An Overview of Heating and Multipurpose Utilization of Phase Change Materials for Thermal Energy Storage in Buildings

Himanshu kumar
Department of Mechanical Engineering
Punjab Engineering College (Deemed to be University) Chandigarh, India

Gurjeet Singh
Department of Mechanical Engineering
Punjab Engineering College (Deemed to be University) Chandigarh, India

Ankit Yadav
Department of Mechanical Engineering
Punjab Engineering College (Deemed to be University) Chandigarh, India

Abstract-Thermal energy storage, particularly phase change materials, is being studied by researchers all over the world for its potential to improve energy efficiency, maintain thermal comfort in buildings, and contribute to the reduction of pollution. PCM technique is used in a wide range of applications in the residential sector that rely on heating and cooling systems. The present study provides a current state-of-the-art evaluation of recent literature on thermal energy storage systems for buildings utilizing PCMs. The applications under consideration are heating and multipurpose use, which are divided into passive and active systems. There is also an overview of the PCMs employed, their uses, thermo-physical properties, and integration procedures. The study emphasizes the importance of PCM system multipurpose use and the prospective effectiveness of PCM in building heating applications. Experiments on commercial structures, as well as the creation and optimization of multipurpose systems, are still needed, according to the study. Finally, several combinations of active and passive heating applications are suggested, each with its own set of advantages in terms of improving energy efficiency.
Keywords – PCM, Latent heat, Hybrid, Thermal energy storage, Building

I. INTRODUCTION

Recent and ongoing research has focused on increasing energy efficiency by increasing the share of renewable energy, managing energy consumption, and lowering heating and cooling costs. This is due to a significant increase in global energy demand as a result of rapid population and economic growth, which is having a negative influence on the environment [1–8]. Economic growth, the intensity of energy consumption, population expansion, and the intensity of carbon emissions all influence overall carbon emissions, according to Kaya and Yokoburi [9]. Over the last 20 years, primary energy production and CO2 emissions have increased by 49 percent and 43 percent, respectively, according to the International Energy Agency (IEA) [10]. The construction sector, which consumes the most energy, accounts for around 25–30% of worldwide final energy consumption [11,12] and is a major source of CO2 emissions [13]. Furthermore, the IEA estimates that if no energy efficiency improvements are made in the building industry, energy consumption will grow by 50% by 2050 [14]. Buildings are the primary source of energy use worldwide, accounting for approximately 40% of overall energy consumption [15–18].

As a result, experts are looking for ways to improve energy conservation and storage in order to reduce global energy consumption. The use of phase change materials, sometimes known as "PCM," is a widely used approach for improving cooling and heating by lowering energy consumption in the building industry. PCMs used as thermal energy storage methods that absorb excess energy in buildings, covering the gap between supply and demand, managing internal temperature, and therefore improving thermal comfort, making it a potential technology [19,20].

PCM has been used to model a diverse spectrum of energy-dependent organisms and resources. Solar energy (for example, solar dryers [21] and solar domestic hot water systems [22]), industrial heat recovery, industrial worker equipment (for example, helmets [23]), electrical power peaking regulation, textiles, healthcare, liquefied natural gas, greenhouse agriculture, buildings, and aerospace [24] are examples of such applications. Researchers from all around the world have studied the use of PCM in buildings for heating and cooling applications as TES systems [19,24,25,26, 27].

1.1. Thermal energy storage system (TESS)

Time afterward, climatic circumstances were considered in the construction of traditional structures, and the use of materials with high thermal mass became the standard way for keeping interiors cool in the summer and warm in the winter [26]. As a result, the use of thermal energy storage (TES) systems in conjunction with buildings has been promoted as a cost-effective and promising technology for lowering energy demand, shifting cooling/heating loads in time (peak shaving), and improving heating/cooling systems by increasing thermal efficiency or lowering harmful greenhouse gas emissions [28]. The key to achieving "Energy Flexibility" in buildings is TES [29]. Sharma et al. [30] classified different forms of solar energy thermal storage into two groups in their study: (1) Thermochemical and (2) Thermal (Fig.1). Sensible heat storage, Latent heat storage, and Thermochemical heat storage are the three basic kinds of TES (TCM-TES) [31,32]. When deciding which storage technology to utilise, the most essential aspect determining the thermal response is the ratio between the building's envelope size, utilised materials and their volume with their corresponding thermal mass [33]. Morrison and Abdulkhalik [34] found that the storage volume of a rock-bed unit (which is a sensible TES approach) in an air-based system is four times bigger than that of a system using Sodium Sulfate Decahydrate ($Na_2SO_4 \cdot 10H_2O$) and double that of a system using paraffin wax (which are latent TES methods).

