Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions

Paula Marin[1], Mohammad Saffari[2], Alvaro de Gracia[3], Xibingyan Zhu [4], Mohammed M. Farid[4], Luisa F. Cabeza[2], Svetlana Ushak[1,5*]
[1] Department of Chemical Engineering and Minerals Processes, and Center for Advanced Study of Lithium and Industrial Minerals (CELiMIN), Universidad de Antofagasta, Campus Coloso, Av.Universidad de Antofagasta, 02800 Antofagasta, Chile
[2] GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001, Lleida, Spain.
[3] Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili, Av. Paisos Catalans 26, 43007 Tarragona, Spain
[4] Department of Chemical and Materials Engineering. The University of Auckland, Auckland, New Zealand
[5] Solar Energy Research Center (SERC-Chile), Av Tupper 2007, Piso 4, Santiago, Chile
*Corresponding author e-mail: svetlana.ushak@uantof.cl

Abstract

Relocatable, transportable or off-site constructed lightweight buildings typically undergo sharp indoor temperature fluctuations in the heating and cooling seasons due to the lack of sufficient thermal mass in their envelopes, resulting in high energy consumption to provide the zone with comfort temperature. The application of phase change materials has been suggested as a promising solution to control the indoor thermal condition in buildings. This work is an attempt to support the application of PCM technology in lightweight relocatable buildings as a passive alternative to save energy under different weather conditions. The numerical results highlighted the potential of using PCM-enhanced gypsum boards in lightweight buildings to increase the energy performance during both heating and cooling seasons in arid and warm temperate main climate areas.

Keywords: Thermal energy storage (TES); phase change material (PCM); passive heating and cooling; simulation; energy efficiency; relocatable building; weather conditions.

1. Introduction

More than one-third of the global energy consumption comes from the building sector (residential and commercial) [1] which is estimated to 20-40% of the total final energy consumption in developed countries [2]. It also accounts for about 8% for direct energy-related CO_2 emissions from final energy consumers [3]. It is expected that without applying any energy efficient solutions, global energy demand will increase by 50 % in 2050 [4].

Improving the building envelope is considered as an appropriate design solution for reducing the space heating and cooling energy consumption and increasing the thermal comfort [5,6]. In buildings, a major part of the energy is consumed by the air conditioning system, on this basis, several technologies have been developed to decrease the energy consumption and to maintain the thermal comfort of occupants. Examples of such technologies are insulation materials [7], development of heat insulation solar glasses [8], double-glazed window reversible systems [9], use of hybrid wall integrated with heat collectors, and solar thermal power generators [10]. Enhancing the building envelopes with thermal insulation has been extensively used as a basic strategy to diminish the heat dissipation from the building environment to the outdoor environment specifically in lightweight buildings [11]. However, major factors affecting the long-term performance of lightweight buildings correspond to the ability to adequately regulate the internal environment since the energy performance in such buildings can be limited because of the overheating problem coming from the high heat gains from internal sources and solar radiation [12,13].

The application of thermal mass has been highlighted as a promising technology for designing high efficient buildings [14–16]. However, traditional thermal mass materials (bricks, stone, etc.) are not appropriate choices for relocatable lightweight buildings since, on one hand, their transportation and implementation would not be feasible due to their massiveness, and on the other hand, they occupy more space because of their higher volume. The building envelope regulates the heat exchange between outdoor and indoor environments and highly affects the energy requirements and comfort of the occupants, besides, it has a high potential to be integrated with new building materials and systems.

Thermal energy storage (TES) systems can create a balance between diurnal and nocturnal energy demand using latent heat thermal energy storage [17]. A considerable amount of literature has been published on the application of phase change material (PCM) in buildings [18–21]. Further on, a great effort has been made by Cabeza et al. [19] and Barreneche et al. [22] in recent years to classify PCM for thermal energy storage (TES) in buildings. The PCM is distinguished from typical thermal mass materials because of its capability to store higher amounts of energy in small temperature interval due to its high heat of fusion [23]. PCM is a unique alternative to improve the energy efficiency and thermal comfort in buildings [24–28].

PCM can be incorporated into building construction materials in different ways to provide passive cooling and heating; such as, gypsum plasterboard with microencapsulated paraffin [29] which is a promising solution to enhance thermal capacity of lightweight buildings, plaster with microencapsulated paraffin [30] that could be applied on the surface of the walls, concrete with microencapsulated paraffin [31], shape-stabilized paraffin panels [32], PCM bricks [33], and wood with PCM [34]. Additionally, the PCM has vast applications for building components such as slabs [35], floors [36], blinds and windows [37-39].

For example, Cabeza el al. [31] experimentally investigated the impact of using microencapsulated PCM in concrete walls to improve the thermal performance of a concrete building. It was shown that the indoor temperature of the PCM-enhanced concrete building was 1 ºC lower than the reference building without PCM inclusion, also, the maximum temperature in the PCM-enhanced wall was shifted two hours. In addition, it was shown by Lee et al. [40] that the integration of a thin PCM layer into the residential building walls can moderate the temperature and heat flux fluctuations. The experimental results showed 30-50% of peak heat flux reductions, 2 to 6 hours delay in peak heat flux, and the maximum daily heat transfer reductions were estimated as 3-27%. Besides, through an optimization-based simulation Soares et al. [13] found that the application of PCM drywalls in lightweight steel-framed buildings can improve the energy efficiency of buildings by 10-60% depending on the climate zone.

