Passive cooling of buildings with phase change materials using whole-building energy simulation tools: A review

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Abstract

Buildings contribute to climate change by consuming a considerable amount of energy to provide thermal comfort for occupants. Cooling energy demands are expected to increase substantially in the world. On this basis, technologies and techniques providing high energy efficiency in buildings such as passive cooling are highly appreciated. Passive cooling by means of phase change materials (PCM) offers high potential to decrease the cooling energy demand and to improve the indoor comfort condition. However, in order to be appropriately characterized and implemented into the building envelope, the PCM use should be numerically analyzed. Whole-building energy simulation tools can enhance the capability of the engineers and designers to analyze the thermal behavior of PCM-enhanced buildings. In this paper, an extensive review has been made, with regard to whole-building energy simulation for passive cooling, addressing the possibilities of applying different PCM-enhanced components into the building envelope and also the feasibility of PCM passive cooling system under different climate conditions. The application of PCM has not always been as energy beneficial as expected, and actually its effectiveness is highly dependent on the climatic condition, on the PCM melting temperature and on the occupants behavior. Therefore, energy simulation of passive PCM systems is found to be a single-objective or multi-objective optimization problem which requires appropriate mathematical models for energy and comfort assessment which should be further investigated. Moreover, further research is required to analyze the influence of natural night ventilation on the cooling performance of PCM.

Keywords: Passive cooling; PCM; EnergyPlus; TRNSYS; ESP-r; Natural night ventilation; Whole-building energy simulation.

1. Introduction

The building sector (both residential and non-residential buildings) is responsible of consuming roughly 32% of the global final energy use (Figure 1) [1] and emitting roughly 36% of all greenhouse gas emissions [2]. For instance, according to the EU reference scenario trend projection 2016, the share of energy consumption in houses and buildings accounts for about one-third of the final energy consumption in all sectors and it is expected to be increased slightly by 2050.This sector also contributes to the urban heat island (UHI) phenomenon in urban areas which causes higher surface and air temperature in city centers than in outskirts [3].

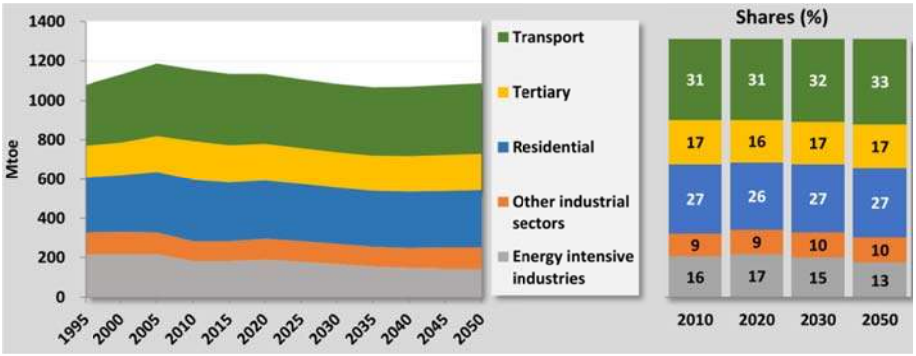

Figure 1.Final energy consumption by sector in EU countries [4].

A substantial upsurge for cooling energy demands is expected by 2050. The estimated increase is roughly 150% worldwide and about 300%-600% in developing countries [5]. Figure 2 shows an outlook of this sharply increasing cooling energy demand in some developing nations (Association of Southeast Asian Nations (ASEAN), Latin America, India, and China) [1].

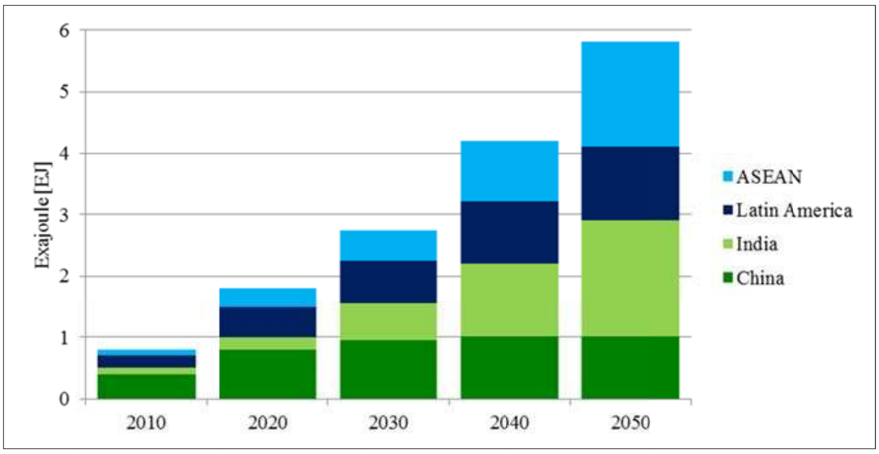

Figure 2. Perspective of cooling energy demand up to 2050 [1].

To overcome this global concern, policy makers are endeavoring to put energy-efficient solutions on the table since the energy efficiency is found to be the most economic and instantly accessible way to diminish carbon emissions [3]. For instance, the Roadmap 2050 long-term policy [6] is seeking pathways to achieve low-carbon economy with a minimum cost in Europe [7]. The improvement of the building envelope is an essential step to achieve this goal, as 20% to 60% of all energy consumed in buildings is affected by the design and construction of the building envelope [5].

Today, the energy beneficial of the thermal energy storage (TES) is well known. TES is a promising technology to achieve a low-carbon future [8]. It is accounted as an initiative to reduce the energy consumption in buildings [8], to alleviate the UHI effects in cities [3] and to increase the energy efficiency and comfort by creating a balance between diurnal and nocturnal energy demand [9] Energy could be stored physically or chemically. In physical processes energy is accumulated as sensible or/and latent heat, on the other hand thermochemical energy storage takes place when a chemical reaction with high heat of reaction happens [10]. For building applications, mostly sensible and latent heat storage are considered, although today thermochemical energy storage is increasing in interest within researchers [11]. For sensible heat TES, massive materials (concrete, stone, etc.) are required to store considerable amounts of heat, however, in latent heat TES higher amounts of energy per volume can be stored. Latent heat storage takes place by phase transition of the storage material. When heat is transferred to the storage material, melting takes place at a specific and quasi constant temperature, storing a large quantity of heat, which is called melting temperature or phase change temperature. After this stage, further increase of heat results in an addition of sensible heat storage. This heat then dissipates by solidification of the storage material. Regularly, for building applications solid-liquid phase change is used since it presents high energy density and no volume expansion problems. Materials with a solid-liquid phase change which are capable to store heat and cold are generally called phase change materials (PCMs) [9,10,12]. Previous researches [13–16] were documented and classified different types of PCM for building applications. These materials can be incorporated in buildings either as passive [17] or active [18] systems. In passive design approach the PCM is incorporated into the building construction and elements as an integrated-design. Enhancing the benefits of sunlight to reduce heating requirements or reducing energy needs for cooling by minimizing heat gains in summer are principal objectives of integrated designs.

An appropriate passive design by means of PCM can provide long-term energy efficiency, thermal comfort, stabilization of indoor air temperature and a reduction of the use and size of the HVAC systems [19,20]. Commonly, in passive design approach for building applications the PCM is incorporated into the building envelope as an integrated material into building walls, roofs, floors, slabs, fenestration, insulation, façade, and shading system [21,22]. However, before applying these innovative materials their performance should be analyzed using validated numerical simulation tools since application of PCM requires special attention to proper materials selection, the location, and the quantity of PCM in the envelope [23].

With the advent of digital computers, mathematical modeling and computer simulation has now become a crucial economical and quickest way to providing a broad understanding of the practical processes involving PCM [24]. Reliable whole-building energy simulation tools can numerically facilitate design, analysis and optimization of the PCM-enhanced building component with no need to set up expensive and time consuming whole-building field experiments [25]. Further on, computer-based simulation tools help designers and engineers to evaluate potential decisions and achieve long-term targets. For example, some researchers developed thermal load predictive models of commercial buildings using building energy simulation software [26]. In another study, whole-building simulation was used for the benchmarking of residential buildings [27]. Additionally, the validated model can always be employed for parametric or optimization studies and has more general applications than an experimental work. Therefore, numerical simulation is a widely-used method for economically and efficiently analyzing complex physical phenomena, such as the modeling of PCM [24].