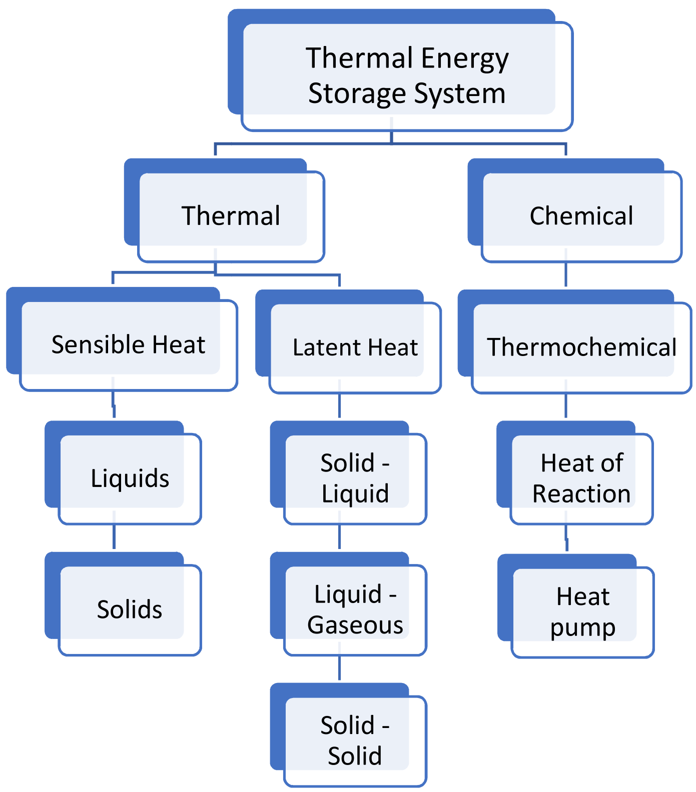

Figure. 1. Classification of thermal energy storage for solar energy [30].

1.2. Phase change materials (PCMs)

Phase change materials are "latent" heat storage materials that undergo an isothermal phase shift from liquid to solid when melted (heat storage) or solidified (crystallization recovery). PCMs store thermal energy in the form of latent heat during phase transition from solid to liquid via an endothermal process that breaks the PCM's chemical bonds, and release it exothermally when cooled to return to solid state [26,35,36]. PCM is thus described as a thermal storage medium [37]. PCM's related phase transition is depicted in Fig. 2. Due to the expected issues in building applications such as heat transfer, fire retardation, sub-cooling, phase separation, and long-term stability [28], as well as uneven melting, coagulation, and leakage, PCM as LHTES technology became one of the most efficient techniques for storing and releasing thermal energy [27].

1.3. PCM classification

Organic, inorganic, and eutectic phase change materials are the three primary kinds of phase change materials that transform from liquid to solid [38-40]. These groups are further split based on the chemical components that make up the PCM. Figure 2 shows a details diagram for the classified PCMs. It's also critical to determine each PCM's working range in order to meet demand while also taking into account its thermal capacity.

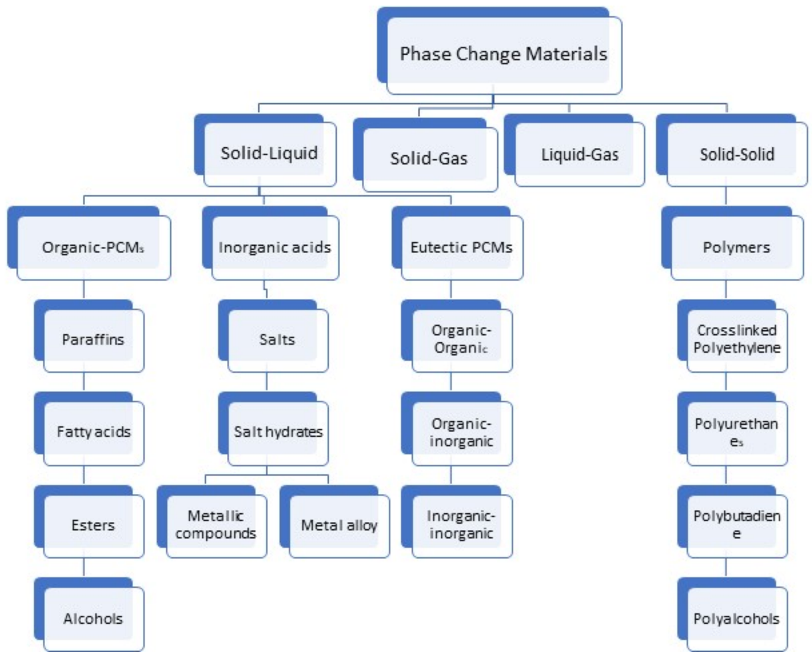

Figure. 2. Classification of PCM [38-40]

1.4. PCM selection criteria

It is crucial to consider certain important considerations while selecting PCM for use as LHTES materials in buildings. The methodology for selecting the best PCM is based on a few rules. The first step is to decide what melting temperature to use; for building applications, it is advised that the melting temperature range be in the range of 15–30 °C [27] or 20–32 °C[26], which is the range of thermal comfort. PCMs, on the other hand, must exhibit the following predicted thermo-physical, kinetic, chemical, technical, and economic qualities [41-45].