The PCM passive system (passive cooling and heating) is a sustainable solution to improve the comfort quality and the energy performance by reducing the cooling and heating demands in lightweight buildings. Passive cooling plays an important role in the sustainable development of the building industry [41–43].

Off-site constructed buildings such as prefabricated lightweight buildings came into practice as an alternative to the on-site method in order to manufacture and preassemble building elements, components or modules before being installed in the building site [44]. Off-site construction is often referred as a modern method of construction which is more environmentally friendly since repeatable performance, minimal waste and high levels of quality can be guaranteed [45]. Other advantages associated with such buildings are rapid construction, minimal handling and lower need for resources which have led to growth of pre-fabricated (off-site) construction [41,45].

Portable, relocatable or transportable buildings are those which could be easily moved and relocated. They may be modular (made up of a number of modules) or single volumes (where there are transported as complete buildings) [46]. Such types of buildings are feasible alternatives for mining camps (Figure 1), rapid post-disaster sheltering in regions with high vulnerability to natural disasters [47], refugee camps, temporary accommodation, and also they could be used in developing countries where there are problems of house delivery due to the lack of skill and housing quality [48]. Lightweight pre-fabricated buildings could be delivered to the job site at any time of the year and any place (on the mountains for example) regardless of the weather condition. As already mentioned herein, overheating or overcooling problems of the indoor environment is the main challenge in such buildings [49] due to their lightweight nature where high cooling and heating loads might be imposed to the HVAC system. Thermally enhancing the envelopes of these buildings using PCM could be an innovative solution to overcome the uncomfortable indoor condition in these buildings considering that a poor-conditioned zone may negatively affect the occupants and may cause sick building syndrome [50].

Figure 1. Fully self-sufficient mining camp for workers [46].

With this knowledge the authors would like to address the high energy consumption in Chile. The mining industry is a major consumer of energy and electricity in Chile. This country is the world largest producer and exporter of copper and it consumes 11% of the total country energy use, 32% of total electricity and 6% of total fuel [51]. These mining camps have their own residential, medical, leisure and sport areas which are built of single or modular prefabricated lightweight buildings such as the modular pre-fabricated construction. Also, the development of new mining projects demand the installation of temporary camps with this type of construction, such as Escondida mine located in the desert of Atacama, with the altitude of 3100 meters and a capacity of inhabiting more than 5500 persons which was constructed in only 8 months (Figure 2) [52,53].

Figure 2. Escondida mining camp [52,53].

In the extreme summer and winter weather conditions these buildings (modular or single) consume a huge amount of energy for air conditioning purposes both in cooling and heating season, especially in regions with high altitudes because of high irradiance all over the year. Due to this reason, PCM-based passive cooling and heating system can play an important role to control the air quality in these lightweight residential buildings. Further on, if sufficient energy saving is attained in such rapidly-built buildings the payback period of the PCM technology is feasible [5]. In the literature, little attention has been paid to such buildings despite to their wide-range application. For this sake, in the present paper, the feasibility of reducing the HVAC energy consumption and the extreme indoor temperature fluctuations in relocatable lightweight buildings will be studied numerically in major Chilean climates for both cooling and heating periods. Moreover, the thermal performance of such buildings will be investigated under other climate conditions.

2. Methodology

2.1.Building energy simulation

The heat transfer in the building envelope is a complex phenomenon. Indoor and outdoor conditions highly influence the thermal comfort and the energy performance in buildings especially when the PCM is incorporated into the building envelope. Building performance simulation gives us the possibility of evaluating a wide range of scenarios to enhance the building energy performance and the indoor thermal comfort [54]. Further on, it is the cheapest and the fastest way to analyze the effects of different architectural designs, innovative building materials, control strategies, etc. on the energy performance and the indoor air quality of buildings; otherwise, constructing different building prototypes without early-stage design would be expensive and time-consuming.

A significant number of studies have been published on the building energy modeling [55]. Several building and system energy simulation tools have been developed to assist engineers and policy makers to implement their energy-efficient scenarios [56];

nonetheless, there are few building energy simulation programs which can simulate the impacts of the PCM technology on the heating, cooling and air conditioning quality of buildings [57]. EnergyPlus [58–61] and TRNSYS [62–64] are extensively used for the PCM modeling in buildings. Due to distinguished capabilities of EnergyPlus building energy simulation software [43], it has been chosen in the present study.

2.2.Numerical model

The numerical simulations were carried out using EnergyPlus v8.1 dynamic building energy simulation software [58–60]. In EnergyPlus, PCM can be simulated by using a Conduction Finite Difference (CondFD) solution algorithm which discretizes the building envelope into different nodes and numerically solves the heat transfer equations using a finite difference method (FDM) which could be selected between Crank-Nicolson or fully implicit [65,66]. In the present study, the fully implicit discretization has been used.

To simulate PCM and to consider the specific heat change due to phase change process, the CondFD method is coupled with an enthalpy-temperature function which reads the user inputs of enthalpies at different temperatures [61]. Then, the enthalpies in each node get updated in each iteration, and then they are used to develop an equivalent specific heat C_p at each time step. This model is a modified version of the enthalpy method which was developed by Pedersen [61,67].

In order to ensure the accuracy of the CondFD model and the simulation, the time step of the simulation was set to one minute and the space discretization was set to 3 [67]. Additionally, PCMs with strong hysteresis cannot be accurately simulated, so that, a PCM with negligible hysteresis should be used to achieve acceptable results [67].

