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A REVIEW ON PHASE CHANGE MATERIALS FOR THERMAL ENERGY STORAGE IN BUILDINGS: HEATING AND HYBRID APPLICATIONS

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Abstract

Phase change materials (PCMs) gathered the attention of researchers and architects world-widely for its prodigious benefits in increasing the share of renewable energy, providing desired thermal comfort in buildings, achieving valuable reduction in energy consumption and contributing to the diminish of environmental pollution. Buildings, being the most demanding sectors of energy broadly, especially for heating and cooling purposes, are being exposed to the PCM technology by several applications. The current article reviews recent literature on the use of PCMs as thermal energy storage systems (TES) in buildings for heating and hybrid applications. A summary of the used PCMs is also presented with their respective applications, incorporation methods and basic thermo-physical properties are presented. It was shown that the applications of heating are promising, however, research of combined applications and combined PCMs are still required, and more experimental analysis of commercial buildings, in priority, are lacking.

1. Introduction

According to the data published by Eurostat, European Union member states have seen a remarkable increase in their final energy demand that reached approximately 1084 Mtoe (Million Tonnes of Oil Equivalent) in 2015, of which 422 Mtoe corresponded to building-related sectors, which is equivalent to 39% of total demand [1]. The building sector, being the largest energy-consuming sector, accounts for over 33.33 % of final energy consumption on global basis and is considered an equally important source of CO₂ emission [2]. Furthermore, it was detected that half of the energy consumption in buildings is caused by Heating, ventilating and air-conditioning (HVAC) systems [3]. For this purpose, researchers and policy makers are promoting new policies toward more sustainable and energy-efficient buildings. The integration of thermal energy storage (TES) technologies in buildings contributes to the reduction of peak loads, uncoupling of energy demand from its availability, allowing the integration of renewable energy sources and providing efficient management of thermal energy, thus leading to the improvement of building energy efficiency [1]. Latent heat TES using phase change materials (PCMs) have gained extensive attention for building applications due to their high energy storage density capability and their ability to store thermal energy in a constant temperature phase transition process [4].

Review articles in the field of phase change materials thermal energy storage (PCM-TES) are published by several researchers. V. Tyagi et al. [5] published a state-of-the-art review paper on PCM thermal storage in buildings, where various possible PCM based technological methods for heating and cooling in building sector were deliberated. Solar passive

building concepts, PCMs for space heating and cooling and their applications in passive and active systems are discussed. Active PCM-TES systems (floor heating, ceiling boards and other systems), and Passive PCM-TES systems (PCM Trombe wall, PCM wall board, PCM shutters, PCM building blocks, Air-based heating systems, floor heating and ceiling boards) described by the authors proved to have good potential for reducing the heating and cooling loads in buildings. A massive recent review paper conducted by K. Du et al. [6] reviewed the applications of PCMs in cooling, heating and energy generation in four temperature ranges where the authors concluded that: For low temperature range (-20°C to 5°C): PCMs used are mainly organic compounds. For medium-low temperature range (5°C to 40°C): PCMs used are mainly organic compounds and salt hydrates. For medium temperature range (40°C to 80°C): Organic PCMs like paraffin and fatty acids are mainly used, where for electric devices the contribution of PCM as a TES cooling system increased its operational efficiency and life span by up to 26% and 300%, respectively. And finally, for high temperature range (80°C to 200°C): Few organic PCMs are used with their acceptable performance improvement, while molten salt still dominates the TES sector for a long time with its lifespan and economic benefits. A critical review on the experimental studies regarding the applications of PCMs and nano-enhanced PCMs in buildings was done by Aibakhsh Kasaeian et al. [7]. The study covered literature on passive and active methods for integrating PCMs for cooling, heating, hybrid, and air-conditioning applications as well as the use of nano-enhanced PCMs in buildings. The current article presents a thorough review on the use of PCM as LHTES in buildings for heating and hybrid mixing of heating and cooling applications.

