Heat Island Mitigation Strategy for Urban Areas Using Phase Change Materials (PCM)

Ganesan Subramanian and Neale R. Neelameggham

Abstract Heat islands are urbanized areas that experience significantly higher day and night time temperatures than the surrounding rural areas on account of the influence of the buildings, roadways, and industries on the local weather. Heat island mitigation strategy depends on the weather patterns at the urban geographical location. Mitigation of heat island effect has been demonstrated by increased use of shade and materials that alter the reflectance and emissivity of the surfaces impacted by solar radiation. Interest in the use of PCM for urban infrastructure for further enhancing the mitigation through heat storage and liberation is more recent. Key physical properties needed for PCM use are the latent heat of fusion, thermal conductivity, density, and specific heat. This paper reviews the physics involved in choosing the right PCM for buildings, placement of PCM in the infrastructure, and modeling methods for optimal energy costs.

Keywords Heat island mitigation · PCM

Introduction

The heat island effect [1, 2] is a well-studied phenomenon in urban areas where the concentration of buildings, roadways, and industries generates local weather conditions that are more extreme than the surrounding rural areas, leading to thermal discomfort or extreme events like flooding. Mitigation of heat island effect has been demonstrated by increased use of shade and materials that alter the reflectance and emissivity of the surfaces impacted by solar radiation. Local weather patterns are further influenced in recent times on account of global climate change. PCM incorporation into urban infrastructure is an efficient, reliable, and inexpensive way to further mitigate the heat island effect and ensure thermal comfort, at the same time

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reducing emissions from the use of fossil fuels and reducing heating and cooling loads.

Building construction and operations accounted for the largest share of both global final energy use (36%) and energy-related CO_2 emissions (39%) in 2018 [3] (Fig. 1). Construction industry is the portion (estimated) of overall industry devoted to manufacturing building construction materials such as steel, cement, and glass. Indirect emissions are emissions from power generation for electricity and commercial heat. The buildings and construction sector should therefore be a primary target for GHG emission mitigation efforts, as it accounted for 36% of final energy use and 39% of energy- and process-related emissions in 2018. Growth of urban areas will increase this share in the future (Fig. 2).

Thermal energy storage (TES) is the equivalent of a battery that stores electrical energy and can be used to store heat or cold during overproduction of heat or electricity for use at a later time, thus improving system efficiency by reducing peak cooling and heating demands. Thermal energy storage using PCMs takes advantage of their high energy density available as latent heat at constant temperature with practical applications using the solid-to-liquid transition. The high latent heat of fusion allows PCMs to store 5–14 times more heat per unit volume than common sensible heat storage materials like rock or water [4, 5]. Common applications of different type of PCMs are shown in Fig. 3.

Any candidate material to be used as PCM shall have first of all large latent heat and ideally high thermal conductivity. There is however no perfect PCM, and the

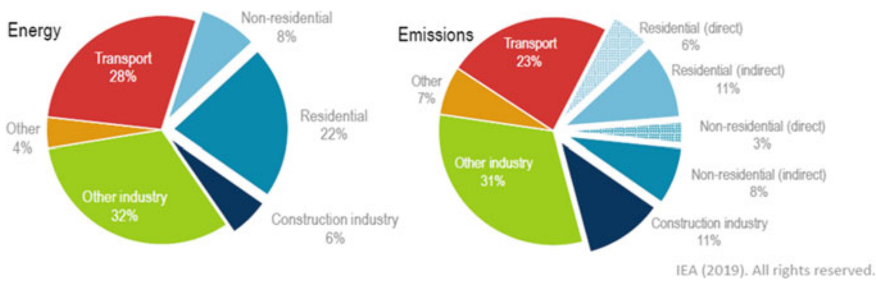


Fig. 1 Building industry global share of energy and emissions in 2018 [3]