Accordingly, a considerable amount of literature was published on the building energy simulation pointing out the advantages of using the PCM as a passive cooling or free cooling approach [21]. The current paper presents a holistic review of the numerical simulation of buildings containing PCM for passive cooling purposes using whole building energy simulation tools. The present study is an attempt to address the methods that have been used to evaluate and analyze the effects of passive PCM-based design on the cooling energy performance in buildings through whole building energy simulation software. In this regard, an extensive study was done to address the previous, current and future research trends toward the application of PCM in buildings for passive cooling by means of building energy modeling tools.

2. Whole-building energy simulation for PCM-based passive design

The use of whole-building energy simulation is an essential step to evaluate and analysis the performance of PCM-enhanced buildings. These tools can numerically analyze the dynamic thermal behavior of the building passively enhanced with PCMs. Today, there are many validated whole-building energy simulation programs which are capable of carrying out dynamic energy simulation for different applications [28] but there are few validated whole building energy simulation programs that can analyze energy performance and indoor comfort of PCM-enhanced passive buildings. This section overviews the commonly used and important simulation tools for building passive cooling design based on the PCM technology. According to literature review, EnergyPlus [29], TRNSYS [30], and ESP-r [31] have been extensively used by researchers to study the behavior of PCM in buildings and several studies have been carried out to validate these simulation tools [32].

2.1. EnergyPlus v8.6.0

EnergyPlus is an open-source and multi-platform building energy performance modeling with the most popular capabilities of BLAST and DOE-2.1E with many highlighted features. Furthermore, it is possible to develop new modules and/or control strategies and integrate them into the program as subroutines using energy management system (EMS) as a dedicated computer that could be programmed to control the whole energy-related systems of the building, such as heating, cooling, ventilation, hot water, interior lighting, exterior lighting, on-site power generation, and mechanized systems for shading devices, window, actuators, and double facade elements [33]. Additionally, functional mock-up unit (FMU) for co-simulation import interface allows EnergyPlus to conduct co-simulation with various simulation programs that are packaged as FMUs [34]. Other capabilities which give power to this software are advanced fenestration analysis as well as general envelope calculations (outside and inside surface convection algorithms), advanced infiltration, ventilation, room air and multi-zone airflow calculations, environmental emissions and developed economic evaluation including energy costs, and life cycle costs. In addition, comparing to other simulation tools, EnergyPlus includes several developed human thermal comfort algorithms for analyzing the occupant's thermal well-being and indoor air quality measures. Moreover, there are several graphical interfaces for EnergyPlus to simplify the use of this software by different types of users such as students, researchers, architects and engineers [28,35].

2.2. TRNSYS v17

TRNSYS is a flexible transient systems simulation program with a modular structure. It is a component-based simulation program, in which the user selects the components that comprise the energy system and interconnects them using appropriate input/output ports. The TRNSYS library consists of various components specifically designed for simulation of buildings, HVAC, lighting, ventilation, solar energy, thermal energy storage, and also component routines to support input of weather data or other time-dependent forcing functions and output of simulation results. In addition it facilitates the addition of new mathematical models not included in the software and couples them with existing components. TRNSYS became globally a well-known software for researchers and engineers. It can simulate solar thermal and photovoltaic systems, low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells, and active and passive PCM systems [36].

2.3. ESP-r

ESP-r is a general purpose, multi-domain building thermal, inter-zone air flow, intra-zone air movement, HVAC systems and electrical power flow, simulation program. ESP-r allows its user to explore the complex relationships between form, envelope, air flow, plant and control of a building. ESP-r is based on a finite volume, conservation approach in which a problem is transformed into a set of conservation equations which are then integrated at consecutive time-steps in response to climate, occupant and control system impacts [28,31]. In ESP-r, the PCM can be modelled using the concept of special materials facility [37,38].

2.4. PCM mathematical models used in whole-building energy simulation software

Energy and comfort analysis of buildings enhanced with PCMs for passive cooling purposes strongly depend on the PCM melting temperature and quantity, its thermal characteristics, the location of PCM in the building envelope, climatic conditions, outdoor and indoor boundary conditions, and design of the building. Mathematical modeling of PCM is an essential step towards optimal design and proper material selection for passive buildings [39]. On this basis, several numerical modeling methods have been used in whole-building energy simulation tools to simulate the thermal response of PCM. These methods could be classified based on their mathematical model, PCM model, and discretization approach. More importantly, various experimental, analytical, and comparative analyses were performed with the objective of producing accurate, reliable, and validated models. Table 1 summarizes the current methods and models used in whole-building energy simulation tools to simulate the thermal performance of PCM-enhanced buildings.

Table 1. Numerical methods used to simulate PCM in dynamic building simulation software, adopted from [32].

Software	Module identification	Mathematical method	PCM model	Discretization	Constrains	Validation	Reference
EnergyPlus	Conduction Finite Difference (CondFD)	FDM: 1D	Enthalpy method	Fully implicit/ Crank-Nicolson	-Time step < 3 min -Hysteresis in PCM cannot be modeled currently -Phase change at isothermal temperature cannot be modeled	Analytical, comparative & experimental	[40–43]

TRNSYS	“TYPE285”	FVM: 1D	Enthalpy method	Fully implicit	-Hysteresis and sub-cooling are not considered	Experimental, comparative	[44]
	“TYPE272”	FVM: 1D	Heat capacity method	Fully implicit	-Internal convective heat transfer of the liquid state PCM is not considered - PCM with multiple peaks is not supported	Experimental	[45]
	Modified "TYPE36"	FDM: 1D	Enthalpy method	Explicit	-Low time step	Limited validation using experimental results for concrete	[46,47]
	"TYPE58"	FDM: 2D	Enthalpy method	Explicit	NA	Experimental	[48]
	"TYPE204"	FDM: 3D	Heat capacity method	Implicit, semi-implicit	-Computationally inefficient	NA	[49]
	"TYPE101"	FDM: 1D	Heat capacity method	Crank-Nicolson	-A correction factor to account for cold bridges has to be used for model accuracy	Experimental	[50]
	TRNSYS "Active Wall"	Equivalent heat transfer coefficients	Variable heat source function mimicking PCM behavior	---	-Real heat transfer physics in PCM is not modeled	Experimental	[51]
	"TYPE241"	FDM: 1D	Heat source method	Implicit	NA	NA	[52]
	"TYPE260"	FDM: 1D	Enthalpy method	Implicit	-Thermal properties including heat capacity are based on previous time step (i.e, explicit scheme)	Experimental	[53]
	Modified "TYPE101"	FDM: 1D	Enthalpy method	Implicit	-Developed for internal partition wall	Experimental	[54]
	"TYPE1270"	Lumped method using heat balance	Quasi-heat source method	---	-Very simplified method -Internal layer within an envelope - Based on lumped heat balance -Low accuracy for PCM at fixed temperature	Experimental data in literature	[55,56]
	"TYPE399" available in TRNSYS v.17	FDM: 1D	Enthalpy method	Crank-Nicolson	-Hysteresis phenomena of PCM are considered in the model -It could be applied in both active and passive systems	NA	[30,57]
ESP-r	SPMCMP53-SPMCMP56	FDM: 1D	Heat capacity and heat source method	---	-Low time step	Experimental	[37,58–61]

1D:One-Dimenssional, FDM:Finite Difference Method, FVM: Finite Volume Method, NA: Not Available.

3. Potential of passive PCM design for energy savings and thermal comfort

Several publications have appeared in recent years addressing the importance of free cooling [62] and the numerical modeling of the PCM for building applications [32] of which a considerable number of studies have been performed using EnergyPlus software [63–69].

Various issues have been discussed and argued among the researchers to clarify to which degree the application of PCM can be more energy beneficial and to see to what extend these materials may or may not increase the thermal comfort of occupants [70], depending on control and implementation strategies as mentioned by Barzin et al. [71]. Moreover, the payback period was an important topic of discussion among the researchers [72,73].