2. Phase change materials in buildings

2.1 Phase change materials concepts and classifications

Jaykumar H. Petal et al. [8] stated that, fundamentally, TES is subdivided into three categories: Sensible heat storage, Latent heat storage, and Thermochemical heat storage (TCM-TES). Nevertheless, due to the lack of commercially available TCM-TES systems, and due to high material costs and unknown lifespan [9], the main categories for TES techniques are: sensible heat storage and latent heat storage [10], [11]. Phase change materials, being the active latent thermal ingredient in LHTES systems, is categorized into three groups based on its phase change state: solid-solid PCMs, solid-liquid PCMs, and liquid-gas PCMs, with the second being the most appropriate PCM for TES applications [10], by which over than 200 compositions are spotted as promising PCMs [12]. Further classification of PCMs are illustrated in Fig. 1.

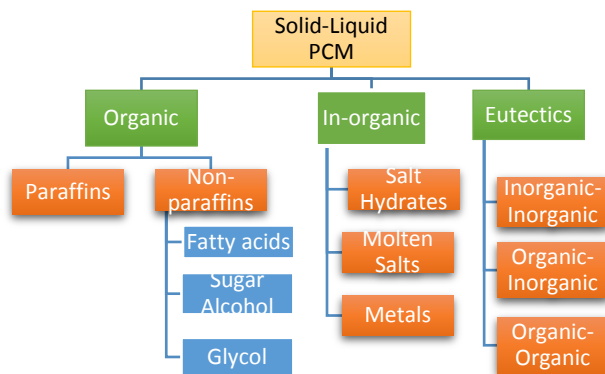


Fig. 1. Classification of liquid-solid PCMs [13].

PCMs experience a phase change between liquid and solid that occurs at a constant temperature. During phase transition from solid to liquid, PCMs absorbs thermal energy endothermally allowing the breaking of chemical bonds, and reject it in an exothermic process upon surrounding temperature drop recovering its solid state [2], [5], [14]–[17] thus acting as a thermal reservoir [18].

2.2 Phase change materials selection criteria and properties measurement methods

Methodology of selecting the suitable PCM depends on several guidelines. Deciding what melting temperature to be used is the initial start, where, it is recommended that the melting temperature range be in the range of 15–30°C [7] or 20–32°C [5] for building applications, which are the range of thermal comfort. However, PCMs have to possess certain anticipated thermo-physical, kinetic, chemical, technical and economic characteristics that are listed as follows [12]:

-Thermo-physical properties: In addition to having the desired temperature range mentioned previously, PCMs ought to have high latent heat of fusion, high specific heat, high conductivity, high density, small phase transition volume changes and congruent melting.

-Kinetic properties: They are two: High nucleation rate and high rate of crystal growth.

-Chemical properties: Complete reversible cycle, chemically stable with no degradation after a large number of freezing/melting cycles, no corrosiveness, not toxic and anti-flammable.

-Economic properties: It has to be cheap (effective cost) and available for large-scale practice.

Several measurement techniques are developed by the scientific community including [10], [11]: (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 Electron Microscopy (SEM) for microstructure observation; (7) Thermo Gravimetric Analysis (TGA) for thermal stability; And, (7) Hot disk apparatus for thermal conductivity measurement.

3. Use of PCM-TES for heating and hybrid applications in buildings.

PCMs applications are suitable for both new buildings and retrofitting of existing ones [19]. Literature including both experimental and numerical analysis are presented in this section. PCM-TES can be used for heating, cooling or for both heating and cooling which is referred as hybrid systems. Each mode is subdivided into passive and active categories. J. Heier et al. [9] states that the difference between active and passive systems is the driving force of charging and discharging the store, where active storage utilizes pumps or fans however passive storage depends only on temperature difference.

3.1 Heating applications of PCM-TES for buildings

In order to decrease the heating load and improve the thermal comfort during cold climates, PCM-TES could be integrated passively or actively in buildings.