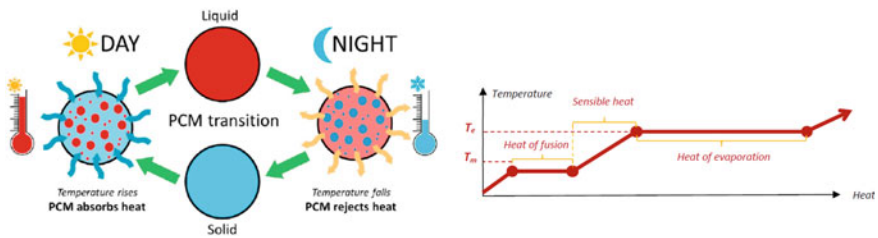


Fig. 2 How PCMs work as thermal storage materials [6, 4]

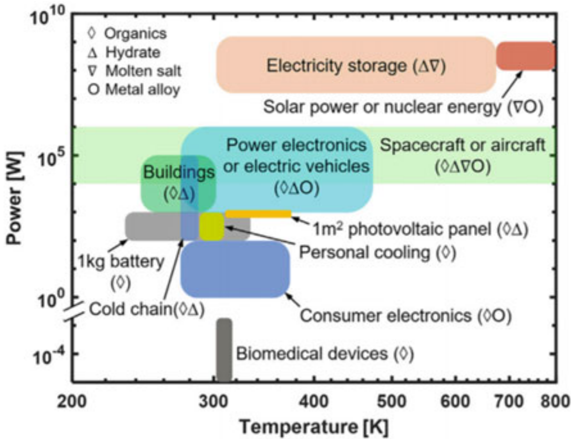


Fig. 3 Emerging applications of PCM thermal storage with PCM types and temperature ranges [20]

choice of material is always a compromise. The main characteristics required for a useful PCM are as follows:

Thermo-physical properties:

- Phase change temperature within the range appropriate to the application.
- Large latent heat per unit volume.
- Large sensible heat per unit volume.
- High thermal conductivity in both phases.
- Small volume changes due to the phase transition.
- Congruent phase change (no component segregation in the solid phase).
- Sharpness of latent heat release and absorption: should occur over a narrow temperature.
- Range, depending on the application [8].

Nucleation and crystal growth:

- High nucleation rate (to avoid supercooling of the liquid during solidification and consecutive temperature hysteresis between solidification and melting).
- High crystal growth rate (enabling fast charging/discharging of the PCM reservoir).

Chemical properties:

- Entirely reversible solidification/melting process.
- No chemical degradation with time and number of charging/discharging cycles.
- No corrosive properties to the construction/encapsulation materials.
- Non-toxic, non-flammable, and non-explosive.

Economics and usability:

- Easily available at low cost.
- Easily recyclable.
- Good environmental parameters based on Life Cycle Assessment.

Characteristics of the different types of PCM are summarized in the table below:

PCM Type	Advantages	Disadvantages
Organics (Paraffin wax, fatty acids and vegetable oils)	• Availability in a wide temperature range • High heat of fusion • No subcooling • No segregation • Stable after many cycles • Chemically and physically stable • Compatibility with a wide range of containers • Corrosiveness materials • Environmentally safe, nonreactive • Recyclable	• Low thermal conductivity • Large volume change during phase transition except for some fatty acids. • Unstable at high temperatures • No sharp phase transition • Noncompatible with the plastic containers • Costly in pure form • Low enthalpy • Flammable • Different toxicity levels
Inorganic (Salt hydrates)	• High thermal storage capacity • Good thermal conductivity • Low cost • Available easily • Sharp melting points • Low vapour pressure • Nonflammable	• Show subcooling • Considerable change in volume • Show phase segregation • Incompatible with metallic containers
Eutectic	• Sharp melting and boiling points • Higher volumetric storage density than the organic PCM	• Costly • Limited data available for thermo-physical properties

For "Green" buildings, inorganic PCMs are preferred if they can be incorporated into the building infrastructure easily. In practice, however, modifications to overcome the disadvantages are done through mixing the different types in the form of composites, encapsulation (macro and micro), or foams, when it becomes a challenge to estimate the basic physical properties of latent heat, density, specific heat, and thermal conductivity. In such cases, there are many experimental techniques available for direct determination of these properties. Temperature range of different PCM types is shown in Fig. 4 from [6].