The PCM passive system has been incorporated into the building envelope by different means such as PCM-enhanced drywall, PCM plaster, macro-encapsulated PCM panels, Multi PCM (honeycomb), PCM-enhanced insulation, and PCM green roof. Further on, these advanced building elements have been installed in different locations of the building envelope such as ceilings, exterior walls, partitions and attic floor. In this section the results of simulation-based studies for different building-integrated passive PCM systems are categorized and discussed with respect to energy savings and thermal comfort.

3.1. Gypsum boards and plaster with PCM

The impact of installing DuPont™ Energain® PCM drywalls (Figure 3) on the energy performance of single-zone residential buildings was studied by Soares et al. [74]. It was found that from 10% to 62% reductions in energy consumption could be achieved by inclusion of PCM depending on the climate zone. Moreover, the best PCM drywall thickness was found as 4 cm for all studied climates.

Figure 3.DuPont™ Energain® installed into the ceilings and walls [75].

Along with the similar lines, some authors [76] have studied the feasibility of energy retrofitting of a historic educational building by using PCM with the aim of improving the thermal comfort and the energy performance. Regarding the PCM application, two different scenarios were examined to reduce the cooling loads of the building; first applying PCM wallboard melting at 27 ºC and 3 cm of thickness over the inside surfaces of the building envelope, and second installing the PCM wallboard melting at 32 ºC on the outer surface of the walls. The analysis of the energy retrofitting scenarios have shown that despite 27% of primary energy savings in summer, the highest annual primary energy savings (38%) for both cooling and heating periods were achieved when a retrofitting scenario without PCM solution was applied. This retrofitting package was consisted of substitution of old windows with low-emissive ones, application of thermal insulation for the roof slab and using thermal plaster for the opaque vertical envelope. However, it is noteworthy to say that the PCM solution was designed to reduce the energy needs in the cooling period, so that, when the annual energy performance (cooling and heating) was evaluated, less annual energy savings were shown in retrofitting scenarios with PCM.

In another study, the cooling energy performance of a massive and highly insulated building with PCM-enhanced plaster envelope was studied under some European regions climate condition by Ascione et al. [77]. Addition of the PCM plaster (Figures 4) to the inner surface of the exterior envelopes with different thicknesses, melting points and locations in walls was analyzed and it was found that the best energy savings and comfort for the cooling period could be obtained when the PCM plaster melting at 29 °C with 3 cm thickness is incorporated into the vertical envelopes in all studied cities. It was concluded that, depending on the region, 2.5 to 7.2% of the cooling energy could be saved.

Figure 4. (a) Electron microscopy of PCM in gypsum plaster Micronal® [78];
(b) PCM gypsum plaster finishing on the wall ©BASF [79,80];
(c) PCM micro-capsules integrated into the interior plaster [61].

Additionally, Marin et al. [81] studied the feasibility of reducing the severe indoor air fluctuations in relocatable lightweight buildings to reduce HVAC needs under major Chilean climate condition. Such single-zone buildings widely used in mining camps or relocatable lightweight buildings. Then, their research was extended to more climate zones according to the Köppen Geiger classification [128]. The PCM plasterboard with 25 ºC of peak melting point containing 18% of microencapsulated PCM was installed on the inner surface of walls and roof to moderate the indoor air temperature. Two approaches were considered; controlled indoor comfort temperature (18 ºC for heating and 25 ºC for cooling) with HVAC system and free floating (FF) mode. In cases with HVAC system the PCM passive system could achieve cooling energy savings from about 10 to 130 kWh in different climate zones. Moreover, in FF condition, the application of PCM could increase the percentage of comfort hours in all studies climates from 10% to 30% except in tropical areas. As it was concluded by the authors, in order to increase the benefits of PCM, the optimization of PCM melting temperature under different climate zones is required. Further on, Ozdenefe and Dewsbury [82] investigated the impact of adding PCM wallboard into lightweight residential buildings in Cyprus to increase their energy performance. Respectively, different retrofitting scenarios with PCM inclusion were applied and eventually for the best scenario 14% of cooling energy savings were obtained.

3.2. Macro-encapsulated PCM panels

Under Australian weather conditions, Alam el al. [83] carried out parametric analysis to find out the potential energy savings by integrating BioPCM pouches with 0.005 m thickness and the latent heat of 219 kJ/kg (Figure 5) with different melting points (from 20 to 23 ºC) into the building envelope. Energy simulation results showed that the energy saving varies from city to city and depending on the climatic region the total annual energy savings could change from 17% to 23%.

Figure 5. BioPCM^{TM} pouches (Left) [84], BioPCM^{TM} inclusion in attic floor (right) [85].

Moreover, the feasibility of enhancing the energy performance of building prototypes containing Rubitherm compact storage modules (CSM) (Figure 6) was investigated by Saffari et al. [96]. The simulation results were shown that about 10-15% of the annual energy could be saved using PCM melting at 27 ºC in their studied climate. However, the energy savings for the cooling period were found much higher than the total heating and cooling consumption. Additionally, it was found that depending on the HVAC control, 20%-60% of the cooling energy could be saved. Also, it should be added that installing this type of PCM panel is simple which enhances the installation speed and reduces the maintenance cost.

Figure 6. Rubitherm CSM [86].

3.3. Multi PCM or Honeycomb

A methodology was presented by Evola el al. [70] to evaluate the summer thermal comfort performance of an office prototype where honeycomb PCM wallboards (Figures 7 & 8) were installed on the inner surface of the partition walls to passively regulate the indoor air temperature. Inclusion of the PCM honeycomb into the partition walls showed about 0.3-0.7 ºC reductions in peak operative temperature and about 5% to 7% increase of thermal comfort in the temperate months of July and August.

Figure 7. Honeycomb panel sample filled with paraffin, before to stick the upper aluminum skin [87].

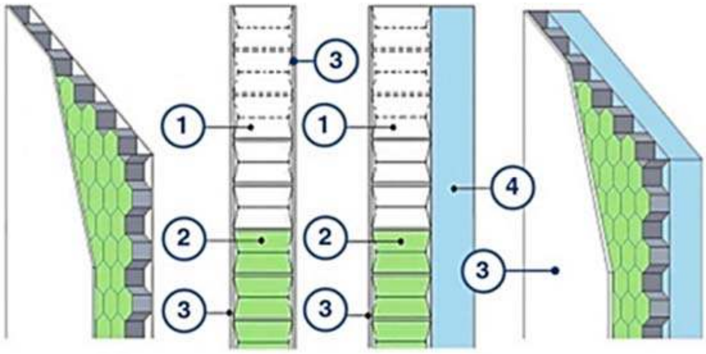

Figure 8.Multilayer Micronal® PCM-enhanced sandwich board with aluminum honeycomb core. Elements: 1. Aluminum Honeycomb 2.RACUS® PCM infill. 3.Magnoboard® 4.PIR or Phenolic Foam [25].

3.4. PCM-enhanced insulating materials

From the previous literature review, it can be seen that the PCM has been commonly applied to the interior and exterior surfaces of the walls, ceilings, and floors as a concentrated layer, or impregnated into the gypsum wallboards, drywalls and gypsum plaster, however, the impregnation of the PCM into the insulation (Figure 9) has gained interest due to its ability to significantly diminishing and shifting peak hour thermal loads by building fabrics [73]. There have been some studies in the literature reporting the energy benefits due to the application of PCM-enhanced insulation [63,88,89].

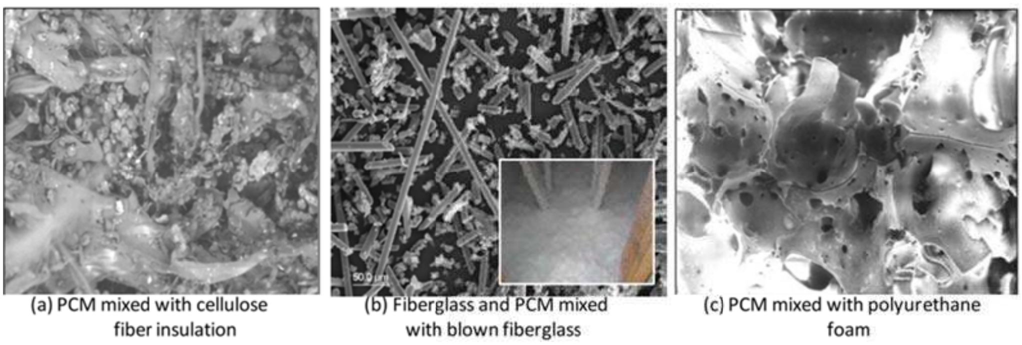

Figure 9. Scanning electron microscope (SEM) images of different mixtures of microencapsulated PCM [73].