3.1.1 Heating passive applications

The application of PCM for passive heating is limited to the adaptation of PCM building envelope (walls, floor and ceiling), particularly in construction materials such as building bricks, stones and concrete, as well as plastering mortar, with special focus is on PCM wallboards.

Amina Mourid et al. [20] tested the thermal behavior of two full-scale real prototypes in the Mediterranean climate of Casablanca, Morocco: a reference prototype and another one equipped with 5.26 mm thick PCM Energain® wallboards. The PCM of melting temperature ranging between 20°C and 35°C and a latent heat enthalpy of 72.4 kJ/kg proved to be efficient in Casablanca climate. It was shown that the temperature of the PCM room was higher than that of the reference one by a maximum deviation of 7.3°C, and the stratification in the room was demolished by the PCM, with a decrease in thermal losses of 50% across the ceiling emphasizing that the placement of

PCM in the ceiling is more efficient than in the wall. Also, an average energy consumption reduction of 20% was accomplished. P. Devaux and M.M. Farid [2] validated the experimental results obtained from experiments done on two identical huts built at Tamaki campus of university of Auckland, New Zealand, numerically via EnergyPlus® software. Two huts were investigated: one with PCM walls and floor and the other serving as a reference that lack the PCM. By their analysis, to the obtained results, the researchers showed that peak load shifting was limited at the morning and profitable at evening over the 10 days study period with a cost saving of 42 % corresponding to an energy saving of 32%. Thermal performance of a ventilated solar façade with macro-encapsulated PCM placed at its air cavity was experimentally investigated by A. Gracia et al. [21] in Spain. Two identical house cubicles one with a ventilated façade incorporating SP22 PCM plates permitting its functioning as a solar collector that discharges its stored latent energy once solar energy is demanded in the conditioned environment. Results employed that a daily increase in the temperature ranging from 9 °C to 18 °C under severe winter conditions is achieved with the ventilated facade incorporating PCM during free-floating mode.

3.1.2 Heating active applications

Starting from the most popular, active heating applications using PCM are: underfloor radiant heating with PCM, solar air heaters, solar heat pumps, heat exchangers, HVAC systems, solar domestic hot water systems, and ventilated façades.

Thermal performances of hot water floor panel with different heating pipes: polyethylene coils (PE pipes) and capillary mat (CAP mat), incorporated with different TES materials (sand and PCM) were experimentally studied by G. Zhou et al. [22]. It was proven that the discharging time of the PCM storage (latent) was twice that of sand (sensible) which ensures that PCM is highly efficient as a thermal mass for floor heating system that releases heat to retain the indoor temperature. On the other hand, half the time is required by sand to reach the indoor desired temperature compared to PCM due to its high latent heat. This gives evidence that the PCM is best used for load shifting. Limited studies on underfloor heating systems incorporating PCM influenced R. Barzin et al. [23] to perform a peak load shifting application for underfloor heating by integrating PCM into the floor with the incorporation of PCM wallboards. The study presented a total energy saving of 18.8% corresponding to an energy saving of 28.7%, with the maximum achieved cost and energy savings being 35% and 44.4%, respectively. Finally, the authors consisted on the importance of the proper selection of PCM melting temperature that best meets thermal comfort requirements.

A.E. Kabeel et al. [24] carried out an experimental investigation of flat and v-corrugated plate solar air heaters with built-in PCM as thermal energy storage material. The integrated solar air heater with PCM was designed and tested under prevailing weather conditions of Tanta city, Egypt. The effect of solar radiation, temperature difference of air across the heater, convective heat transfer coefficient between absorber plate and flowing air, instantaneous thermal

efficiency, daily average efficiency and PCM freezing time on thermal performance were investigated. Results confirmed that upon using PCM, the outlet temperature of the v-corrugated plate solar air heater was higher than ambient temperature by 1.5–7.2 °C during 3.5 h after sunset compared with 1–5.5 °C during 2.5 h after sunset for flat plate solar air heater when the mass flow rate was 0.062 kg/s. where at this flow rate, the daily efficiency of the v-corrugated solar heater using PCM was higher by 12% than the corresponding ones without using the PCM, 15% than the corresponding values when the flat plate was used with PCM and 21.3% than the corresponding values when the flat plate was used without PCM.