2.3.Validation

The PCM and CondFD models of EnergyPlus were verified and validated against different test suites by Tabares-Velasco et al. [67,68], which consist of analytical verification, comparative testing, and empirical validation [31]. In addition, PCM algorithm of EnergyPlus was validated against experimental data by other researchers [69–71]. The CondFD solution and PCM algorithms of EnergyPlus were verified and validated against analytical verification (Stefan problem), comparative testing (against Heating v7.3) and empirical validation (DuPont Hotbox) by Tabares-Velasco et al. [67,68]. Moreover, the EnergyPlus PCM model was validated [72,73] against the experimental data of Kuznik and Virgone [71] where strong agreement was achieved between the experimental data and the numerical simulation results for zone air temperature. Additionally, the EnergyPlus simulation model was validated against field data by other researchers [74–77] and good consistency between the numerical simulation and the experimental data was shown from their results.

2.4. Building model

A single-zone building prototype with 5.76 m^2 of floor area (2.4 m width × 2.4 m length × 2.4 m height) with no internal partitions and 1 m^2 (1 m width × 1 m height) of glazing and 1.6 m^2 (0.8 m width × 2 m height) of door located on the north wall, has been selected which is very similar to transportable or relocatable buildings (Figure 3). Additionally, it is supposed that all exterior walls and roof are exposed to the outdoor environment and colored in grey to enhance the solar absorptivity, and the exterior floor is separated from the ground. The building model is considered as a residential living space. To investigate the effects of PCM on the heating and cooling energy performances and the thermal comfort, two building prototypes have been considered. A reference model without PCM inclusion is compared to another one with PCM incorporated into its envelopes. The PCM plasterboard (Knauf comfortboard) [78] filled with about 18% of Micronal® PCM microcapsules was installed on the interior surfaces of the exterior walls and the roof enclosure. The physical properties of the utilized PCM are listed in Table 1.

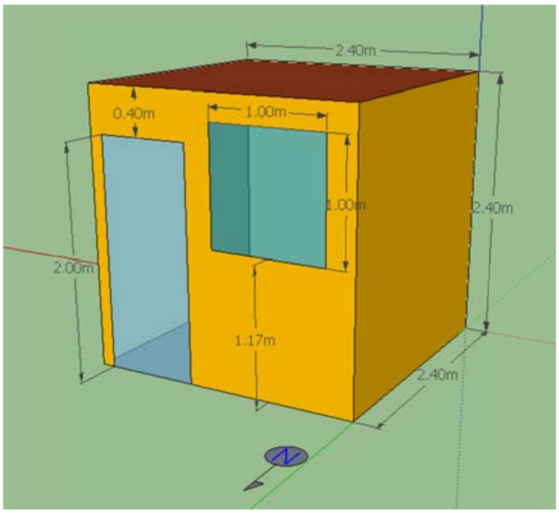

Figure 3. Building model geometry.

Table 1. Properties of Knauf comfortboard as provided by the manufacturer [78].

Thickness	0.0125 [m]
Peak melting temperature	25 [°C]
Thermal conductivity	0.23 [W/m·K]
Latent heat capacity	200 [kJ/m^2]
Specific heat capacity	13 [kJ/m^2·K]
Density	800 [kg/m^3]
Specific heat	1625 [J/kg·K]

The construction details of the lightweight building model as well as the thermophysical properties of the used materials are shown in Tables 2 to 4.

Table 2. Exterior walls and roof construction

Material	d [m]	λ [W/m·K]	ρ [kg/m^3]	C_p [J/kg·K]
Galvanized steel	0.008	40	7824	500
Insulation	0.04	0.038	32	835
PCM gypsum board	0.0125	0.23	800	1625

Table 3. Door and floor construction

Material	d [m]	λ [W/m·K]	ρ [kg/m^3]	C_p [J/kg·K]
Plywood door	0.04	0.12	510	1380
Plywood floor	0.018	0.12	510	1380

Table 4. Window construction.

Optical data type	Spectral Average
Thickness [m]	0.003
Solar Transmittance at Normal Incidence	0.837
Front Side Solar Reflectance at Normal Incidence	0.075
Back Side Solar Reflectance at Normal Incidence	0.075
Visible Transmittance at Normal Incidence	0.898
Front Side Visible Reflectance at Normal Incidence	0.081
Back Side Visible Reflectance at Normal Incidence	0.081
Infrared Transmittance at Normal Incidence	0
Front Side Infrared Hemispherical Emissivity	0.84
Back Side Infrared Hemispherical Emissivity	0.84
Thermal conductivity [W/m·K]	0.9

2.5. Air conditioning system

A packaged terminal heat pump (PTHP) (Figure 4) with an electric supplemental heating coil was selected to provide air conditioning to the building zone. This type of air conditioning system is commonly used in relocatable buildings [79]. The PTHP is a compound component made up of an outdoor air mixer, direct expansion (DX) cooling coil, DX heating coil, supply air fan, and a supplementary electric heating coil [65]. The supply fan total efficiency and motor efficiency are 0.7 and 0.9, respectively. Furthermore, the cooling coil has an Energy Efficiency Ratio (EER) of 2.52 (Wh) and the heat pump heating coil gross rated coefficient of performance (COP) is 2.75 as recommended by ASHRAE 90.1 standard [80]. Also, it should be added that the HVAC system operates 24-hours per day throughout the year.