For instance, Kośny et al. [63] evaluated the thermal performance of a complex thermal storage membrane containing pouches filled with 80 wt.% of bio-based PCM separated by fiber glass strips (Figure 10.a) to enhance the energy performance of a residential building (Figure 10.b). The PCM membrane was installed into the exterior walls and the attic floor which resulted in 10% reduction in annual wall-generated heating and cooling loads. However, it should be noted that, addition of the PCM may not increase the thermal resistance of the building components significantly; hence, a proper combination of thermal mass and insulation should be considered [63].

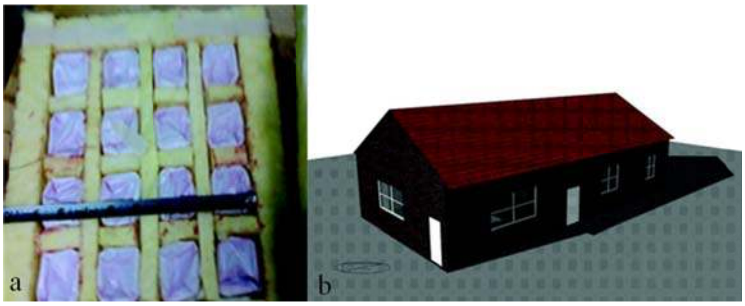

Figure 10. (a) PCM-enhanced fiberglass; (b) Single-story ranch house [63].

Similarly, the potential benefits of incorporating the PCM-enhanced blown fiber glass insulation into the residential attics (Figure 11) was investigated through experiment and numerical analysis under hot and mixed U.S. climates [89]. Therefore, it was concluded that the application of PCM-enhanced insulation can improve the roof-generated peak loads by 70-80 %. By the way, as it has been discussed in the literature, further research is required to investigate the heat transfer in such composites and to evaluate their potential contribution to energy saving in buildings [90].

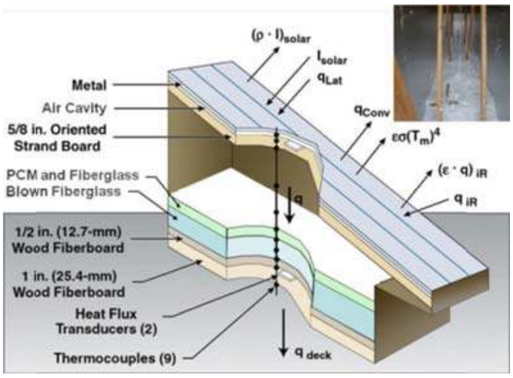

Figure 11. Instrumentation of attic containing PCM-enhanced fiber glass insulation [89].

Kośny et al. [59] studied the passive cooling potential due to addition of PCM-enhanced insulation into residential attics under weather condition of Phoenix, Arizona. Two types of PCM were used. A 30% by weight uniform blend of PCM with fiber insulations, and a 90% by weight blend of shape stabilized PCM with plastic composite, both with 26.5 ºC of melting point. Different scenarios (as shown in Figure 12) were investigated by ESP-r whole-building simulation tool to understand the underlying effects of using PCM in the studied building.

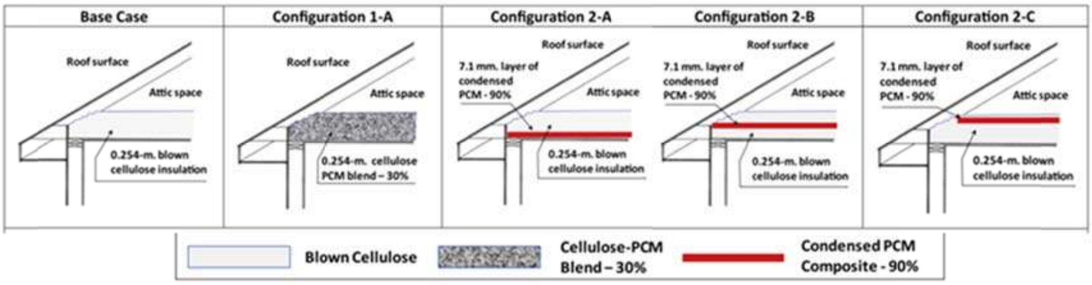

Figure 12. Different scenarios of PCM-enhanced cellulose insulation & concentrated PCM into attic envelope [59].

Several results were achieved by the authors; the simulation study showed that the attic insulation scenario with concentrated PCM achieves lower cooling loads than the scenario with PCM-enhanced cellulose (Configuration 1-A). Higher cooling savings obtained for Configurations 2-A and Configurations 2-B with 6.8% and 6.6% of cooling energy savings which are better than dispersed PCM (Configuration 1-A) with 3.1% cooling savings. Further on, the best strategies to integrate concentrated PCM were found to be PCM on the bottom and in the middle of the attic floor insulation, Configurations 2-A and 2-B, respectively.

3.5. PCM in roof

Until now, far too little attention has been paid to the potential of passive PCM systems to reduce the UHI. In a recent paper by Roman et al. [91] the possibility of reducing the energy consumption and UHI effect applying cool roof and PCM-enhanced roof technologies was investigated (Figure 13). From the simulation results it was concluded that the PCM has great potential to improve both indoor and outdoor environment thermal conditions. The PCM roof could reduce 54% of heat flux entering the building indoor environment through the roof and more interestingly, the PCM-incorporated roof showed 40% lower heat flux emitting from the roof surface to the outdoor environment in peak hours comparing with the cool roof technology. These results are consistent with the finding of Karlessi et al. [92] which has shown that PCM doped coatings can reduce the surface temperature by 12%. These findings are promising since they have proved that the PCM can improve both the microclimate and the macroclimate thermal conditions. Further on, Pisello et al. [93] investigated the influence of integrating PCM into two different types of roofing membranes to increase the energy performance of a building prototype. A traditional bitumen roofing membrane and an advanced cool polyurethane-based membrane enhanced with PCM with 26 ºC of melting point were studied under the climate condition of Perugia. Their simulation results showed 10% and 23% of cooling energy savings by the integration of PCM-enhanced bitumen roofing membrane and PCM-enhanced cool polyurethane-based membrane, respectively. Additionally, when the insulation layer was removed, cooling savings increased to 39.4%. The recent study of Pisello et al. [94] is confirmatory evidence that the use of PCM as a passive cooling approach can enhance the durability of cool roof membrane by reducing its severe thermal stress under solar radiation. These promising results open a new horizon over the application of PCM to improve the cooling performance of buildings and to enhance the durability of building materials. With this regard, further whole-building energy simulation and optimization studies are necessary to evaluate the cooling energy performance of these innovative passive systems under different climatic conditions, and with different construction design to evaluate their contribution to enhance the thermal comfort of occupants.

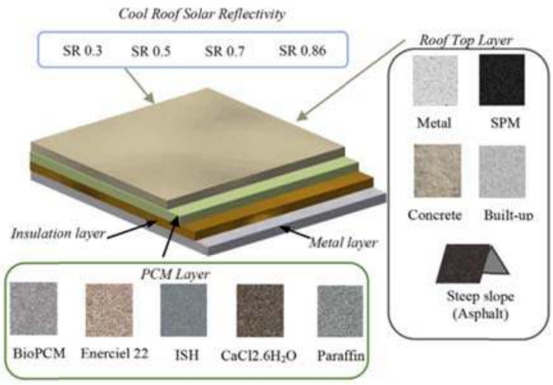

Figure 13. PCM-enhanced cool roof [91].