W. Youssef et al. [25] performed a novel experimental study to control an indirect solar assisted heat pump (IDX-SAHP) system integrated with a latent heat storage (PCM) tank. The special design of the PCM heat exchanger tank allowed an automatic control that permitted storing excess energy during day and releasing it upon request. Results showed that the PCM tank has a significant effect on the system operation stability and a respective improvement in the COP of 6.1% and 14% on sunny and cloudy days has been achieved compared to the system lacking the PCM.

In the same study of A. Gracia et al. [21], they tested the thermal improvement of the ventilated solar façade achieved by activating installed fans to meet the desired set study targets: controlled temperature and demand profile experiments. Experimental outcomes of measured electrical energy consumption of the heat pumps and fans proved that the use of mechanical ventilation in this system is unnecessary unless a fast heating supply is needed.

Aiming to perform off-peak auxiliary power shaving and to work under power outage, J. Deng et al. [26] performed an assessment and improvement of a solar domestic hot water system with PCM in its mantle. It was realized that 70.7% of the PCM heat storage was donated to the water in the tank. Also, according to the assessment of 16 test cycles lasting for more than 3 months, no performance degradation occurred for the PCM composite implying that it is stable, indicating that the PCM heat storage worked well as a thermal battery and would be a potential for promotion in domestic heat storage of dwellings in the low-temperature solar thermal market. In order to increase the amount of the stored energy in a limited portion of time during maximum solar radiation, M. Gorzin et al. [27] studied the possibility of reducing the melting time of the PCM used in a heat exchanger placed in a flat solar heater plate utilizing water as the heat transfer fluid. In order to find the best PCM distribution between inner and outer annulus of the proposed multi-tube heat exchanger, the authors studied the charging process of RT-50 as the PCM on a shell and multi-PCM-tube by heated water from flat plate solar collector. The results show that by distributing the PCM mass in which 40% of PCM mass is in inner tube and 60% in the circumferential annulus, a reduction in melting time reached 52%, emphasizing that solar energy can be used more efficiently in the time of maximum solar radiation.

A summary of the used PCMs in active and passive heating applications is presented in Table 1.

Table 1 Properties of PCMs used in buildings for heating

Used PCM	Incorporation method	Application	Melting point, °C	Latent heat, kJ/kg	Ref
Sodium acetate trihydrate (SAT)	Macro-encapsulation	SDHW system	58	264	[26]
Paraffin wax	Macro-encapsulation	Solar air heater	54	190	[24]
Paraffin RT50	Macro-encapsulation	SDHW system	51	168	[27]
SP22	Macro-encapsulation	Ventilated facade	22	170	[21]
DuPont sheets Energain® (Paraffin)	Macro-encapsulation	Walls and ceiling	20-35	72.4	[20]
Paraffin	impregnation	Underfloor heating	28	120	[2], [23]
DuPont sheets Energain® (Paraffin)	Macro-encapsulation	PCM wallboard	21.7	70	[23]
In-organic	Macro-encapsulation	Underfloor heating	29	220	[22]
Coconut oil	Macro-encapsulation	Underfloor heating	28	254	[28]
SAT-urea/EG CPCM	Shape-stabilization	Radiant heating	47.84	232.1	[29]

3.2 Hybrid applications of PCM-TES for buildings

Thermal energy storage in buildings is necessary to present a balance between the energy demand and availability annually during both heating and cooling seasons [7]. For that, a good TES system is that working in several seasons and weather conditions. Hybrid applications for buildings are that which involves overheating reduction during summer, and heat storage during winter.