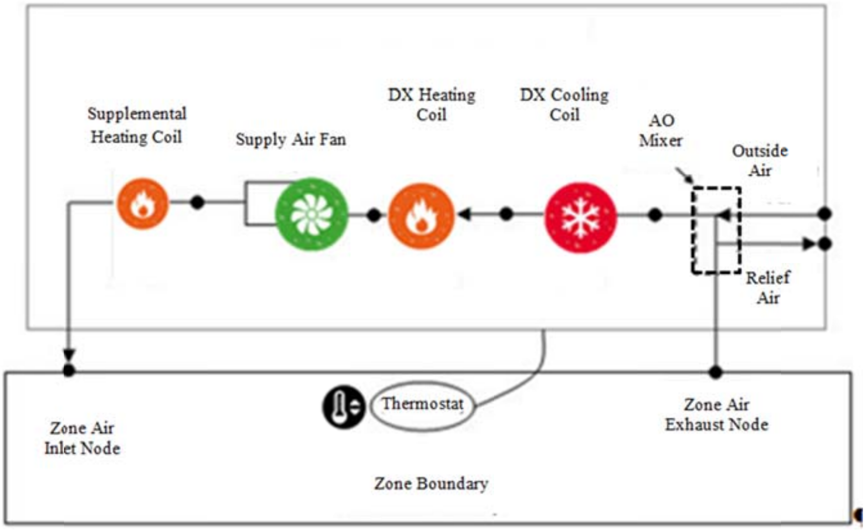

Figure 4. PTHP with supplemental electric heating coil, adopted from [65]. Note: DX, direct expansion; OA, outdoor air.

The single-zone building is considered to be a residential space with high thermal comfort (Category I). On this basis, a dual setpoint thermostat with deadband was selected according to the recommended indoor temperatures for energy calculations of BS EN 15251 [81]. Accordingly, the indoor temperature is maintained between 18 ºC for heating and 25 ºC for cooling, during the occupancy period.

2.6. Operational conditions

The impact of climate condition on the energy performance of buildings has been the center of attention of many researchers, notably in buildings with passive PCM system [13,24,82]. In fact, the PCM performance in the buildings is very depended to the weather conditions and geographical location. For instance, a particular type of PCM which has the potential of increasing the cooling energy savings in a specific climate zone, might decrease the cooling energy performance in another climate [83]. Under these circumstances, it seems essential to analyze the energy performance in relocatable buildings due to the incorporation of PCM under different climate conditions and to find out the degree in which the passive PCM solution could be influential. In the current study, the Köppen-Geiger (Figure 5) [84] climate classification was used. 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, and m: monsoonal. Moreover, 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.

The weather data files for building simulations were mostly obtained from the EnergyPlus Weather (EPW) database [85] which includes weather data provided in EnergyPlus format from 20 sources [86]. However, in the case of Calama, in situ measurements were used. Table 5 presents a summary of the studied climates.

Table 5. Selected locations and climate characteristics according to Köppen Geiger classification.

Köppen climate	City	Latitude	Longitude	Time zone* (GMT)	Elevation [m]	Annual CDD base 10 ºC	Annual HDD base 18 ºC
Aw	Brasilia	S 15° 52'	W 47° 55'	-3.0	1061	4207	8
Af	Kuala Lumpur	N 3° 7'	E 101° 33'	8.0	22	6262	0
Af	Singapore	N 1° 22'	E 103° 58'	8.0	16	6374	0
BSk	Albuquerque	N 35° 2'	W 106° 37'	-7.0	1619	2157	2303
BSk	Mexico	N 19° 25'	W 99° 4'	-6.0	2234	2503	547
BSh	New Delhi	N 28° 34'	E 77° 11'	+5.5	216	5363	278
BWh	Abu Dhabi	N 24° 25'	E 54° 39'	+4.0	27	6254	24
BWk	Calama	S 22° 50'	W 68° 90'	-4.0	2312	2109	1919
Cfa	Brisbane	S 27° 22'	E 153° 6'	+10.0	5	3652	329
Cfa	Madrid	N 40° 27'	W 3° 32'	+1.0	582	2057	1965
Cfa	Tokyo	N 36° 10'	E 140° 25'	+9.0	35	1911	2311
Cfb	Berlin	N 52°	E 13° 23'	+1.0	49	1125	3156

		28'					
Cfb	Johannesburg	S 26° 7'	E 28° 13'	+2.0	1700	2216	1052
Csb	Antofagasta	S 23° 25'	W 70° 25'	-4.0	120	2557	598
Csb	Auckland	S 37° 1'	E 174° 48'	+12.0	6	1909	1163
Csb	Bogota	N 4° 41'	W 74° 7'	-5.0	2548	1165	1755
Csb	Concepción	S 36° 46'	W 73° 3'	-4.0	16	1207	1843
Csb	Quito	S 0° 9'	W 78° 28'	-5.0	2812	1366	1554
Csb	San Francisco	N 37° 37'	W 122° 24'	-8.0	2	1681	1504
Csb	Santiago de Chile	S 33° 22'	W 70° 46'	-4.0	476	1784	1570
Dfa	Chicago	N 41° 46'	W 87° 45'	-6.0	186	1964	3106
Dfb	Montreal	N 45° 28'	W 73° 45'	-5.0	36	1185	4493
Dfb	Moscow	N 55° 45'	E 37° 37'	+3.0	156	862	4655
Dfb	Stockholm	N 59° 39'	E 17° 57'	+1.0	61	683	4239
Dwa	Beijing	N 39° 47'	E 116° 28'	+8.0	32	2321	2750

NB: *Hours from universal coordinated time. *CDD, cooling degree days; HDD, heating degree days.

