difference presented in this study is in line with the expected results for PCM ceiling panels for cooling applications.

Further research investigation into cold storage would strengthen the application of this technology for building energy saving. This would represent that serial production of cold storage components and PCM manufacturing will reduce the production costs. The possibility of integrating cold storage into buildings should be simplified by using pre-fabricated assemblies or module-type construction, facilitating retrofits (Stritih et al., 2018).

ACKNOWLEDGEMENTS

The authors wish to acknowledge that this work was funded by Innovate UK (Project 105917).

COMPETING INTERESTS

Saffa Riffat is the Editor in Chief of this journal and was removed from all editorial duties involving the review and processing of the submission.

AUTHOR AFFILIATIONS

Mariana Velasco-Carrasco *orcid.org/0000-0002-0361-1910*
Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, UK

Omar Ramadan *orcid.org/0000-0001-5551-3522*
Geo Green Power Ltd, Nottingham, UK

Saffa Riffat *orcid.org/0000-0002-3911-0851*
Department of Architecture and Built Environment, Faculty of Engineering, University of Nottingham, UK

REFERENCES

Akeiber, H, Nejat, P, Majid, MZA, Wahid, MA, Jomehzadeh, F, Zeynali Famileh, I, Calautit, JK, Hughes, BR and **Zaki, SA.** 2016. A review on phase change material (PCM) for sustainable passive cooling in building envelopes. *Renewable and Sustainable Energy Reviews*, *60*: 1470–1497. DOI: *https://doi.org/10.1016/j.rser.2016.03.036*

Belusko, M, Saman, W and **Bruno, F.** 2004. Roof integrated solar heating system with glazed collector. *Solar Energy*, *76*(1–3): 61–69. DOI: *https://doi.org/10.1016/j.solener.2003.08.020*

Cabeza, LF, Castell, A, Barreneche, C, De Gracia, A and **Fernández, AI.** 2011. Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews*, *15*(3): 1675–1695. DOI: *https://doi.org/10.1016/j.rser.2010.11.018*

Elsanusi, OS and **Nsofor, EC.** 2020. *Melting of multiple PCMs with different arrangements inside a heat exchanger for energy storage*. DOI: *https://doi.org/10.1016/j.applthermaleng.2020.116046*

Jayalath, A, Aye, L, Mendis, P and **Ngo, T.** 2016. Effects of phase change material roof layers on thermal performance of a residential building in Melbourne and Sydney. *Energy and Buildings*, *121*: 152–158. DOI: *https://doi.org/10.1016/j.enbuild.2016.04.007*

Jelle, BP and **Kalnæs, SE.** 2017. Phase Change Materials for Application in Energy-Efficient Buildings. In *Cost-Effective Energy Efficient Building Retrofitting: Materials, Technologies, Optimization and Case Studies*. Elsevier Ltd. DOI: *https://doi.org/10.1016/B978-0-08-101128-7.00003-4*

Liu, Z, Yu, Z(Jerry), Yang, T, Qin, D, Li, S, Zhang, G, Haghighat, F and **Joybari, MM.** 2018. A review on macro-encapsulated phase change material for building envelope applications. *Building and Environment*, *144*, 281– 294. July. DOI: *https://doi.org/10.1016/j.buildenv.2018.08.030*

Marin, P, Saffari, M, de Gracia, A, Zhu, X, Farid, MM, Cabeza, LF and **Ushak, S.** 2016. Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions. *Energy and Buildings*, *129*: 274–283. DOI: *https://doi.org/10.1016/j.enbuild.2016.08.007*

Mazzeo, D, Oliveti, G and **Arcuri, N.** 2017. Data demonstrating the influence of the latent storage efficiency on the dynamic thermal characteristics of a PCM layer. *Data in Brief*, *12*: 274–276. DOI: *https://doi.org/10.1016/j.dib.2017.04.005*

Mehling, H and **Cabeza, LF.** 2008. *Heat and cold storage with PCM an up to date introduction into basics and applications* (Luisa F. Cabeza (ed.)) [Book]. Springer. DOI: *https://doi.org/10.1007/978-3-540-68557-9*

Micklethwait, J and **Wooldridge, A.** 2014. The State of African Cities 2010, Governance, Inequalities and Urban Land Markets. In *Foreign Affairs, 93*(4). DOI: *https://doi.org/10.1080/10455750308565526*

Moreno, P, Castell, A, Solé, C, Zsembinszki, G and **Cabeza, LF.** 2014. PCM thermal energy storage tanks in heat pump system for space cooling. *Energy and Buildings*, *82*: 399–405. DOI: *https://doi.org/10.1016/j.enbuild.2014.07.044*