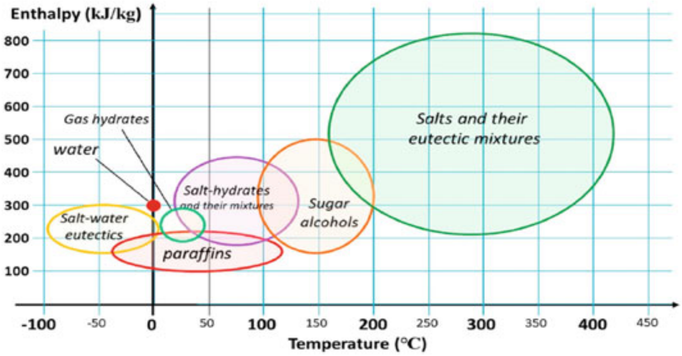
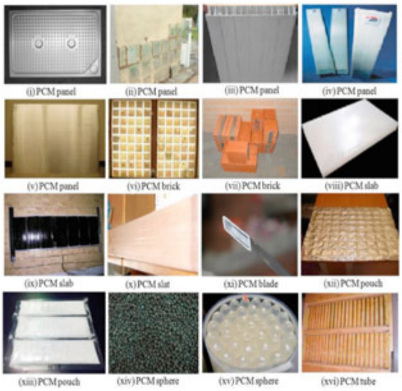


Fig. 4 Working range of enthalpy and temperature of various PCMs [6]

PCM Incorporation into Buildings

Practically, PCMs are incorporated into building envelope elements by one of the following methods: (a) direct incorporation, (b) immersion, (c) encapsulation (micro- or macroencapsulation), (d) shape-stabilized PCMs, and (e) form-stable PCM composites. In the *direct incorporation* method, the PCM in powder or liquid state is added directly to the construction material, such as gypsum mortar, cement mortar, and concrete mixture. This method is the easiest and most economical because it does not require any experience and is easy to incorporate. On the contrary, the major drawback of this method is the leakage of PCM during the melting phase. This leakage causes incompatibility of mixed materials and increases the risk of fire (for flammable PCMs). In addition, this method weakens the mechanical properties of constructed elements during high temperatures given that the PCM is added to the mixture in a liquid state, thereby decreasing the water content ratio. In the *immersion method*, a porous construction material immerses into the liquid PCM; it is absorbed due to capillarity. The main drawbacks of this method are leakage, construction incompatibility, and the corrosion of reinforced steel when incorporated with concrete elements, thereby affecting its service life. *Encapsulation* is a suitable method to avoid the leakage issues of PCM and to enhance its compatibility with the building structure. Encapsulation is performed by covering the PCM by a shell for protection from the outside environment as well as for leakage prevention. This method is also essential to increase the heat transfer area and, hence, the thermal conductivity of PCM to ensure effective utilization of its storage capacity. The PCM can be macroencapsulated using shells, tubes, channels, and thin plates or microencapsulated when the microsized PCM is covered by unique polymeric material [7, 8, 13]. In both methods, the encapsulation material should have unique characteristics, such as preventing leakage, retaining all thermal characteristics of PCM, not reacting with PCM, compatible with PCM and its application, providing structural stability and securing handling [9]. Furthermore, it should control any volumetric change of PCM during phase changes and provide appropriate protection for the PCM against environmental degradation and good thermal conductivity and mechanical strength over PCM life cycles [10]. Pipes, panels, and foils made from aluminum, copper, and stainless steel are commonly used for macroencapsulation because they offer excellent thermal conductivity, compatibility, and support to the mechanical strength of building materials [11]. More macroencapsulation forms are shown in Fig. 5. The *shape-stabilized* method contains the PCM inside a carrier matrix. This method is promising because it provides better thermal conductivity, large specific heat, and maintain the shape over many cycles of phase transition. More information regarding its configurations and preparation techniques have been described by Refs. [12]. The *form-stabilized* PCM is also an advanced method of incorporation. It is a specific definition of composite material, retaining the maximum amount of one or more types of PCM and showing no leakage at melting temperatures. Although the two latter methods are expensive to implement, they are the most reliable amongst others. Reliability indicates that the PCM cycles (melting/solidification) are repeated in high performance without degradation, and this feature is crucial for applications that require high performance for long term, such as buildings.