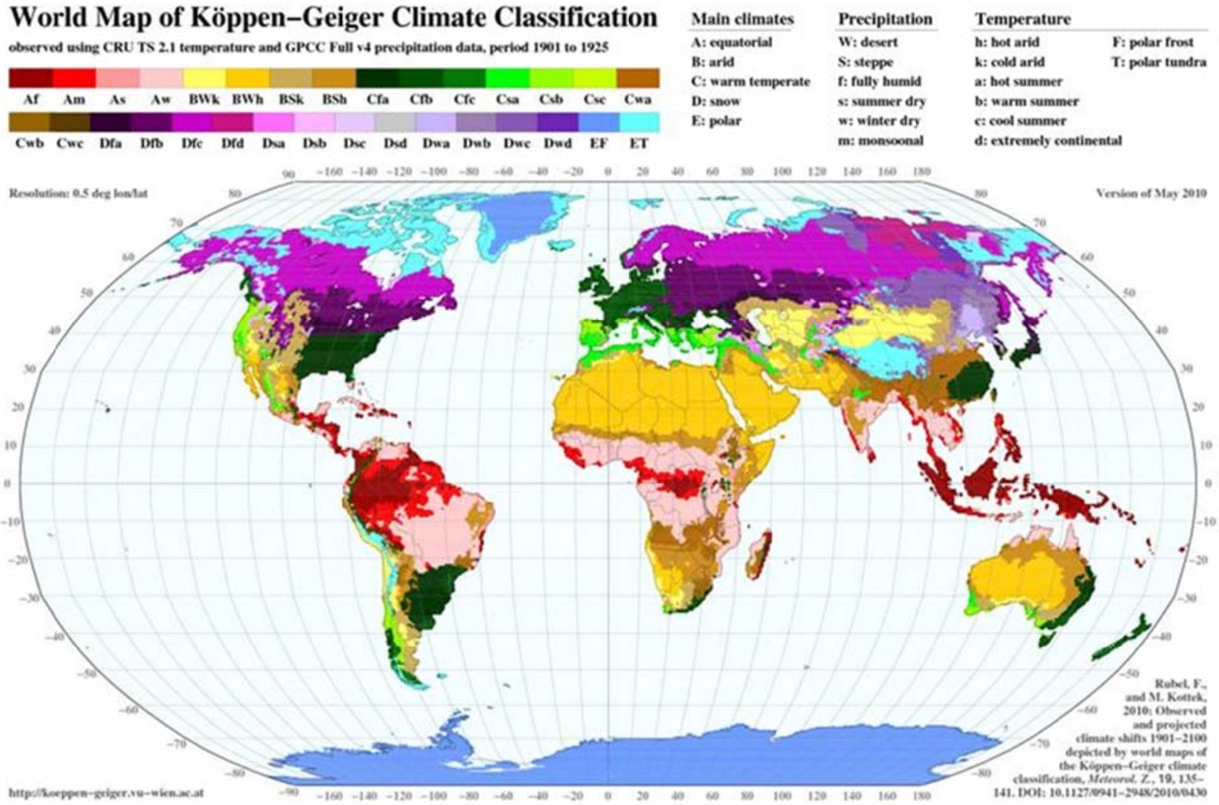

Figure 5.World Map of Köppen–Geiger climate classification [27].

3. Results and discussion

3.1 Thermal response under controlled temperature conditions

The annual overall electrical energy consumed for heating and cooling of the studied building model and the achieved electrical savings due to the use of PCM in the building envelope are shown in Figure 6 for each analyzed city. Results show that the inclusion of PCM has a significant potential in arid (B) and warm temperate (C) main climate areas, except in Tokyo (Cfa) and Berlin (Cfb), where PCM does not provide any energy benefit. On the other hand, in equatorial (A) and snow (D) main climates the inclusion of PCM has negligible impact, with the exception of Brasilia, which corresponds to equatorial main climate and presents a 49% of energy consumption reduction due to the use of PCM.

The highest energy savings achieved due to the use of PCM are found in Calama (BWk), Johannesburg (Cfb), Santiago de Chile (Csb) and Mexico DF (BSk) presenting 271, 169, 155 and 150 kWh of reduction per year, respectively. These cities achieve this high reduction because the PCM is able to reduce significantly the HVAC consumption during both heating and cooling periods, as shown in Figure 7.

On the other hand, there are cities that provide significant benefits due to the use of PCM but limited to one period, either heating or cooling seasons. The melting temperature of the used PCM (25ºC) is appropriate to reduce both heating and cooling loads, however, it could be the case that in certain locations, it would be more beneficial to select the PCM melting temperature to reduce either heating and cooling loads instead of trying to reduce both. Within this context, Bogota and Quito (both Csb) presented high potential for energy consumption reduction for heating, being able to achieve a yearly reduction of 85 and 57 kWh, respectively, as they can only reduce 25 and 13 kWh the electrical consumption during the cooling season. This indicates that the melting temperature of the PCM might have not been well selected in those cities, since a PCM with lower melting temperature would even maximize the benefits during heating season. On the other hand, Brasilia (Aw) and Brisbane (Cfa) could reduce significantly the cooling loads, achieving energy reductions of 114 and 85 kWh, while the load reduction during heating period is limited to values around 40 kWh, which indicates that a PCM with higher melting point would maximize the benefits during the cooling period, and might increase the economic benefits. Moreover, there are some cases, especially in arid areas, in which the heating demand is very limited, and hence there is a weak potential for its reduction, such as, Albuquerque (BsK) and Abu Dhabi (BWh). In these cases, as well as for Brasilia and Brisbane, a PCM with higher melting temperature would lead to higher benefits.