Furthermore, the thermal performance of a typical naturally ventilated single-story residential building with PCM-enhanced roof construction was investigated by Jayalath et al. [56] under weather condition of Melbourne and Sydney. The BioPCM melting at 23 ºC was integrated into the roof construction before interior steel layer to moderate the temperature fluctuations of the indoor environment and to improve the thermal performance of the residential building. Later on, PCM with 21 ºC, 23 ºC, 25 ºC, and 27 ºC melting points were used to investigate the melting point influence on the cooling performance in the simulated building under two different climate zones. Eventually, it was found that in both cities the optimum temperature of PCM to increase the thermal comfort is 23 ºC. As concluded by the authors, 25% and 39% of cooling load savings were achieved in Sydney and Melbourne, respectively. It was also mentioned that addition of PCM as a roof layer was more effective in reducing cooling loads than heating loads. However, regarding the results presented in above-mentioned article the authors of the present paper would like to comment that both cities of Melbourne and Sydney are heating dominant and the addition of PCM with 23 ºC resulted in higher savings for heating period than cooling period with 42.5 and 17.9 mJ/m^2 per year for Melbourne and Sydney, respectively.

3.6. Comparison between existing technologies

Different building models such as office buildings, residential buildings, and simple single-story were numerically analyzed by researchers, using macro-encapsulated or microencapsulated PCMs. Various strategies have been applied to integrate the PCM into the building envelope such as adding concentrated or compact PCM layer [72], PCM dispersed into insulation materials [95], PCM added to the gypsum boards and plaster [77]. In a great number of articles parametric analysis has been used to find out the best PCM melting point, latent heat capacity and layer thicknesses considering its addition in different locations of walls, ceiling, roof and floor. A considerable number of literatures were been published on the application of PCM gypsum boards or PCM-enhanced wallboards and concentrated PCM layers/panels for their high contribution in cooling energy saving, feasibility of installation on the inner surface of walls an being cheap [96]. More recently, special attention was paid to apply PCM in cool roof to increase the thermal comfort of occupants, to reduce the cooling energy consumption and to enhance the durability of cool roof membranes [94,97]. Additionally, through whole-building energy simulation, now it is possible to analyze the effects of PCM in reducing the heat island effects in urban area [91] and enhancing the thermal inertia of residential buildings to resist severe thermal shocks of heat waves by peak load and discomfort hours reduction of indoor temperature [98]. In addition, the feasibility of improving the thermal performance of lightweight relocatable buildings for mining camps or post-disaster rapid housing was investigated [81]. A detailed literature review was done regarding numerical analysis of PCM-integrated buildings based on EnergyPlus, TRNSYS, and ESP-r whole-building energy simulation tools which is presented in Table 2. According to this literature review on the simulation-based passive cooling for building applications, EnergyPlus software was the most prominent tool to investigate the passive cooling effects of PCM in buildings; however, this does not deny the strength of other energy simulation tools at all.

Table 2. Passive cooling in buildings by means of whole-building energy simulation tools.

Building type	Encapsulation	Latent heat [kJ/kg]	Melting [ºC]	Thickness [m]	Installation	Results	Simulation tool	Reference
1. Office building	NA	175	26 to 29	0.005, 0.01 0.02, 0.03	Inner surface of vertical walls	• Greater cooling performance and comfort were achieved with 3 cm PCM in all vertical walls. • From 3% to 7.2% cooling savings, depending on the climate zone were achieved.	EnergyPlus	Ascione et al. [77]
2. Office building	Microencapsulated	NA	23 to 28	0.02	Inner surface of partition walls	• The organic honeycomb PCM was more effective in temperate climate rather than in hot Mediterranean climate.	EnergyPlus	Evola el al. [70]
3. Single-room house	Macroencapsulated	165-200	20 to 25	0.005	Parametric analysis was performed	• From 17% to 23% of energy savings depending on the climate zone were achieved. • PCM had very little effect in hot and humid climates.	EnergyPlus	Alam et al. [83]
4. Passive house duplex home	Macroencapsulated	165-200	23, 25	0.015	Interior surface of the envelopes	• PCM installed on the interior surface of the walls provided higher comfort. • About 50% of discomfort hours were decreased using PCM melting at 25 ºC.	EnergyPlus	Sage-Lauck et al. [99]
5. Passive house duplex home	Macroencapsulated	165-200	23, 25, 27, 29	0.015	All exterior & interior vertical and horizontal envelopes	• Zone uncomfortable hours were reduced by 93% adding PCM (3.1 kg/m2) melting at 25 ºC.	EnergyPlus	Campbell et al. [100]
6. Residential building	Microencapsulated	70	18 to 28	0.01, 0.015, 0.02, 0.025, 0.03, 0.035, 0.04	Interior surface of the interior envelopes	• From 46% to 62% of cooling savings were achieved under warm climate condition. • The best savings achieved with 4 cm layer PCM.	EnergyPlus	Soares et al. [74]
7. Research center building	Macroencapsulated	281 230, 235, 267	20, 21, 24, 29	0.0064	Between insulation & interior gypsum board of all exterior walls	• The cooling savings were insignificant (1%). • Night ventilation coupled with PCM increased the cooling performance to about 9%.	EnergyPlus	Seong et al. [68]
8. Historic building	NA	110	27, 32	0.03	Interior and exterior faces of the envelope	• PCM application was not feasible and it increased the annual energy consumption.	EnergyPlus	Ascione et al. [76]
9. Office building	Microencapsulated	33.5	21 to 26	0.013	Interior and exterior faces of the envelope	• Cooling savings were increased in all cases with PCM. • Annual savings between -25% to 33% depending on	EnergyPlus	Vautherot et al. [101]

						the PCM melting point were achieved.		
10. Single-story house	Microencapsulated	112	23	0.01117	Between interior framing and the air gap	• 10% reduction in annual wall-generated heating and cooling. • Proper combination of thermal mass and insulation is required.	EnergyPlus	Kosny et al. [63]
11. Single-story house	Microencapsulated	170	29	0.1	On the attic floor	• 70-80% reductions of roof-generated peak hour loads.	EnergyPlus	Kosny et al. [23]
12. Office building	Microencapsulated	41	23	0.02	Inner surface of the interior partition walls	• PCM storage efficiency increased by 10% to 30 %.	EnergyPlus	Evola et al. [64]
13. Residential building	Microencapsulated	110	23, 25, 27	0.012, 0.024, 0.036, 0.48, 0.06	On the inner surface of the vertical walls	• PCM cooling savings in August 2011 was recorded as 40%. • The cooling savings are expected to increase further by 2050.	EnergyPlus	Sajjadian et al. [65]
14. Residential building	Microencapsulated	70	26	0.052	On the inner surface of the vertical walls and ceiling	• The use of PCM during the cold months of Montreal was not very effective; however, energy savings were achieved in warmer seasons. • In Mediterranean climate (Palermo) 87% of cooling reduction was shown at peak hours.	EnergyPlus	Guarino et al. [69]
15. Simplified cubicle	NA	223	22 to 32	0.003-0.020	Parametric analysis for different locations of PCM	• 21-32% reduction of heat gains achieved by using PCM • Better energy performance achieved when PCM was installed to the exterior surface of the envelope.	EnergyPlus	Lei et al. [66]
16. Residential building	Microencapsulated	70	21.7	0.005	After exterior layer of mosaic tile and cement.	• Low annual cooling energy savings achieved (2.9%). • PCM with higher melting points should be studied in Hong Kong climate.	EnergyPlus	Chan [67]
17. ASHRAE-140 case-600	Macroencapsulated	148	23, 25, 27	0.005 0.01	Interior surface of vertical walls & ceiling	• 10 to 15 % annual energy savings achieved with 10 mm concentrated PCM melting at 27 ºC.	EnergyPlus	Saffari et al. [72]
18. Residential building	Macroencapsulated	200	23	0.015	Inner surface of the exterior walls.	• 47-76% cooling savings at peak hour were obtained. • Higher energy savings (28-63%) achieved in the heating period.	EnergyPlus	Nghana et al. [102]
19. Hospital building	Macroencapsulated	196 177 188	21-24 18-29 26-28	0.074 0.003 0.0063	Rooftop, innermost layer, middle layer	• The PCM-enhanced roof reduced the heat flux through the roof to the building interior by 54% at peak hour. • The sensible heat flux from roof surface to the	EnergyPlus	Roman et al. [91]