Recently, Peiran Wei et al. [14] examined the direct insertion of PCM into a building material using 3D printing for scalability. Paraffin wax as PCM was mixed with liquid resin as the supporting structure, creating a soft, paste-like material that can be shaped as needed. Once it's in the desired shape, it can be cured with UV light to harden the resin. The end result is a solid material strong enough to build with, containing pockets of PCM inside. Without the need for extra shells, the PCM can be packed in more densely, comprising up to 63 weight percent of the material, which boosts its ability to regulate the ambient temperature. But perhaps most importantly, the material is now easier to make in bulk. Its squishiness means it can be made into a 3D-printable ink, which could then be made into whatever shape or size is desired, for much lower cost than other PCM building materials (Fig. 6).



Commercially available PCMs

PCM type	PCM symbol	PCM from manufacturer's data sheet (°C)	Manufacturer
Bulk	RT21 HC	21	Rubitherm
	RT22 HC	22	Rubitherm
	RT25 HC	25	Rubitherm
	RT27	27	Rubitherm
	PureTemp 23	23	Entropy Solutions
Microencapsulated	Micronal DS5040X	23	BASF
	Micronal DS5008X	25	BASF
	MPCM24D	24	BASF
	Micronal DS5038X	25	Microteklabs
Microencapsulated	MacroPCM28	28	Microteklabs
	MacroPCM24	24	Microteklabs

Fig. 5 Different macroencapsulation forms used with building structure [6]

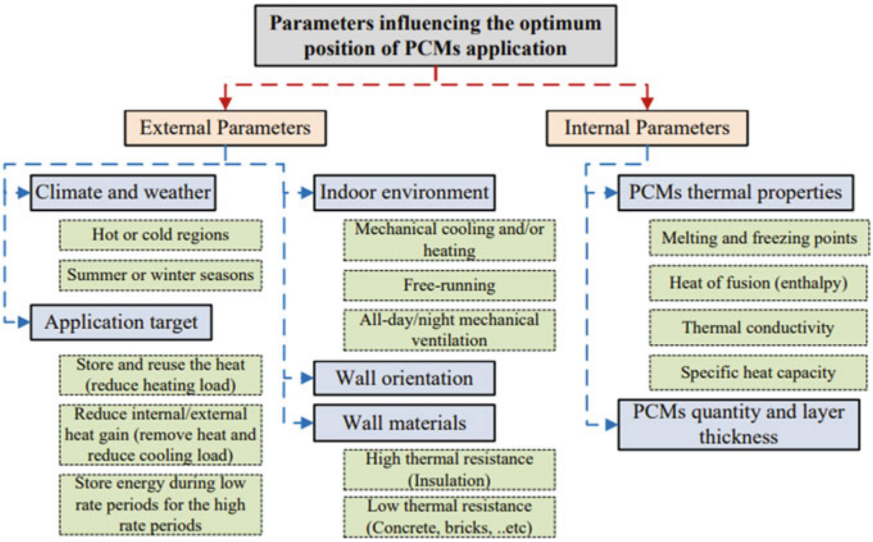


Fig. 6 Main parameters that influence the optimum position of the PCM application in building [6]

Air Conditioning Application with PCM as Air Heat Exchanger

So far we have reviewed PCMs in a passive mode as part of the building infrastructure. Chaiyat and Kiartsiriroot [19] experimentally demonstrated that the active mode use of PCM (Paraffin wax Rubitherm20, RT-20) as an air heat exchanger in conjunction with the air conditioning system can result in reducing cooling loads as much as 10%. The air conditioner controls the room temperature at around 15–20 °C. The return air with temperature of around 22–25 °C, slightly higher than the PCM melting point of 20 °C, is fed to the PCM bed (Fig. 7c) and would enter the evaporator at 20 °C, lower than the ambient, thus reducing the cooling load. In the charging mode (Fig. 7b), the supply air from the evaporator is bypassed through the PCM bed, allowing it to freeze.