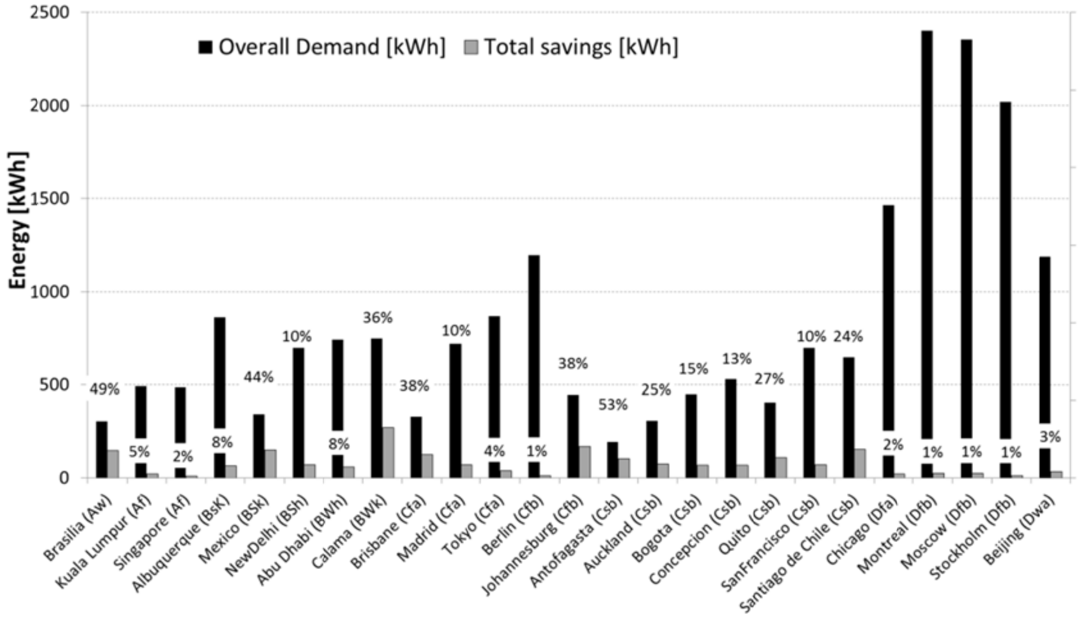

Figure 6.Overall yearly demand and total energy savings for each analyzed city

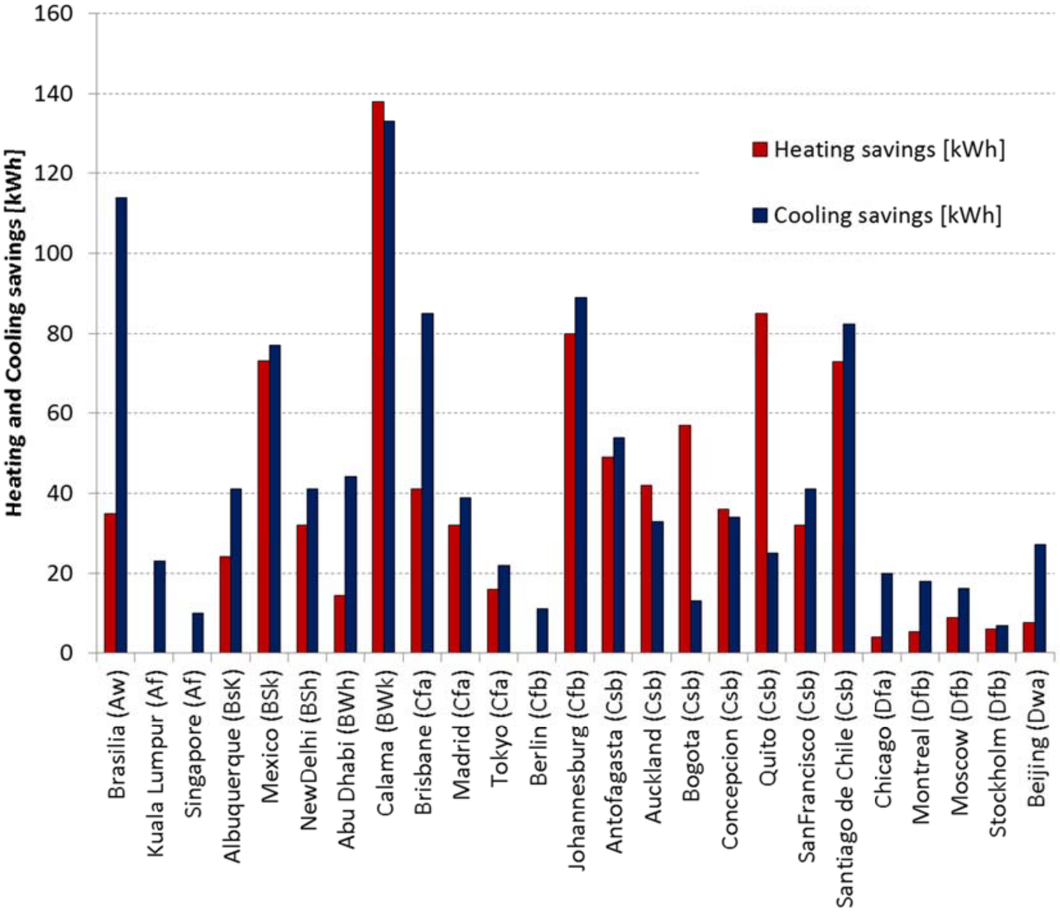

Figure 7. Annual heating and cooling energy consumption reduction in each analyzed city.