		152 160	21-24 28.5-30.2	0.0033 0.0162		surrounding environment decreased by 40%.		
20. Office building	Macroencapsulated	219	27, 29	0.01	Before the inner layer of walls, attic, ceiling, floor	• Annual cooling loads were reduced by 47% using PCM melting at 27 ºC coupled with fan-assisted night ventilation.	EnergyPlus	Solgi et al. [103]
21. Cubicle (single-zone building)	Microencapsulated	46	25(peak melting)	0.0125	Inner surface of vertical walls & roof	• The highest cooling savings recorded from 150 to 171 kWh. • PCM optimization is needed to improve savings in some climates.	EnergyPlus	Marin et al. [81]
22. Cubicle (single-zone building)	Macroencapsulated	170	26	0.01, 0.02	Interior surface of exterior walls before bricks	• The most influential factors for cooling savings were defined as PCM melting point and thermal conductivity.	EnergyPlus	Mazo et al. [104]
23. Residential building	Microencapsulated	140	26	0.15	Inner surface of vertical walls & ceilings	• The cooling energy consumption reduced by 14%.	EnergyPlus	Ozdenefe & Dewsbury [82]
24.Prototype test-room	Microencapsulated	110	26	0.004, 0.01	Exterior surface of the roof	• PCM in roofing membranes resulted in 9.4% to 39.4% of cooling energy savings.	EnergyPlus	Pisello et al. [93]
25.Test-room	Microencapsulated	70	18-24	0.005	Interior surface of walls	• The annual cooling reduced by 50% in heating-dominant climate. • Natural/fan-assisted ventilation can increase the cooling performance in highly glazed buildings.	EnergyPlus	Guarino et al. [105]
26.Single-story building	Macroencapsulated	182	25, 27, 29	0.03	Interior surface of walls, exterior surface of walls, interior & exterior surface of walls	• PCM finishing layer melting at 25 ºC could save cooling energy from 2% to 13% under Mediterranean climate condition.	EnergyPlus	Ascione et al. [106]
27. Multi-story office building	Macroencapsulated	250	27	0.010	Before interior vertical mortar wall	• PCM saved summer cooling energy needs from 1500 to 2300 kWh in 3 cities of China with cold and hot summer climate condition. • Optimization of PCM melting temperature has been suggested as a solution to increase energy savings and economic benefits.	EnergyPlus	Mi et al. [107]

28. Two-story residential building	Macroencapsulated	219	29	0.02 (optimization applied)	Interior Surface of roof before gypsum board	• PCM layer melting at 29 ºC added to roof envelope and no economic savings observed under climate condition of Iran.	EnergyPlus	Baniassadi et al. [108]
29.Two-story house	Macroencapsulated	134	25	0.02	Into ceiling and into ceiling and walls interior surfaces	• PCM could reduce discomfort hours from 34% to 52% depending on the behavior of occupants.	EnergyPlus	Jamil et al. [109]
30. Two-story house	Microencapsulated	86	24	0.22	Inner Surface of all external walls	• PCM has significant effect in reducing overheating in residential building in the UK. • A proper combination of insulation and PCM level should be investigated. • The effectiveness of PCM in lightweight buildings is higher.	EnergyPlus	Auzeby et al. [110]
31. Residential building	Macroencapsulated	219	27	0.02	Inner Surface of walls and ceiling	• PCM passive cooling system combined with mechanical night ventilation could reduce the hours of extreme heat stress by 23% to 32% in Melbourne.	EnergyPlus	Ramakrishnan et al. [98]
32. Residential building	Macroencapsulated	200 (parametric study 50 to 300)	20 to 27 (parametric study)	0.0125	Interior surface of walls, exterior surface of walls, in the middle of wood assembly	• In Phoenix cooling savings were insignificant (0.8% annual cooling savings) • In Seattle 15.8% of annual cooling savings recorded.	TRNSYS	Al-Saadi and Zhai [44]
33. Single-story residential building	Macroencapsulated	210	21, 23, 25, 27	0.0121	Interior Surface of roof before steel finishing	• In Melbourne 39% and in Sydney 25% of cooling energy savings achieved.	TRNSYS	Jayalath et al. [56]
34. Single-story residential building	Microencapsulated	119	26.50	0.15, 0.255, 0.357, 0.459, 0.083, 0.050	Homogenously blended PCM into cellulose insulation of attic, condensed layer of PCM into different locations of the attic	• PCM-enhanced cellulose achieved 3.1% of cooling savings. • Concentrated PCM layer achieved from 0.56% to 6.6% of cooling savings.	ESP-r	Kośny et al.[59]

NA: Not available

4. Passive PCM-enhanced building with natural ventilation

Natural ventilation is considered as a passive or free cooling method in which the cool nighttime air flows into the building zone to provide cooling [111]. In natural ventilation cooling system, the flow process is driven by wind and/or stack effect. An appropriate use of natural ventilation techniques can enhance the PCM performance by increasing the possibility of full charging and discharging process [112]. Coupling PCM as an innovative thermal mass with natural night ventilation could be an ideal solution to increase the cooling performance of buildings, nevertheless, it is not the only parameter found to be critically important for the appropriate and efficient operation of PCM in buildings. Many factors such as outdoor air temperature, wind speed, wind direction etc. affect the performance of this passive system. Therefore, using numerical simulation tools which are capable of simulating both the PCM and the natural ventilation effects on the energy performance of the building is essential. Natural night ventilation creates a heat sink system by help of wind and indoor-outdoor temperature difference to provide cool air or to remove excessive or unwanted heat stored in the building envelope resulting better indoor air quality, comfort and cooling loads reduction.

Several publications have mentioned the advantages of passive cooling by means of natural ventilation using numerical simulation [113–115].

In the literature, there are numerous studies of coupling thermal mass and natural night ventilation by means of whole-building energy simulation [116,117], nevertheless, there are only a few examples in which the effect of coupling PCM with natural night ventilation is analyzed [68,70,109]. Also, some authors have investigated the effect of fan-assisted night ventilation with high ratios of air exchange per hour (ach) which was highly effective to discharge the PCM. Studies have found that the integration of natural night ventilation strategies [69,82] or fan-assisted night ventilation [103] can effectively increase the cooling performance of the PCM-enhanced buildings in climates with cool nighttime outdoor temperature. For example the effectiveness of night ventilation to enhance the performance of PCM passive system was investigated by Evola et al. [70]. Different air change rates per hour (2-8 ach) were applied between 21:00 and 06:00 which caused a reduction in the mean daily and peak operative temperature; nevertheless, introducing more than 4 ach did not add significant benefits. However, the simulation results showed that coupling the proper night ventilation with PCM system can improve the thermal comfort by 10% in comparison to the PCM-enhanced model without night ventilation. With the same objective Seong et al. [68] showed that adding 6 m3/m2-h of ventilation during the night period can enhance the annual cooling performance by about 9% compared to the PCM model without night ventilation. With the same objective, the feasibility of reducing peak zone temperature and improving occupant thermal comfort in a naturally ventilated 5-star energy rated house located in Melbourne using passive PCM cooling approach was studied by Jamil et al. [109]. Two different scenarios were considered to apply the PCM into the building envelope; spreading PCM melting at 25 ºC only in ceiling, and incorporating the same PCM in ceiling and walls. Additionally, controlled (manual) night ventilation by opening 20% of windows from 19:00 to 7:00 to boost the solidification of PCM since the nighttime outdoor temperature was always below 23 ºC (below the melting point of used PCM). Their results showed that a combination of PCM in ceiling coupled with natural night ventilation can increase the effectiveness of PCM for passive cooling and reduce the discomfort hours (according to ASHRAE 55-2013 [118]) up to 34% (with PCM only in ceilings), and 52% (with PCM in ceilings and walls); nonetheless, this improvement strongly depends on the behavior of occupants to properly follow the proper night ventilation strategy. In addition, Solgi et al. [103] applied fan-assisted night ventilation to an office building in order to improve the annual cooling performance and the thermal comfort condition. The night ventilation with specific indoor-outdoor temperature control strategy was considered between 24:00-7:00 with different fan ach (5 to 30). The simulation results were shown that the annual cooling load could be reduced from 30% in the PCM-enhanced case to about 46% in the PCM model with fan-assisted night ventilation with 15 ach, nevertheless, further increase of air change per hour showed an increase in the total energy consumption.