1.5. PCM characterization techniques

The scientific community has developed a number of measurement techniques, including [46, 33]: (1) Differential Scanning Calorimetry (DSC), (2) Differential Thermal Analysis (DTA), and (3) T-history method for thermo-physical properties; (4) Thermal Cycling Analysis and (5) Fourier Transformed Infrared Spectroscopy (FT-IR) for chemical properties; (6) Scanning Electro Microscopy (SEM) for microstructure observation; (7) Thermo Gravimetric Analysis (TGA).

II. USE OF PCM-TES FOR HEATING APPLICATIONS IN BUILDINGS

PCM uses are appropriate for both new construction and retrofitting existing structures [42]. The use of various encapsulation techniques to include them into construction materials is becoming more common around the world [47]. This area contains literature that includes both experimental and numerical analysis. PCM-TES can be used for heating, cooling, or hybrid systems, which combine heating and cooling. Each category is separated into two categories: passive and active. The distinction between active and passive systems, according to Heieret al. [28], is the driving force for charging and discharging the store; active storage uses pumps or fans, whereas passive storage relies solely on temperature differences.

2.1. Heating passive methods

The adaptation of PCM to the building envelope, starting with the walls, is primarily focused on construction materials such as building bricks, stones, and concrete, as well as plastering mortar, with a special focus on PCM wallboards. Designers of PCM integration for buildings are also looking at floors and ceilings. Trombe walls and Solar facades with PCM for thermal energy storage are examples of other designs.

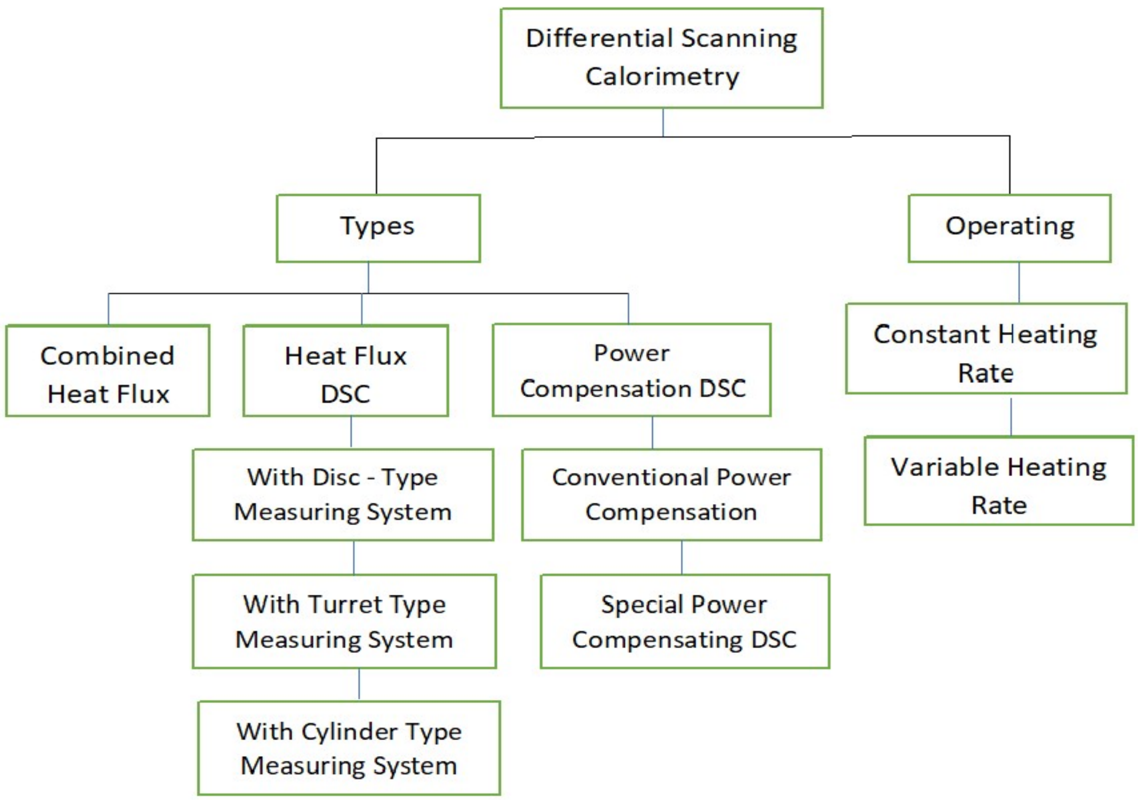

Figure. 3. DSC classifications and operating modes [48]