As shown in Figure 8, Calama (BWk) is the analyzed city which achieves the highest reduction both for heating and cooling period. The arid conditions achieved due to its high altitude (2312 m) makes necessary the use of cooling and heating during the whole year. Furthermore, the high thermal gradients achieved during both, winter and summer periods, makes suitable the use of PCM in the building envelope in the Atacama Desert climate conditions. As it can be seen in Figure 8, there is a cooling and heating demand during the whole year (temperature would be higher than 25ºC and lower than 18ºC in case of not having any HVAC system) and the inclusion of PCM can reduce effectively both loads during each season. For instance, during winter, the lightweight building without PCM requires cooling at around 11:00, the use of PCM delays significantly this load until (14:00 or 17:00 depending on the day), which reports significant reduction on energy consumption for cooling. Moreover, in winter, a heating supply is required at nighttime, which is significantly delayed due to the use of PCM. Similar trends can be found in spring, summer and autumn, which lead to important energy savings during the whole year as shown in Figure 9. Thus, highlights the potential of the PCM of reducing both heating and cooling loads during the whole year in this kind of extremely lightweight buildings.

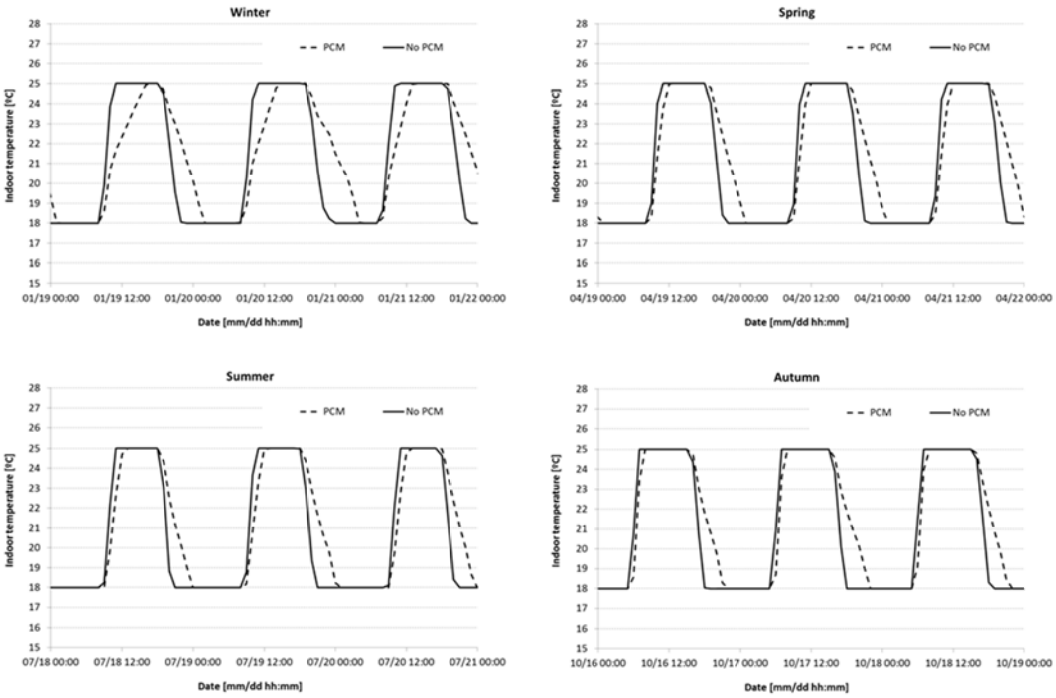

Figure 8. Indoor temperature in case with and without PCM in Calama (BWk) during each season.

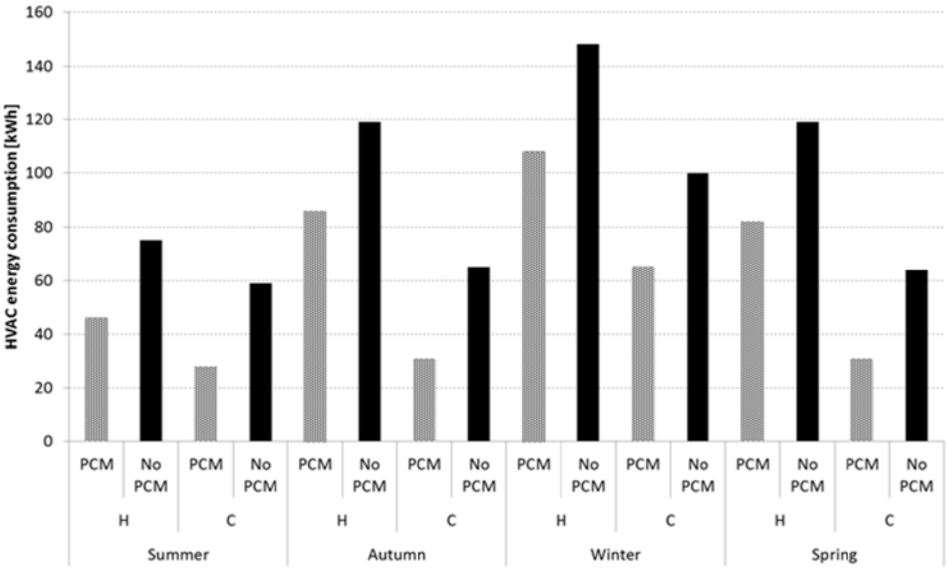

Figure 9. Energy consumption for heating and cooling during each season in Calama.