Nisrine Hanchi et al. [30] conducted a numerical study on the thermal behavior of a dynamic regime for a multilayer roof with two PCM layers of different melting points. The study focuses on comparing two conditioned zones for the cases of a reference conventional roof and another roof with integrated PCM above and below its concrete layer. Anna Laura Pisello et al. [31] worked on an innovative multifunctional concrete incorporating 5% paraffin-based micro-capsulated PCM compared to a normal concrete of the same thickness. Results showed that thermal conductivity and thermal diffusivity decrease with time during change of phase, while volumetric specific heat increase, and the thermal buffer potentiality of the PCM is observed by which a difference in the thermal behavior between normal concrete and 5% paraffin-based micro-capsulated PCM doped concrete is obtained. Using type 204 in TRNSYS 17 software, Lotfi Derradji et al. [32] completed a thermal dynamic simulation for two top floor offices in Algeria: one with conventional walls and the other with walls incorporating PCM. Results showed that PCM contributed to

an increase in the indoor temperature in winter by 4°C, and a decrease by 7°C in summer, compared to the conventional office. This lead to an overall of 25% energy savings for heating and cooling in Algeria climate.

R. Vanaga et al. [33] performed a small-scale experiment on a developed solar façade module comprising a combination of Paraffin RT21HC PCM, granulated aerogel for heat losses reduction, Fresnel lens and copper plate with 25 cylindrical pins as heat transfer enhancers, and a reference box with neither lens, enhancer nor PCM. Results showed that the indoor temperature difference ranges between 0.5°C to 9°C between opaque wall and solar façade module. Both simulations and experimental results indicate that the use of Fresnel lens for solar radiation concentration combined with insulation materials and PCM, can increase the indoor temperature and reduce building energy consumption for heating in cold climates compared to opaque wall, however it caused overheating in hot weather conditions (summer).

D. Li et al. [34] investigated the thermal behavior of glazed windows filled with nano-PCM in different seasons. The numerical model was validated with the experimental results obtained. The authors proved that a temperature difference between interior surface of glazed windows and indoor environment are in the range of 1-4 in summer, 5-10 in autumn, 14-16 in winter. Nevertheless, energy consumption can be reduced by 4% only corresponding to the suitable selection of the nano particles sizes.

HVAC systems are dedicated to provide thermal comfort to occupants all seasons. Thus, the integration of TES systems is best adapted if they contribute to energy efficiency increase during cooling and heating seasons. A. Maccarini et al. [4] performed a numerical analysis for evaluating the performance of a PCM-based heat exchanger coupled with a novel HVAC. Results inferred that for a typical office building, the integrated free cooling devices, of which is the PCM-TES, are capable of reducing the primary energy use of the novel HVAC system, with energy savings by the PCM-TES system of about 67% when compared to the base-line thermal plant configuration. W. Wu et al. [35] applied an experimental study on the performance of a novel solar water heater incorporating PCM. A radiant heat exchanger was numerically and experimentally analyzed by H. Garg et al. [36]. G. Guldentops and S.V. Dessel [37] performed an experimental test on a cellular passive solar façade. A developed ventilated double skin façade was numerically studied by A. Gracia et al. [38] for different weather conditions. R. Ansuini et al. [39] performed an experimental study on a radiant floor integrated with PCM for indoor temperature control. N. Sarter and E. Onder [40] prepared a massive overview on the evolving technology of Organic nano-PCM and its applications in clothings and textiles, particularly their integration in fibers, fabrics and foams using direct impregnation and microencapsulation techniques. Finally, a schematic diagram showing the classification of the applications for heating, cooling and hybrid systems utilizing PCMs in buildings are illustrated in Fig. 2