2.1.1. Walls, wallboards, floors and ceilings

In the Mediterranean environment of Casablanca, Morocco, Mouridet al. [39] investigated the thermal behaviour of two full-scale genuine prototypes. The goal of the experiment was to measure the indoor, wall, ceiling, and outside ambient temperatures, as well as the heat flow through the wall and ceiling. These tests were carried out on a reference prototype as well as another with 5.26 mm thick PCM Energain wallboards.

2.1.2. Trombe walls

Kara and Kurnuç[49] studied the performance of two Trombe walls built in conjunction with triple pane windows in two test facilities in Erusurm, Turkey, that shared the same side and faced south. In the first wall, GR35 PCM was used, while in the second, GR41 was used. The ratio of solar energy gain over PCM walls to heat load varied between 4% and 70%, with daily overall efficiency for PCM walls ranging from 20% to 36%. Furthermore, in this application, GR35 has been demonstrated to be more efficient than GR41.

2.1.3. Solar façade

Graciaet al. [50] in Spain evaluated the thermal performance of a ventilated solar façade with macro-encapsulated PCM inserted in the air cavity. Two similar house cubicles, one with a vented façade including SP22 PCM plates and the other as a control. The ventilated facade including PCM during free-floating mode produced a daily increase in temperature from 9 °C to 18 °C during harsh winter circumstances, according to the results. Furthermore, the free-floating studies showed that during the mild winter months, the operation of an HVAC system is almost unnecessary. a phase change material-filled ventilated multilayer glazing façade.

2.2. Heating active methods

Underfloor radiant heating with PCM, including electrical heating systems, hydronic water systems, and hot water capillary mats, solar water heaters, solar air heaters, ventilated façades, solar heat pumps, heat exchangers, HVAC systems, and solar domestic hot water systems are among the most popular active heating applications using PCM.

2.2.1. Underfloor heating with PCM

Radiant or convection heating technologies are expected to play a significant role in developing a functional zone space [51]. Zhou et al.[52] investigated the thermal performance of a hot water floor panel with several heating pipes: polyethylene coils (PE pipes) and capillary mat (CAP mat) integrated with various TES materials (sand and PCM). Four distinct floor arrangements were investigated, each with its own set of heating coil and TES options.

2.2.2. Solar water heater

Huang et al.[53] conducted a computational analysis and experimental validation for a new design of a solar water heating system that uses capillary pipes positioned above and below a prefabricated concrete skeleton with 169 voids filled by macro-encapsulated capric acid. In Shenyang Jian Zhu university, northern China, ANSYS software was used to model the floor, and two sides identical 2nd floor rooms were prepared for the experimental investigation: one with PCM floor and the other with concrete. The energy storage capacity of the floor was considerably increased, with the added benefit of reducing space in the water tank.

2.2.3. Solar air heater

The spherical encapsulation of PCM producing a packed bed LHTES system proven to offer the advantage of higher storage density, configurational simplicity, and a large surface to volume ratio for solar air heater (SAH) applications employing PCM as thermal storage system. The effect of varying flow rates on the TES system performance was the topic of a study by Esakkimuthu.[60], who did experiments on the charging and discharging characteristics of a SAH packed with HC58 PCM as a TES system in India. In an experiment, Kabeeletal.[55] investigated flat and v corrugated plate SAHs with built-in PCM as thermal energy storage material.

2.2.4. Ventilated façades

Gracia et al. [56] investigated a double-skin ventilated solar façade with 112 PCM panels dispersed across 14 air channels in an experimental study. Figure 18 depicts the mechanism. The results showed that the thermal performance of the building improved, and that a better improvement can be attained if a thermal management system is implemented. In a subsequent work [57], the authors validated a numerical model based on a finite volume control technique in an attempt to construct an operating plan for the PCM melting and freezing process.

III. USE OF PCM-TES FOR HYBRID APPLICATIONS IN BUILDINGS

Thermal energy storage in buildings is required to maintain a balance between annual energy demand and supply during both the heating and cooling seasons [27]. A good TES system is one that can work in a variety of seasons and weather situations. Overheating reduction in the summer and heat storage in the winter are examples of hybrid building applications.