5. Technical barriers

When designing a passive system based on the PCM technology, one crucial fact that should be considered is that the PCM passive system can improve the energy efficiency of buildings, nonetheless, the discomfort due to the elevated humidity ratio should be considered in hot and humid climates. Very high humidity ratios might affect the thermal comfort of the occupants which is consistent with findings of [67,69,83,102]. Although high cooling energy savings could be achieved by proper PCM passive solutions but the ability of these materials to absorb the latent heat is very limited. Accordingly, in regions with high ratios of humidity, a proper HVAC system should be selected to control the dehumidification in order to provide the occupants with thermal comfort [119]. Also, solar renewable system could be a solution to provide cooling and dehumidification [120].

On the other hand, a proper PCM design ties with a balance between energy provisions and comfort criteria. It should be considered that adding the PCM does not always ensure the increase of comfort but in order to get the best results, the PCM melting range should be within the comfort range [101], otherwise limited energy savings could be achieved [121]. Moreover, the highest comfort level does not certainly lead to high savings in energy, but, the highest comfort might be achieved by cost of higher energy consumption which is also discussed by other authors [72].

As it has been discussed, night cooling could be an effective way to enhance the performance of the passive PCM system. For example, in office buildings it offers the opportunity for system downsizing in climates where the air temperature decreases at night [100]. However, it should be considered that this outdoor temperature decrease should be lower than the PCM melting point in order to be able to solidify the PCM; otherwise, night ventilation may have reverse effect on the cooling performance in climate with high temperature nights [122]. In addition, more sophisticated night ventilation techniques [113] considering the outdoor boundary conditions such as wind pressure coefficients and wind velocity along with customized control strategies coupled with passive PCM approach could be studied and investigated using whole-building energy simulation tools.

Also it is noticeable to mention that in many simulation-based studies the parametric analysis is unfairly referred as optimization; however, to the best of authors knowledge, no report was found so far using optimization algorithms to optimize the e.g. PCM melting point temperature, and very few literature is available on the multi-dimensional analysis [74] and until now little importance has been given to single- and multi-objective mathematical optimizations [101] and there few cases of multi-objectives optimization of PCM-enhanced passive buildings, however, recently more attention has been paid to simulation-based optimization of passive PCM buildings to increase the thermal comfort and energy performance of building [106], to optimization the thickness of insulation and PCM layers [121], and to investigate the life cycle and environmental impact of building with PCM [123–125]. Parametric analysis may help to find the best solution among the available options but not always the optimum solution and it is time consuming. In order to find the optimum solution in such systems, optimization tools and statistical methods are appreciable to reduce the simulation cost and to increase the energy efficiency [126].

Simulation-based studies can give valuable information about the energy and comfort benefits due to the integration of PCM in buildings, however, it should be taken into account that today, only few commercially available computer models use separate enthalpy–temperature curves for melting and freezing such as ESP-r [37]. Currently, in EnergyPlus whole-building energy simulation software identical algorithm for thermal characteristics of melting and freezing processes is used. On this basis, PCMs without noticeable subcooling should be considered for simulation [127].

6. Potential of passive PCM use in different climates

According to the findings of researchers, the application of PCM yielded different results in terms of energy saving in different climates. On this basis, in the following sections the feasibility of using passive PCM system will be discussed and categorized according to the Köppen Geiger main climates classification (Figure 14). In this classification the main climates are categorized in A: equatorial, B: arid, C: warm temperate, D: snow and E: polar. Additionally, the level of precipitation is defined as W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, m: monsoonal. Further details are provided regarding temperature as h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, and F: polar frost.

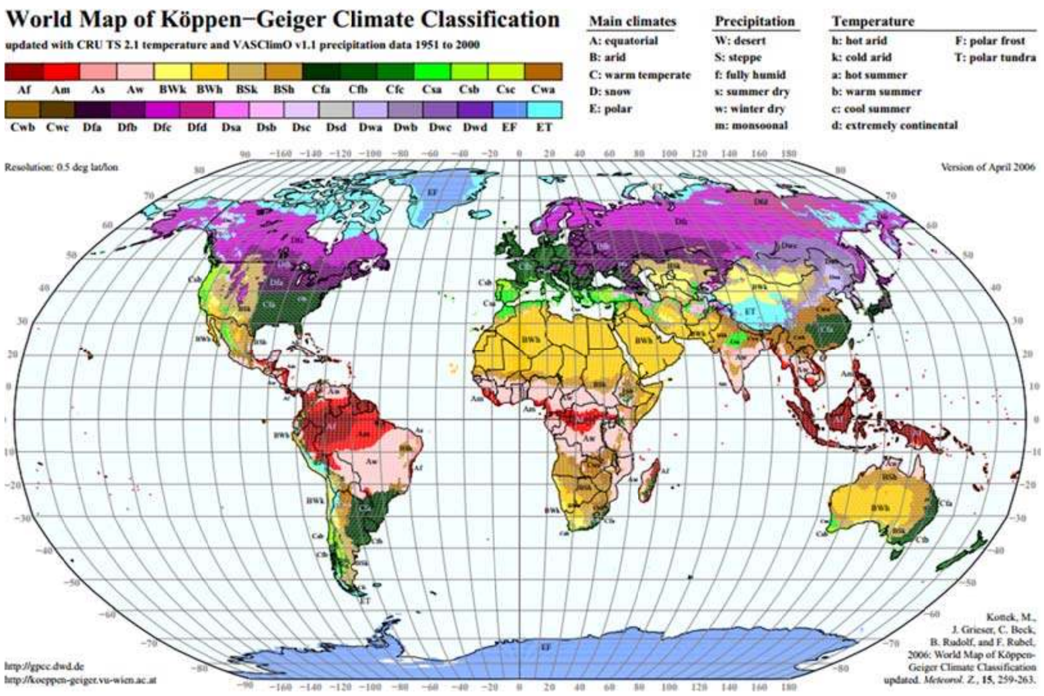

Figure 14.World Map of Köppen–Geiger climate classification [128].

The feasibility of enhancing the cooling energy performance and the indoor thermal comfort in buildings by applying the PCM technology has been studied under various climatological conditions worldwide such as some regions in Europe [69,70,77], North America [102], South America [81], Australia [83], New Zealand [101], and some specific regions in Asia [66,67] and the Middle-East . A considerable amount of literature was published on the application of PCM for passive cooling in buildings under warm temperature climates (C). The practicability of using the PCM has been studied for new construction buildings and for retrofitting of the existing buildings [77] including historical buildings [76].

6.1. Equatorial (A)

Lei et al. [66] examined the effectiveness of PCM in climate of Singapore (Af) conducting parametric studies. The PCM with 28 ºC melting point temperature was used which could significantly decrease the heat gains which was estimated about 21-32% per year, nonetheless, the energy savings results were not presented. Further on, in the studied climate, better energy performance was achieved when the PCM was applied to the exterior walls since during night the stored heat could dissipate to the outdoor environment and not to the air-conditioned zone. In another study which was performed by Alam et al. [83] the potential of PCM to reduce the annual energy consumption was negligible in Darwin (Aw) due to hot and humid summers and hot winters.

6.2. Arid (B)

Campbell and Sailor [100] measured the impacts of integrating PCM in high performance super-insulated homes lacking from insufficient thermal mass to increase the thermal storage and stabilize the temperature fluctuation in such buildings in cooling season over different climate zones across the United States. The simulation results were shown only 6.4% of occupants thermal comfort increase in hot-arid climate of Phoenix (BWh) due to elevated nighttime temperatures and low storage density of PCM melting at 25 ºC. However, these results are in consistent with findings of Al-Saadi and Zhai [44], where 0.8% savings of annual cooling load achieved in Phoenix. Also, it should be highlighted that some researchers achieved about 46% savings in cooling energy consumption using the PCM with 27 ºC melting temperature into the external walls, ceiling and roof under climate condition of Yazd (BWk) by taking advantage of the night cooling and control strategy [103]. From the results mentioned above, it can be seen that the PCM passive system works better in cold arid climates since at nighttime the accumulated heat in the PCM can be dissipated by the cool outdoor air temperature. This effect could be increased in regions with high altitudes. For example some researchers [83] achieved about 23.5% annual energy savings with PCM melting at 22 ºC under climate condition of Adelaide (BSk) with about 700 m of altitude.