Mozafari, M, Lee, A and **Cheng, S.** 2022. A novel dual-PCM configuration to improve simultaneous energy storage and recovery in triplex-tube heat exchanger. *International Journal of Heat and Mass Transfer*, *186*: 122420. DOI: *https://doi.org/10.1016/j.ijheatmasstransfer.2021.122420*

Nagano, K, Takeda, S, Mochida, T, Shimakura, K and **Nakamura, T.** 2006. Study of a floor supply air conditioning system using granular phase change material to augment building mass thermal storage – Heat response in small scale experiments. *Energy and Buildings*, *38*(5): 436–446. DOI: *https://doi.org/10.1016/j.enbuild.2005.07.010*

Ochedi, ET and **Taki, A.** 2021. A framework approach to the design of energy efficient residential buildings in Nigeria. *Energy and Built Environment*. DOI: *https://doi.org/10.1016/j.enbenv.2021.07.001*

Panayiotou, GP, Kalogirou, SA and **Tassou, SA.** 2016. Evaluation of the application of Phase Change Materials (PCM) on the envelope of a typical dwelling in the Mediterranean region. *Renewable Energy*, *97*: 24–32. DOI: *https://doi.org/10.1016/j.renene.2016.05.043*

Riahi, A, Mosleh, HJ, Kavian, S and **Shafii, MB.** 2021. Performance analysis and transient simulation of a vapor compression cooling system integrated with phase change material as thermal energy storage for electric peak load shaving. *Journal of Energy Storage*, *35*: 102316. DOI; *https://doi.org/10.1016/j.est.2021.102316*

Riffat, J, Kutlu, C, Tapia-Brito, E, Su, Y and **Riffat, S.** 2022. A preliminary experimental study of a novel incorporation of chilled ceiling with phase change materials and transparent membrane cover. *International Journal of Low-Carbon*, *17*: 258–265. DOI: *https://doi.org/10.1093/ijlct/ctab104*

Saffari, M, de Gracia, A, Ushak, S and **Cabeza, LF.** 2017. Passive cooling of buildings with phase change materials using whole-building energy simulation tools: A review. *Renewable and Sustainable Energy Reviews*, *80*: 1239–1255. DOI: *https://doi.org/10.1016/j.rser.2017.05.139*

Santos, T, Kolokotroni, M, Hopper, N and **Yearley, K.** 2019. Experimental study on the performance of a new encapsulation panel for PCM's to be used in the PCM-Air heat exchanger. *Energy Procedia*, *161*: 352–359. DOI: *https://doi.org/10.1016/j.egypro.2019.02.105*

Stritih, U, Tyagi, VV, Stropnik, R, Paksoy, H, Haghighat, F and **Joybari, MM.** 2018. Integration of passive PCM technologies for net-zero energy buildings. *Sustainable Cities and Society*, *41*: 286–295. April 2018. DOI: *https://doi.org/10.1016/j.scs.2018.04.036*

Takeda, S, Nagano, K, Mochida, T and **Shimakura, K.** 2004. Development of a ventilation system utilizing thermal energy storage for granules containing phase change material. *Solar Energy*, *77*(3): 329–338. DOI: *https://doi.org/10.1016/j.solener.2004.04.014*

Velasco-Carrasco, M, Chen, Z, Aguilar-Santana, JL and **Riffat, S.** 2020a. Experimental evaluation of phase change material blister panels for building application. *Future Cities and Environment*, *6*(1): 1–7. DOI: *https://doi.org/10.5334/fce.84*

Velasco-Carrasco, M, Chen, Z, Aguilar-Santana, JL and **Riffat, S.** 2020b. Experimental Evaluation of Thermal Energy Storage (TES) with Phase Change Materials (PCM) for Ceiling Tile Applications. *Future Cities and Environment*, *6*(1). DOI: *https://doi.org/10.5334/fce.101*

Weinläder, H, Klinker, F and **Yasin, M.** 2017. PCM cooling ceilings in the Energy Efficiency Center – Regeneration behaviour of two different system designs. *Energy and Buildings*, *156*: 70–77. DOI: *https://doi.org/10.1016/j.enbuild.2017.09.010*

Zhang, P, Xiao, X and **Ma, ZW.** 2016. A review of the composite phase change materials: Fabrication, characterization, mathematical modeling and application to performance enhancement. *Applied Energy*, *165*: 472–510. DOI: *https://doi.org/10.1016/j.apenergy.2015.12.043*

TO CITE THIS ARTICLE:
Velasco-Carrasco, M, Ramadan, O and Riffat, S. 2022. Experimental Study of PCM Cooling Storage System for Hot Climates. *Future Cities and Environment,* 8(1): 4, 1–11. DOI: *https://doi.org/10.5334/fce.148*

Submitted: 11 February 2022 Accepted: 05 April 2022 Published: 13 April 2022

Future Cities and Environment is a peer-reviewed open access journal published by Ubiquity Press.