3.1. Hybrid passive methods

PCM integration in the building envelope, which includes walls, wallboards, plastering mortar bricks, windows, roofs, and floors, is the most prevalent passive technique. Sun et al.[58] investigated the best place for PCM spherical capsules in lightweight construction walls. The walls that were put to the test were as follows: Wall A has five XPS insulation layers, Wall B has four XPS layers plus a cavity integrated sheet, and Wall C has four XPS layers plus a PCM integrated sheet. The authors demonstrated that the third layer is the ideal place for PCM spheres in summer and annual cases, whereas the fourth layer is best for winter cases.

3.2. Hybrid active methods

In the meteorological conditions of Ljubljana, Slovenia, Stritihet al. [59] examined the thermal performance of a solar air heater using an LHTES unit with PCM plates. TRNSYS was also used by the authors to run numerical simulations for the test facility. If only the operating costs were evaluated, the system without PCM saved 58 percent annually compared to 68 percent for the system with PCM. When compared to district heating, however, annual savings for the PCM system and the reference one are 91 percent and 93 percent, respectively. Osterman et al. [60] presented a TES system for an office solar air heater that uses 15 or 30 RT22HC paraffin-based PCM plates (depending on the case study).

IV. CONCLUSION

This article provides a review of recent research literature on the use of phase change materials as latent heat thermal energy storage techniques in residential and commercial buildings. To begin, phase change materials were discussed, including their ideas, classification, selection criteria, and property tests. Then two types of applications in buildings were discussed: heating applications and hybrid (heating and cooling to satisfy annual needs) applications. In each researched feature, the presented literature was divided into two categories: passive and active systems. Each study's thermal performance analysis has been analysed and it has been concluded that:

- There are still few studies on PCM size, mass, and placement, and most current optimization studies are based on pure numerical models that lack experimental evidence.
- To have a better picture of PCM capabilities, economic analysis should be combined with thermal performance and energy efficiency study.
- Most importantly, the majority of the articles reviewed focused on one application of PCM, with only a few coverings combined applications such as using PCM wallboards in walls and ceilings as a passive heating method in conjunction with underfloor electrical heating with incorporated PCM as an active heating method.
- The majority of commercially available PCMs are based on paraffin. Many PCMs, including bio-based, inorganic, and eutectic mixes, need to be commercialized.
- The most common incorporation procedures in the literature were macro-encapsulation into containers, packages, and capsules, among other things. Despite the benefits of such an integration technique, extra attention must be paid to other incorporation strategies, particularly micro-encapsulation and the use of nano-PCM.
- Aside from the type of application and design difficulties, the spectrum of human thermal comfort varies with climatic change, resulting in variations in melting temperatures of each PCM in each study.

REFERENCES

[1] M. He, L. Yang, W. Lin, J. Chen, X. Mao, Z Ma, Preparation, thermal characterization and examination of phase change materials (PCMs) enhanced by carbon-based nanoparticles for solar thermal energy storage, J. Energy Storage (2019) 25, https://doi.org/10.1016/j.est.2019.100874.

[2] Y. Zhang, J. Zhang, X. Li, X. Wu, Preparation of hydrophobic lauric acid / SiO2 shape-stabilized phase change materials for thermal energy storage, J. Energy Storage 21 (2019) 611–617, https://doi.org/10.1016/j.est.2018.12.022.

[3] N. Aslfattahi, R. Saidur, A. Arifutzzaman, R. Sadri, N. Bimbo, M.F.M. Sabri, P.A. Maughan,L. Bouscarrat, R.J. Dawson, S.M. Said, B.T. Goh, N.A.C. Sidik, C. Sidik, Experimentalinvestigation of energy storage properties and thermal conductivity of a novel organic phasechange material/MXene as A new class of nanocomposites, J. Energy Storage (2020) 27, https://doi.org/10.1016/j.est.2019. 101115.

[4] S.G. Ranjbar, G. Roudini, F. Barahuie, Fabrication and characterization of phase changematerial-SiO2 nanocomposite for thermal energy storage in buildings, J. Energy Storage (2020)27, https://doi.org/10.1016/j.est.2019.101168.

[5] W. Yang, R. Xu, B. Yang, J. Yang, Experimental and numerical investigations on the thermalperformance of a borehole ground heat exchanger with PCM backfil, Energy (2019), https://doi.org/10.1016/j.energy.2019.02.172.

[6] X. Bao, Y. Tian, L. Yuan, H. Cui, W. Tang, W.H. Fung, Development of high performancePCM cement composites for passive solar buildings, Energy Build. 194 (2019) 33–45, https://doi.org/10.1016/j.enbuild.2019.04.011.

[7] S. Jeong, S. Wi, S. Jin, J. Lee, S. Kim, An experimental study on applying organic PCMs togypsum-cement board for improving thermal performance of buildings in different climates,Energy Build. 190 (2019) 183–194, https://doi.org/10.1016/j. enbuild.2019.02.037.