Experimental Measurement of PCM Physical Properties

Experimental measurement of specific heat, thermal conductivity, and density can be done by various techniques and for complex PCMs, for example, microencapsulated or composites, this is the only reliable method [7]. Common methods are conventional calorimetry, differential thermal analysis (DTA), and differential scanning calorimetry (DSC). Although DTA and DSC methods are well developed, the

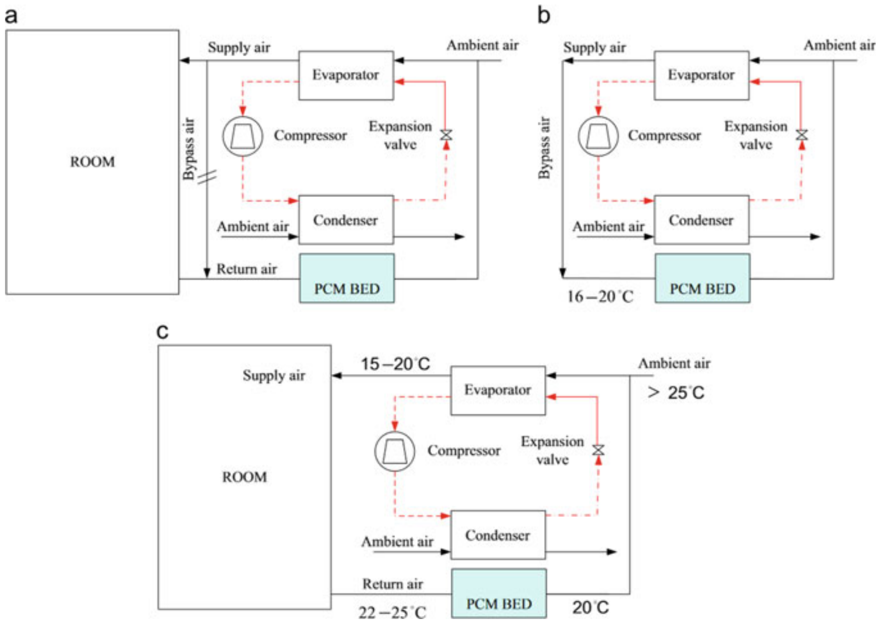


Fig. 7 Air conditioning scheme with PCM air heat exchanger [19]

samples tested by them are very small (1–10 mg) and the thermophysical properties of samples are usually different from those of the bulk materials used in practical systems. DTA and DSC measurement rigs are complicated and expensive; they cannot measure heats of fusion, specific heats, and thermal conductivities of several PCM samples simultaneously. Besides, the phase change process of a PCM sample during a measurement is hard to observe clearly when using conventional methods. Zhang et al. [15] have developed a "T-history" method, of determining the melting point, degree of supercooling, heat of fusion, specific heat, and thermal conductivity of several PCM samples simultaneously. It is especially useful for the selection from a list of candidate PCMs or for the preparation of new PCMs for use in practical systems.

Modelling of PCM-Enhanced Building Envelope

In recent years, different types of modelling and simulation tools have been applied to describe the thermal behavior of PCM and energy saving gained from its incorporation with building components. Experimentally, some researchers work on a laboratory-scale level whilst others work on whole-building level to validate the tools. The most widely used tools for modelling and simulating PCM behavior are compared by Vadiee et al. [16]. ANSYS FLUENT, COMSOL multiphysics, EnergyPlus, TRYNSYS, MATLAB, ABAQUS™ solver, and DIANA–finite element analysis. Although many researchers reported good agreement of computational tools with the experimental results, IEA states that the confidence level of these tools is still low and cannot be adapted for designing and coding. To model PCM-incorporated buildings, most researchers deal with the building element as a 1D convective heat transfer, unsteady-state without internal heat source to describe the heat behavior of PCM [16]. Zhang et al. [17] developed a new approach to model the building envelope that picks the optimum PCM that satisfies the material and energy balances in the building environment within the thermal comfort constraints (Fig. 8). Some of their results comparing the savings with PCM are shown in Fig. 9.