6.3. Warm Temperate (C)

A great effort has been made to study the energy-related impacts by applying the PCM into the building envelope in warm temperature climate. For example, the study carried out by Ascione et al. [106] adds more results regarding the application of passive PCM technology to improve the cooling energy performance of a single-story building under the Mediterranean climate condition (Csa). Different wall compositions enhanced with PCM-enhanced gypsum plasterboard melting at 25 ºC, 27 ºC, and 29 ºC were numerically studied and optimized. According to their results, the integration of PCM melting at 25 ºC, adding PCM to the inner surface of vertical walls could improve the annual cooling energy performance by roughly 2%, 4%, 7% and 13% in Madrid, Nice, Athens, and Naples, respectively. Moreover, the simulation results of Campbell et al. [100] showed significant improvements in occupant comfort in Los Angeles (Csb), Portland (Csb), and Denver (Cfa). The results were shown up to 44% and 79% reductions in zone discomfort hours in Los Angeles and Denver, respectively. However, the highest thermal comfort was achieved in Portland with about 93% reductions in uncomfortable hours using 3.1 kg/m^2 of PCM melting at 25°C. As argued by the authors, these thermal comfort improvements could be associated with less severe daytime temperature and also cool nighttime temperature which facilitated the proper charging and discharging of the PCM. Similarly, Ramakrishnan et al. [98] concluded that enhancing the thermal inertia of non-air-conditioned buildings in Melbourne (Cfb) by adding PCM with 27 ºC melting point into vertical walls and ceiling can effectively reduce heat stress risks during extreme heat waves by 23%, however, when mechanical night ventilation was considered, discomfort hours reduced to 32%. However, it should be considered that when mechanical ventilation system is considered the building is no longer non-air-conditioned.

Furthermore, Chan [67] investigated the cooling energy performance of the living room and bedroom of a typical residential flat with PCM-enhanced facade under the climate condition of Hong Kong (Cwa). The results showed very low annual cooling energy savings (2.9%) for the living room and approximately 1% rise in the cooling energy consumption for the bedroom. Consequently, a very long payback period in years (91 years) was estimated. As it was argued by the author, the melting point temperature of the selected PCM which was 21.7 ºC could not adequately absorb the heat; and the interior surface temperature of the PCM wall was mostly above 28 ºC, even at night and the PCM could barely discharge. So that, the existence of the low cooling savings implies that PCM with higher melting point should be used under this climatic region. Likewise, Mi et al. [107] investigated the energy and economic benefit of adding PCM to vertical walls of a multi-story office building under climate zones of China. They used PCM with melting temperature of 27 ºC to increase the summer cooling performance. However, in spite of achieving some cooling savings (e.g. 2100 kWh in case of Hong Kong), generally low energy and economic benefits were obtained for summer cooling period. Although, when energy savings for both heating and cooling periods were considered, the energy and economic benefits increased further.

Additionally, Vautherot et al. [101] carried out a parametric study to find out the best PCM solution from two different aspects of energy saving and comfort level for the weather condition of Auckland (Cfb). Different energy savings were shown due to the application of PCM with various melting point temperatures. It was shown that higher thermal comfort could be achieved (17-31%) by using PCM with higher melting point temperature (24 ºC), however, the best annual cooling and heating energy performance was achieved (23-32%) when PCM with lower melting point (20 ºC) was applied into the building envelope. Also, this trend was observed in the simulation results of other researchers [83,106] under the weather condition of Canberra (Cfb). This could be justified since in heating dominant climates such as New Zealand, with proportionally higher heating demands, optimizing the PCM melting point temperature for the heating period would result in higher annual energy savings. The authors of the present paper would like to highlight that; far too little attention has been paid to above mentioned issue and in the available literature regarding the passive PCM technology for building applications further studies are required for numerical optimization studies under different weather conditions.

6.4. Snow (D)

As reported by Seong & Lim [68] installing PCM pouches with various melting points into the vertical envelopes of a research center in Seoul (Dfa) showed no evidence of significant cooling energy reductions (only around 1%). Several arguments were given in an attempt to explain the scant effects due to the application of PCM in their studied climate such as the location of the PCM layer in the envelope, PCM quantity, PCM latent heat capacity, melting temperature, and HVAC operation schedule. However, the cooling savings increased to 9% when night ventilation was coupled to the passive system. Besides, it has been shown by some researchers [72] that the HVAC operation in office buildings may unfavorably influence the energy performance depending on the climate condition (e.g. sunshine hours and the intensity of solar irradiation), but also, other factors such as internal gains [129], ventilation, control strategies [84,86] and PCM thermal characteristics are highly influential. Further on, it was added by Kosny et al. [89] that in climate of Chicago (Dfa) about 11% of the annual cooling loads were decreased by application of PCM-enhanced insulation in attic floor of a building.

According to the findings of Soares el al. [74] in cold climates of Warsaw (Dfb) and Kiruna (Dfc), the total energy savings due to application of PCM was limited to 24% and 10%, respectively. Furthermore, they added that the optimized incorporation of PCM in the room could reduce the cooling energy demand by 74% and 87% in Warsaw and Kiruna, respectively. Similarly, Guarino et al. [69] investigated the energy benefits of adding PCM to a small and lightweight test-hut under the weather condition of Montreal (Dfb). Energy analysis results showed about 47% to 76 % of the peak cooling energy reduction in cold climate of Montreal; nevertheless, the annual energy performance in Montreal was limited to 11-19%. In lines with previous simulation results, some researchers [81,107] achieved limited energy savings due to the use of PCM in cold climates with no optimized PCM melting temperature in those specific climate zones.

It should be considered that in heating dominant climates, high amount of energy is needed for heating than cooling, so that, in such climates the PCM melting temperature should be optimized to enhance the total annual cooling and heating energy performance and not only the cooling period.

7. Conclusions

Passive cooling technologies with phase change material (PCM) have the potential of reducing the increasing cooling demand, however, in order to properly implement this technology in buildings, numerical simulation is essential. The present paper set out to review numerical methods provided by whole-building energy simulation tools to analyze the passive cooling potentials of PCM-enhanced buildings. It was shown that EnergyPlus, TRNSYS, and ESP-r were used to analyze the cooling energy performance of buildings when PCM integrated into the building envelope in different ways such as dispersed PCM in drywall, dispersed PCM in gypsum board, pouches filled with PCM, PCM-enhanced insulation and PCM plaster. Additionally, researchers incorporated PCM in various parts of the building such as vertical walls, partitions, floors, ceilings, attic floor and as a component of green roofs as well as cool roofs.

The application of PCM-enhanced wallboards was popular among researchers due to their feasibility of incorporation into the interior surface of walls and ceilings, lower price, and high effectiveness to moderate the indoor temperature and reduce the cooling energy requirements. In many simulation-based studies, the PCM was added to the interior surface of the building envelope.

The application of PCM for passive cooling purposes under warm temperature climates (Köppen Geiger classification (C)) was investigated numerically more than other climates and considerable cooling energy savings were shown, however, in heating dominant climates the melting point temperature of PCM should be optimized in order to achieve higher total annual savings.

In addition, the importance of coupling the PCM passive system with natural night ventilation to enhance the PCM performance is highlighted by many researchers; however, literature reviews indicated that there was no detailed analysis of such system using more sophisticated numerical methods and it was limited to the simple analysis methods. More interestingly, the whole-building energy simulation tools have been used to investigate the effectiveness of PCM in reducing the urban heat island and extreme summer heat waves. In addition, the application of PCM to enhance the durability and effectiveness of cool roof elements was suggested and investigated recently.

Furthermore, many researchers used a parametric method to find out the best PCM solution, however, the numerical optimization of PCM-enhanced passive buildings is getting more popular.

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