[8] Y. Song, C. Li, H. Yu, Y. Tang, Z. Xia, Optimization of the phase-change wallboard testmethod: experimental and numerical investigation, J. Energy Storage (2020) 30, https://doi.org/10.1016/j.est.2020.101559.

[9] A.O. Acheampong, Economic growth, CO2emissions and energy consumption: what causeswhat and where? Energy Econ. 74 (2018) 677–692, https://doi.org/ 10.1016/j.eneco.2018.07.022.

[10] International Energy Agency, IEA Roadmap targets 2015 2035, (n.d.). https:// www.iea.org/publications/freepublications/publication/IEA_Solar_HC_Roadmap_ Foldout_Print.pdf.

[11] M. Rabani, M. Rabani, Heating performance enhancement of a new design trombe wall using rectangular thermal fin arrays: an experimental approach, J. Energy Storage (2019) 24, https://doi.org/10.1016/j.est.2019.100796.

[12] N. Putra, S. Rawi, M. Amin, E. Kusrini, E.A. Kosasih, T. Mahlia, Preparation of beeswax/multi-walled carbon nanotubes as novel shape-stable nanocomposite phase change material for thermal energy storage, J. Energy Storage 21 (2019) 32–39, https://doi.org/10.1016/j.est.2018.11.007.

[13] P. Devaux, M.M. Farid, Benefits of PCM underfloor heating with PCM wallboards for space heating in winter, Appl. Energy 191 (2017) 593–602, https://doi.org/10.1016/j.apenergy.2017.01.060.

[14] R. Vanaga, A. Blumberga, R. Freimanis, T. Mols, D. Blumberga, Solar facade module for nearly zero energy building, Energy 157 (2018) 1025–1034, https:// doi.org/10.1016/j.energy.2018.04.167.

[15] M.R. Poole, S.B. Shah, M.D. Boyette, L.F. Stikeleather, T. Cleveland, Performance of a coupled transpired solar collector — Phase change material-based thermal energy storage system, Energy Build. 161 (2018) 72–79, https://doi.org/10.1016/ j.enbuild.2017.12.027.

[16] X. Sun, M.A. Medina, K.O. Lee, X. Jin, Laboratory assessment of residential building walls containing pipe-encapsulated phase change materials for thermal management, Energy 163 (2018) 383–391, https://doi.org/10.1016/j.energy. 2018.08.159.

[17] F.F.D.A. Landi, C. Fabiani, A.L. Pisello, Palm oil for seasonal thermal energy storage applications in buildings: the potential of multiple melting ranges in blends of bio-based fatty acids, J. Energy Storage (2020) 29, https://doi.org/10.1016/j.est. 2020.101431.

[18] C. Piselli, V. Lucia, A. Laura, How to enhance thermal energy storage effect of PCM in roofs with varying solar reflectance: experimental and numerical assessment of a new roof system for passive cooling in different climate conditions, Solar Energy (2018) 0–1, https://doi.org/10.1016/j.solener.2018.06.047.

[19] K. Du, J. Calautit, Z. Wang, Y. Wu, H. Liu, A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges, Appl. Energy 220 (2018) 242–273, https://doi.org/10.1016/j. apenergy.2018.03.005.

[20] M.R. Kadivar, M.A. Moghimi, P. Sapin, C.N. Markides, Annulus eccentricity optimisation of a phase-change material (PCM) horizontal double-pipe thermal energy store, J. Energy Storage (2019) 26, https://doi.org/10.1016/j.est.2019.101030.

[21] V.M. Swami, A.T. Autee, A.T R, Experimental analysis of solar fish dryer using phase change material, J. Energy Storage 20 (2018) 310–315, https://doi.org/10. 1016/j.est.2018.09.016.

[22] T. Bouhal, T.E. Rhafiki, T. Kousksou, A. Jamil, Y Zeraouli, PCM addition inside solar water heaters : numerical comparative approach, J. Energy Storage 19 (2018) 232–246, https://doi.org/10.1016/j.est.2018.08.005.

[23] M. Ali, R.F. Viegas, M.B.S. Kumar, R.K. Kannapiran, M. Feroskhan, Enhancement of heat transfer in para ffi n wax PCM using nano graphene composite for industrial helmets, J. Energy Storage (2019) 26, https://doi.org/10.1016/j.est.2019. 100982.

[24] X. Huang, G. Alva, Y. Jia, G. Fang, Morphological characterization and applications of phase change materials in thermal energy storage : a review, Renew. Sustain. Energy Rev. 72 (2017) 128–145, https://doi.org/10.1016/j.rser.2017.01. 048.

[25] S.S. Chandel, T. Agarwal, Review of current state of research on energy storage, toxicity, health hazards and commercialization of phase changing materials, Renew. Sustain. Energy Rev. 67 (2017) 581–596, https://doi.org/10.1016/j.rser. 2016.09.070.