Multiphysics modeling of PCMs at different length scales is governed by different scale-dependent mechanisms. Based on these mechanisms and empirical parameters, computational methods are developed to predict, design, and optimize materials, devices, and systems. Experimental methods provide approaches that enable material synthesis and characterization, property measurements, and manufacturing and

Traditional Approach:

Use Knowns: Climate Information, Building Geometry, Building Envelope Materials with known thermophysical Properties (k, Cp, etc. -constant), ACH Air Exchange rate & Q_D- Indoor termal disturbance.

To Find: Indoor air temperature, Q, etc.

New Approach:

Use Knowns: Cimate information, Q building geometry, thermal comfort demand..

To Find: Building Envelope Materials with ideal thermophysical properties (k, Cp, etc) which can be function of temperature; Optimized ACH & Minimal Q

Fig. 8 Modeling method for choosing the best PCM by optimizing the right variables (Derived from [17])

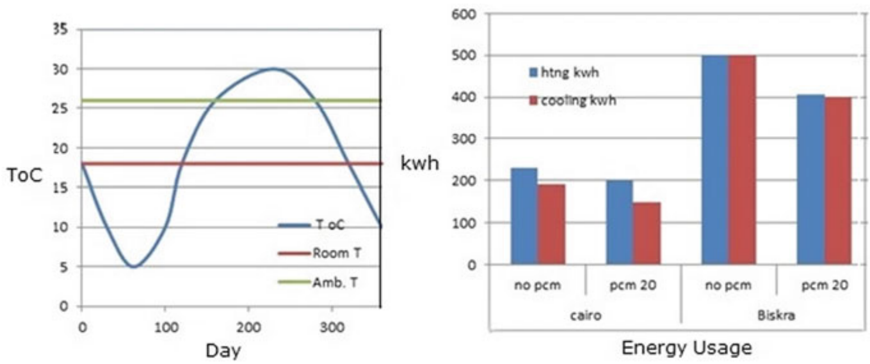


Fig. 9 Results for thermal comfort range and energy savings using new approach for optimal PCM (derived from [17])

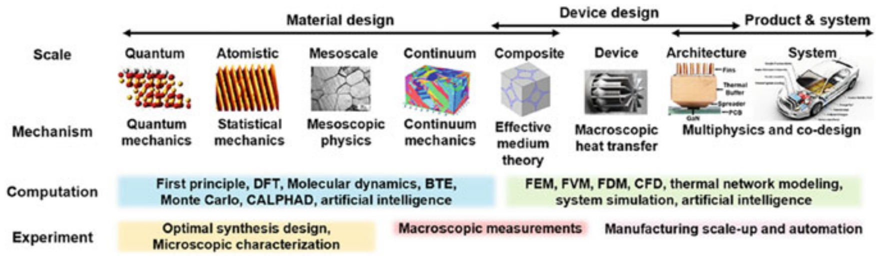


Fig. 10 Length scales and associated modeling, design, and test methods for PCMs, devices, and systems [20]

prototype testing. BTE, Boltzmann transport equation; CFD, computational fluid dynamics; and FDM, finite difference method.

Summary

This paper has surveyed the role of phase change material incorporation into buildings as an inexpensive means of mitigating the heat island effect that has been exacerbated in recent times on account of climate change. Recent advances in micro- and macroencapsulation technology have made the incorporation of PCMs into building infrastructure practical and economical. The research and development opportunity for material and building scientists and engineers from the material design stage through device design to the product and system is captured in Fig. 10 from [20].

Declaration The authors declare no commercial use of the figures referenced and used in this review paper for personal gain.