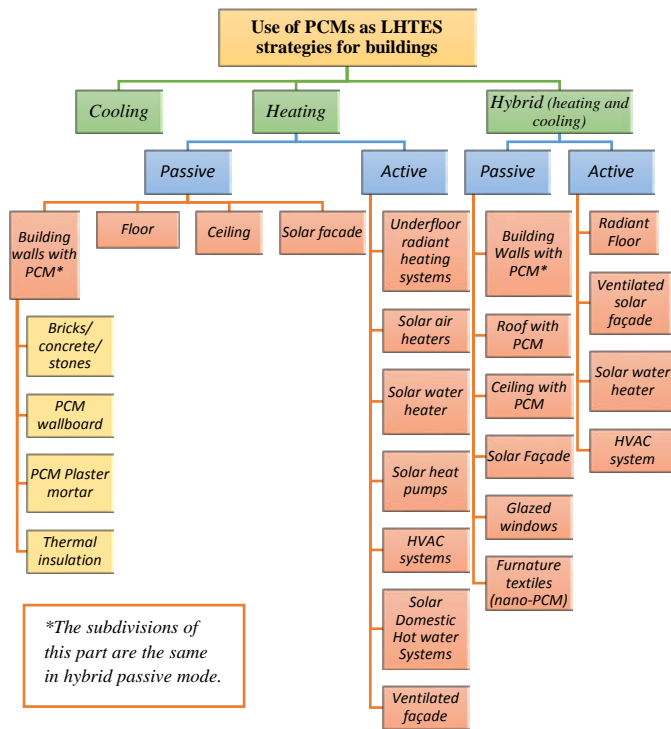


Fig. 2. Schematic diagram for heating and hybrid applications of PCM-TES in buildings as discussed in the current review article.

6. Conclusions

A review on recent research literature in regarding to the usage of phase change materials as latent heat thermal energy storage strategies applied to residential and commercial buildings is presented in this article. Two application aspects were presented: Heating applications and Hybrid applications in buildings. Presented literature were classified into two categories in each studied aspect: Passive and active systems. Thermal performance analysis with a summary of the used PCMs in each classified application with their respective thermophysical properties and encapsulation techniques are tabled. It was concluded that:

- PCM do serve as thermal buffers that prevails load shifting and consequently reduces indoor temperature swings resulting in residential thermal comfort.
- A plenty of PCMs such as bio-based, inorganic, and eutectic mixtures need commercialization.
- More experiments and less assumptions in numerical approaches are required for the purpose of optimizing PCM properties, size, mass, location, ...etc.
- Special focus must be given to real and regional weather conditions in experiments.

References

- [1] L. Olivieri, J. A. Tenorio, D. Revuelta, L. Navarro, and L. F. Cabeza, "Developing a PCM-enhanced mortar for thermally active precast walls," *Constr. Build. Mater.*, vol. 181, pp. 638–649, 2018.
- [2] P. Devaux and M. M. Farid, "Benefits of PCM underfloor heating with PCM wallboards for space

heating in winter," *Appl. Energy*, vol. 191, pp. 593–602, 2017.