[26] Y. Lin, Y. Jia, G. Alva, G. Fang, Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage, Renew. Sustain. Energy Rev. 82 (2018) 2730–2742, https://doi.org/10. 1016/j.rser.2017.10.002.

[27] A. Kasaeian, L. bahrami, F. Pourfayaz, E. Khodabandeh, W.M. Yan, Experimental studies on the applications of PCMs and nano-PCMs in buildings: a critical review, Energy Build. 154 (2017) 96–112, https://doi.org/10.1016/j.enbuild.2017.08. 037.

[28] J. Heier, C. Bales, V. Martin, Combining thermal energy storage with buildings - A review, Renew. Sustain. Energy Rev. 42 (2015) 1305–1325, https://doi.org/10. 1016/j.rser.2014.11.031.

[29] N. Morovat, A.K. Athienitis, J.A. Candanedo, V. Dermardiros, Simulation and performance analysis of an active PCM-heat exchanger intended for building operation optimization, Energy Build. 199 (2019) 47–61, https://doi.org/10.1016/j. enbuild.2019.06.022.

[30] A. Sharma, V.V. Tyagi, C.R. Chen, D. Buddhi, Review on thermal energy storage with phase change materials and applications, Renew. Sustain. Energy Rev. 13 (2009) 318–345, https://doi.org/10.1016/j.rser.2007.10.005.

[31] J.H. Patel, M.N. Qureshi, P.H. Darji, Experimental analysis of thermal energy storage by phase change material system for cooling and heating applications, Mater. Today Proc. 5 (2018) 1490–1500, https://doi.org/10.1016/j.matpr.2017. 11.238.

[32] K.S. Reddy, V. Mudgal, T.K. Mallick, Review of latent heat thermal energy storage for improved material stability and effective load management, J. Energy Storage 15 (2018) 205–227, https://doi.org/10.1016/j.est.2017.11.005.

[33] L. Boussaba, A. Foufa, S. Makhlouf, G. Lefebvre, L. Royon, Elaboration and properties of a composite bio-based PCM for an application in building envelopes, Constr. Build. Mater. 185 (2018) 156–165, https://doi.org/10.1016/j. conbuildmat.2018.07.098.

[34] D.J. Morrison, S.I. Abdel-Khalik, Effects of phase-change energy storage on the performance of air-based and liquid-based solar heating systems, Solar Energy 20 (1978) 57–67, https://doi.org/10.1016/0038-092X(78)90141-X.

[35] S.M. Wang, P. Matiašovský, P. Mihálka, C.M. Lai, Experimental investigation of the daily thermal performance of a mPCM honeycomb wallboard, Energy Build. 159 (2018) 419–425, https://doi.org/10.1016/j.enbuild.2017.10.080.

[36] S. Motahar, Experimental study and ANN-based prediction of melting heat transfer in a uniform heat flux PCM enclosure, J. Energy Storage (2020) 30, https://doi. org/10.1016/j.est.2020.101535.

[37] Q. Wang, R. Wu, Y. Wu, C.Y. Zhao, Parametric analysis of using PCM walls for heating loads reduction, Energy Build. 172 (2018) 328–336, https://doi.org/10. 1016/j.enbuild.2018.05.012.

[38] K.P. Venkitaraj, S. Suresh, B. Praveen, S.C. Nair, Experimental heat transfer analysis of macro packed neopentylglycol with CuO nano additives for building cooling applications, J. Energy Storage 17 (2018) 1–10, https://doi.org/10.1016/ j.est.2018.02.005.

[39] A. Mourid, M. El Alami, F. Kuznik, Experimental investigation on thermal behavior and reduction of energy consumption in a real scale building by using phase change materials on its envelope, Sustain. Cities Soc. 41 (2018) 35–43, https:// doi.org/10.1016/j.scs.2018.04.031.

[40] S.E. Kalnæs, B.P. Jelle, Phase Change Materials and Products for Building Applications: A State-of-the-Art Review and Future Research Opportunities, Elsevier, 2015, https://doi.org/10.1016/j.enbuild.2015.02.023 B.V.

[41] C. Zeng, S. Liu, A. Shukla, Adaptability research on phase change materials based technologies, Renew. Sustain. Energy Rev. 73 (2017) 145–158, https://doi.org/ 10.1016/j.rser.2017.01.117

[42] B.P. Jelle, S.E. Kalnæs, Phase Change Materials for Application in Energy-Efficient Buildings, Elsevier Ltd, 2017, https://doi.org/10.1016/B978-0-08-101128-7. 00003-4.