References

1. Kalnay E, Cai M (2003) Impact of urbanization and land-use change on climate. Nature 423(6939):528–531
2. https://www.epa.gov/heatislands
3. Global share of buildings and construction final energy and emissions (2019) 2018 IEA. https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019
4. Sevault A, Kauko H, Bugge M, Banasiak K, Haugen NE, Skreiberg Ø (2017) SINTEF energy research report TR A7638
5. Memon SA (2014) Phase change materials integrated in building walls: a state of the art review. Renew Sust Energy Rev 31:870–906
6. Al-Yasiri Q, Szab´o M (2021) Incorporation of phase change materials into building envelope for thermal comfort and energy saving: a comprehensive analysis, vol 36, April 2021, Article 102122. https://doi.org/10.1016/j.jobe.2020.102122

7. Saxena R, Rakshit D, Kaushik SC (2020) Experimental assessment of Phase Change Material (PCM) embedded bricks for passive conditioning in buildings, Renew. Energy 149:587–599. https://doi.org/10.1016/j.renene.2019.12.081
8. Liu Z, Yu Z(Jerry), Yang T, Qin D, Li S, Zhang G, Haghighat F, Joybari MM (2018) A review on macro-encapsulated phase change material for building envelope applications. Build Environ 144:281–294. https://doi.org/10.1016/j.buildenv.2018.08.030
9. Lu S, Li Y, Kong X, Pang B, Chen Y, Zheng S, Sun L (2017) A review of PCM energy storage technology used in buildings for the global warming solution. In: Zhang X, Dincer I (eds) Energy solutions to combat global warming. Springer International Publishing, Cham, pp 611–644. https://doi.org/10.1007/978–3–319–26950–4_31
10. Pereira da Cunha J, Eames P (2016) Thermal energy storage for low and medium temperature applications using phase change materials—a review. Appl Energy 177:227–238
11. Mili´an YE, Guti´errez A, Gr´ageda M, Ushak S (2017) A review on encapsulation techniques for inorganic phase change materials and the influence on their thermophysical properties. Renew Sustain Energy Rev 73:983–999. https://doi.org/10.1016/j.rser.2017.01.159
12. Bland A, Khzouz M, Statheros T, Gkanas EI (2017) PCMs for residential building applications: a short review focused on disadvantages and proposals for future development. Buildings 7:78. https://doi.org/10.3390/buildings7030078
13. Singh Rathore PK, Shukla SK, Gupta NK (2020) Potential of microencapsulated PCM for energy savings in buildings: a critical review. Sustain Cities Soc 53:101884. https://doi.org/10.1016/j.scs.2019.101884
14. Wei P, Cipriani CE, Pentzer EB (2021) Thermal energy regulation with 3D printed polymer-phase change material composites. Matter 4:1975–1989. https://doi.org/10.1016/j.matt.2021.03.019
15. Yinping Z, Yi J, Yi J (1999)A simple method, the T –history method, of determining the heat of fusion, specific heat and thermal conductivity of phase-change materials. Meas Sci Technol 10:201–205
16. Vadiee A, Dodoo A, Gustavsson L (2019) A comparison between four dynamic energy modeling tools for simulation of space heating demand of buildings. In: Johansson D, Bagge H, Wahlström Å (eds) Cold climate HVAC 2018. CCC 2018. Springer Proceedings in Energy. Springer, Cham, pp. 701–711. https://doi.org/10.1007/978-3-030-00662-4_59
17. Zeng R, Wang X, Di H, Jiang F, Zhang Y (2011) New concepts and approach for developing energy efficient buildings: ideal specific heat for building internal thermal mass. Energy Build 43:1081–1090
18. Al-Absi ZA, Mohd Isa MH, Ismail M (2020) Phase change materials (PCMs) and their optimum position in building walls. Sustainability 12:1294. https://doi.org/10.3390/su12041294
19. Chaiyat N, Kiatsiriroat T (2014) Energy reduction of building air-conditioner with phase change material in Thailand. Case Stud Thermal Eng 4:175–186
20. Yang T, King WP, Miljkovic N (2021) Phase change material-based thermal energy storage. Cell Rep Phys Sci 2:8, article 100540. https://doi.org/10.1016/j.xcrp.2021.100540