- [3] B. A. Young, G. Falzone, Z. Wei, G. Sant, and L. Pilon, "Reduced-scale experiments to evaluate performance of composite building envelopes containing phase change materials," *Constr. Build. Mater.*, vol. 162, pp. 584–595, 2018.
- [4] A. Maccarini, G. Hultmark, N. C. Bergsøe, and A. Afshari, "Free cooling potential of a PCM-based heat exchanger coupled with a novel HVAC system for simultaneous heating and cooling of buildings," *Sustain. Cities Soc.*, vol. 42, no. June 2017, pp. 384–395, 2018.
- [5] V. V. Tyagi and D. Buddhi, "PCM thermal storage in buildings: A state of art," *Renew. Sustain. Energy Rev.*, vol. 11, no. 6, pp. 1146–1166, 2007.
- [6] K. Du, J. Calautit, Z. Wang, Y. Wu, and H. Liu, "A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges," *Appl. Energy*, vol. 220, no. March, pp. 242–273, 2018.
- [7] A. Kasaeian, L. bahrami, F. Pourfayaz, E. Khodabandeh, and W. M. Yan, "Experimental studies on the applications of PCMs and nano-PCMs in buildings: A critical review," *Energy Build.*, vol. 154, pp. 96–112, 2017.
- [8] J. H. Patel, M. N. Qureshi, and P. H. Darji, "Experimental analysis of thermal energy storage by phase change material system for cooling and heating applications," *Mater. Today Proc.*, vol. 5, no. 1, pp. 1490–1500, 2018.
- [9] J. Heier, C. Bales, and V. Martin, "Combining thermal energy storage with buildings - A review," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 1305–1325, 2015.
- [10] D. Zhou, C. Y. Zhao, and Y. Tian, "Review on thermal energy storage with phase change materials (PCMs) in building applications," *Appl. Energy*, vol. 92, pp. 593–605, 2012.
- [11] L. Boussaba, A. Foufa, S. Makhlof, G. Lefebvre, and L. Royon, "Elaboration and properties of a composite bio-based PCM for an application in building envelopes," *Constr. Build. Mater.*, vol. 185, pp. 156–165, 2018.
- [12] Y. Cui, J. Xie, J. Liu, and S. Pan, "Review of Phase Change Materials Integrated in Building Walls for Energy Saving," *Procedia Eng.*, vol. 121, pp. 763–770, 2015.
- [13] R. Zeinelabdein, S. Omer, and G. Gan, "Critical review of latent heat storage systems for free cooling in buildings," *Renew. Sustain. Energy Rev.*, vol. 82, no. November 2017, pp. 2843–2868, 2018.
- [14] A. Sharma, V. V. Tyagi, C. R. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renew. Sustain. Energy Rev.*, vol. 13, no. 2, pp. 318–345, 2009.
- [15] F. Souayfane, F. Fardoun, and P. H. Biwole, "Phase change materials (PCM) for cooling applications in