[43] S.A. Memon, H.Z. Cui, H. Zhang, F. Xing, Utilization of macro encapsulated phase change materials for the development of thermal energy storage and structural lightweight aggregate concrete, Appl. Energy 139 (2015) 43–55, https://doi.org/ 10.1016/j.apenergy.2014.11.022.

[44] A. Solé, L. Miró, C. Barreneche, I. Martorell, L.F. Cabeza, Review of the T -history method to determine thermophysical properties of phase change materials (PCM), Renew. Sustain. Energy Rev. 26 (2013) 425–436, https://doi.org/10.1016/j.rser. 2013.05.066.

[45] Y. Cui, J. Xie, J. Liu, S. Pan, Review of phase change materials integrated in building walls for energy saving, Procedia Eng. 121 (2015) 763–770, https://doi. org/10.1016/j.proeng.2015.09.027.

[46] D. Zhou, C.Y. Zhao, Y. Tian, Review on thermal energy storage with phase change materials (PCMs) in building applications, Appl. Energy 92 (2012) 593–605, https://doi.org/10.1016/j.apenergy.2011.08.025.

[47] A. Hassan, A.I. Mourad, Y. Rashid, N. Ismail, Thermal and structural performance of geopolymer concrete containing phase change material encapsulated in expanded clay, Energy Build. 191 (2019) 72–81, https://doi.org/10.1016/j.enbuild. 2019.03.005.

[48] H. Günther, W.F. Hemminger, H. Flammersheim, Differential Scanning Calorimetry, Springer, 2013.

[49] Y. Kara, A. Kurnuc, Performance of coupled novel triple glass and phase change material wall in the heating season : an experimental study, Solar Energy 86 (2012) 2432–2442, https://doi.org/10.1016/j.solener.2012.05.012.

[50] A. de Gracia, L. Navarro, A. Castell, Á. Ruiz-Pardo, S. Alvárez, L.F. Cabeza, Experimental study of a ventilated facade with PCM during winter period, Energy Build. 58 (2013) 324–332, https://doi.org/10.1016/j.enbuild.2012.10.026.

[51] R.J.D. Wong, M. Al-jethelah, S. Ebadi, A. Singh, S. Mahmud, Investigation of phase change materials integrated with fin-tube baseboard convector for space heating, Energy Build. 187 (2019) 241–256, https://doi.org/10.1016/j.enbuild.2019.02. 005.

[52] G. Zhou, J. He, Thermal performance of a radiant floor heating system with different heat storage materials and heating pipes, Appl. Energy 138 (2015) 648–660, https://doi.org/10.1016/j.apenergy.2014.10.058.

[53] K. Huang, G. Feng, J. Zhang, Experimental and numerical study on phase change material floor in solar water heating system with a new design, Solar Energy 105 (2014) 126–138, https://doi.org/10.1016/j.solener.2014.03.009.

[54] S. Esakkimuthu, A. Hakim, C. Palaniappan, M. Spinnler, J. Blumenberg, R. Velraj, Experimental investigation on phase change material based thermal storage system for solar air heating applications, Solar Energy 88 (2013) 144–153, https://doi.org/10.1016/j.solener.2012.11.006.

[55] A.E. Kabeel, A. Khalil, S.M. Shalaby, M.E. Zayed, Experimental investigation of thermal performance of flat and v-corrugated plate solar air heaters with and without PCM as ther[1]Kabeel AE, Khalil A, Shalaby SM, Zayed ME. Experimental investigation of thermal performance of flat and v-corrugated plate, Energy Convers. Manag. 113 (2016) 264–272, https://doi.org/10.1016/j.enconman. 2016.01.068.

[56] A. De Gracia, L. Navarro, A. Castell, Á. Ruiz-pardo, Solar absorption in a ventilated facade with PCM, Exp. Results 30 (2012) 986–994, https://doi.org/10.1016/j. egypro.2012.11.111.

[57] A. De Gracia, L. Navarro, A. Castell, L.F. Cabeza, Numerical study on the thermal performance of a ventilated facade with PCM, Appl. Therm. Eng. 61 (2013) 372–380, https://doi.org/10.1016/j.applthermaleng.2013.07.035

[58] X. Sun, J. Jovanovic, Y. Zhang, S. Fan, Y. Chu, Y. Mo, S. Liao, Use of encapsulated phase change materials in lightweight building walls for annual thermal regulation, Energy 180 (2019) 858–872, https://doi.org/10.1016/j.energy.2019.05.112

[59] U. Stritih, P. Charvat, R. Koželj, L. Klimes, E. Osterman, M. Ostry, V. Butala, PCM thermal energy storage in solar heating of ventilation air—experimental and numerical investigations, Sustain. Cities Soc. (2017), https://doi.org/10.1016/j.scs. 2017.10.018