- buildings: A review,” *Energy Build.*, vol. 129, pp. 396–431, 2016.
- [16] T. A. Vik, H. B. Madessa, P. Aslaksrud, E. Folkedal, and O. S. Øvrevik, “Thermal Performance of an Office Cubicle Integrated with a Bio-based PCM: Experimental Analyses,” *Energy Procedia*, vol. 111, no. 1876, pp. 609–618, 2017.
- [17] S. M. Wang, P. Matiašovský, P. Mihálka, and C. M. Lai, “Experimental investigation of the daily thermal performance of a mPCM honeycomb wallboard,” *Energy Build.*, vol. 159, pp. 419–425, 2018.
- [18] Q. Wang, R. Wu, Y. Wu, and C. Y. Zhao, “Parametric analysis of using PCM walls for heating loads reduction,” *Energy Build.*, vol. 172, pp. 328–336, 2018.
- [19] B. P. Jelle and S. E. Kalnæs, *Phase Change Materials for Application in Energy-Efficient Buildings*. Elsevier Ltd, 2017.
- [20] A. Mourid, M. El Alami, and 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.*, vol. 41, no. January, pp. 35–43, 2018.
- [21] A. de Gracia, L. Navarro, A. Castell, Á. Ruiz-Pardo, S. Álvarez, and L. F. Cabeza, “Experimental study of a ventilated facade with PCM during winter period,” *Energy Build.*, vol. 58, pp. 324–332, 2013.
- [22] G. Zhou and J. He, “Thermal performance of a radiant floor heating system with different heat storage materials and heating pipes,” *Appl. Energy*, vol. 138, pp. 648–660, 2015.
- [23] R. Barzin, J. J. J. Chen, B. R. Young, and M. M. Farid, “Application of PCM underfloor heating in combination with PCM wallboards for space heating using price based control system,” *Appl. Energy*, vol. 148, pp. 39–48, 2015.
- [24] A. E. Kabeel, A. Khalil, S. M. Shalaby, and M. E. Zayed, “Experimental investigation of thermal performance of flat and v-corrugated plate solar air heaters with and without PCM as thermal energy storage,” *Energy Convers. Manag.*, vol. 113, pp. 264–272, 2016.
- [25] W. Youssef, Y. Ge, and S. A. Tassou, “Indirect expansion solar assisted heat pump system for hot water production with latent heat storage and applicable control strategy,” *Energy Procedia*, vol. 123, pp. 180–187, 2017.
- [26] J. Deng, S. Furbo, W. Kong, and J. Fan, “Thermal performance assessment and improvement of a solar domestic hot water tank with PCM in the mantle,” *Energy Build.*, vol. 172, pp. 10–21, 2018.
- [27] M. Gorzin, M. J. Hosseini, A. A. Ranjbar, and R. Bahrampoury, “Investigation of PCM charging for the energy saving of domestic hot water system,” *Appl. Therm. Eng.*, vol. 137, pp. 659–668, 2018.
- [28] K. Faraj *et al.*, “Experimental Study of Underfloor Electrical Heating System with Integrated Experimental Study of Underfloor Electrical Heating System with Integrated CO-PCM Plates,” *6th Eur. Conf. Renew. Energy Syst. Proceedings, Istanbul, Turkey*, 2018.
- [29] W. Fu *et al.*, “Thermal properties and thermal conductivity enhancement of composite phase change material using sodium acetate trihydrate–urea/expanded graphite for radiant floor heating system,” *Appl. Therm. Eng.*, vol. 138, no. April, pp. 618–626, 2018.
- [30] N. Hanchi, H. Hamza, J. Lahjomri, and A. Oubarra, “Thermal behavior in dynamic regime of a multilayer roof provided with two phase change materials in the case of a local conditioned,” *Energy Procedia*, vol. 139, pp. 92–97, 2017.
- [31] A. Laura Pisello, C. Fabiani, and F. Cotana, “New experimental technique to investigate the thermal behavior of PCM/doped concrete for enhancing thermal/energy storage capability of building envelope,” *Energy Procedia*, vol. 126, pp. 139–146, 2017.
- [32] L. Derradji, F. B. Errebai, and M. Amara, “Effect of PCM in Improving the Thermal Comfort in Buildings,” *Energy Procedia*, vol. 107, no. September 2016, pp. 157–161, 2017.
- [33] R. Vanaga, A. Blumberga, R. Freimanis, T. Mols, and D. Blumberga, “Solar facade module for nearly zero energy building,” *Energy*, vol. 157, pp. 1025–1034, 2018.
- [34] D. Li, Y. Wu, C. Liu, G. Zhang, and M. Arıcı, “Energy investigation of glazed windows containing Nano-PCM in different seasons,” *Energy Convers. Manag.*, vol. 172, no. July, pp. 119–128, 2018.
- [35] W. Wu *et al.*, “Experimental study on the performance of a novel solar water heating system with and without PCM,” *Sol. Energy*, vol. 171, no. July, pp. 604–612, 2018.
- [36] H. Garg, B. Pandey, S. K. Saha, S. Singh, and R. Banerjee, “Design and analysis of PCM based radiant heat exchanger for thermal management of buildings,” *Energy Build.*, vol. 169, pp. 84–96, 2018.
- [37] G. Guldentops and S. Van Dessel, “A numerical and experimental study of a cellular passive solar faïçade system for building thermal control,” *Sol. Energy*, vol. 149, pp. 102–113, 2017.
- [38] A. de Gracia, L. Navarro, A. Castell, and L. F. Cabeza, “Energy performance of a ventilated double skin facade with PCM under different climates,” *Energy Build.*, vol. 91, pp. 37–42, 2015.
- [39] R. Ansuini, R. Largetti, A. Giretti, and M. Lemma, “Radiant floors integrated with PCM for indoor temperature control,” *Energy Build.*, vol. 43, no. 11, pp. 3019–3026, 2011.
- [40] N. Sarier and E. Onder, “Organic phase change materials and their textile applications: An overview,” *Thermochim. Acta*, vol. 540, pp. 7–60, 2012.