3.2 Thermal response under free floating conditions

As it was previously stated, the aim of the paper is to test the impact of using PCM in the envelopes of lightweight relocatable buildings. In section 3.1 the results presented the influence of PCM in the energy consumption of the installed HVAC of this sort of buildings, however, the relocatable nature of the buildings could imply the absence of any HVAC system (naturally ventilated buildings) [87]. Within this context, it is important to determine how the inclusion of PCM can provide benefits in the performance of the building in case there is no HVAC. In this case, same dual set-point used in the controlled temperature simulations are used to define the upper and lower limits of the comfort range, 25ºC and 18ºC respectively [24].

Figure 10 shows the influence of PCM in the time that the indoor temperature of the building is inside comfort range for each analyzed climate conditions. There is a clear positive effect of using PCM in all cities, except in Kuala Lumpur and Singapore, both tropical areas, in which the use of PCM reduces the amount of yearly hours inside comfort range. Moreover, as occurred in the case of controlled temperature cases, there is a limited potential in snow main climate areas (D according to Köppen-Geiger classification [23]). Figure 10 also highlights that the lightweight nature of the buildings, makes that the indoor temperature is only inside comfort conditions between

10-30% of the time in case of not using PCM depending on the climate. The use of PCM improves significantly the performance of the buildings in most of the analyzed climates; however, there is still an important period when indoor temperature is out of comfort conditions, which has to be taken into consideration for engineers and architects involved in the design of this sort of buildings when used without HVAC systems.

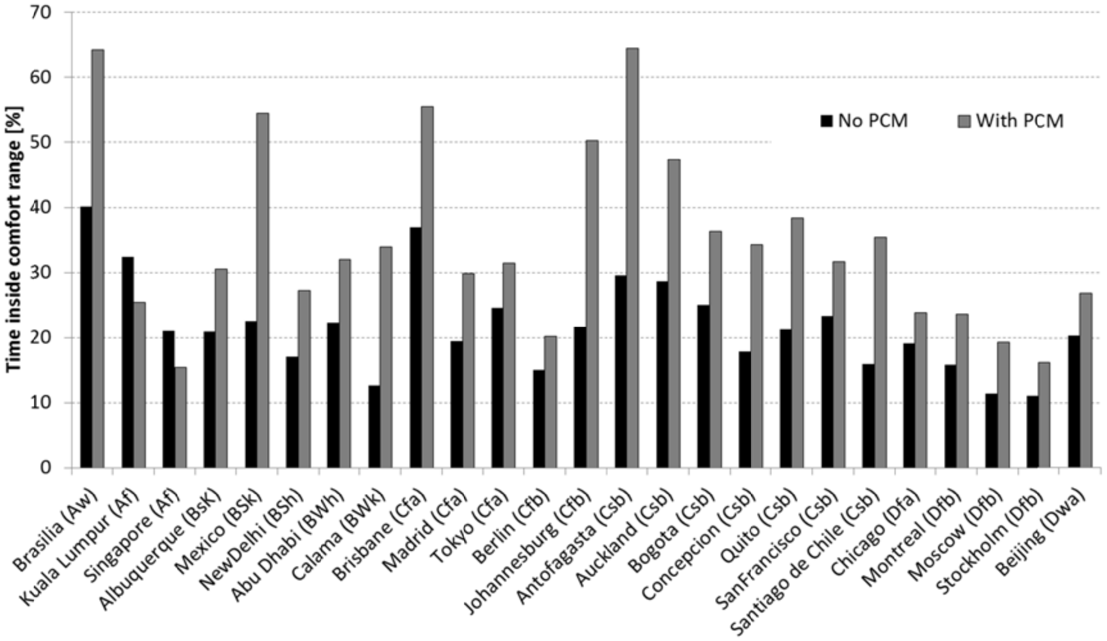

Figure 10. Annual percentage of time inside comfort conditions with and without PCM.

4. Conclusions

This study intends to support the application of PCM technology in lightweight building as a passive alternative to save energy and evaluates its influence on the building energy performance under different weather conditions. Moreover, the use of numerical models provides a faster tool to evaluate the applicability of specific technologies and/or materials in the building sector regarding to each specific boundaries such as weather conditions and energy requirements.

The numerical results presented in this study highlight the potential of energy consumption reduction due to the implementation of PCM in the gypsum board used in the lightweight building envelopes both for heating and cooling periods in arid and warm temperate main climate areas. On the other hand, the potential of energy reduction is very limited in tropical and snow main climate areas. The PCM implemented in the gypsum board used in the envelopes presents a melting point of 25ºC, which allows achieving important reductions of energy consumption for heating and cooling in several weather conditions. Furthermore, it was noticed that the PCM used in certain cities should have been selected with a lower or higher melting point and hence focus its performance of heating or cooling reduction, respectively. Within this context the authors identify as a future work, the optimization of the PCM melting temperature depending on the weather conditions, which could lead to maximize the benefits, as well as opening the possibility of having benefits in areas in which they were not achieved with the studied PCM (25 ºC) such as tropical and snow main climate areas.

The impact of using PCM in the building envelopes is maximized when applied to extremely lightweight buildings, as the one used in this research. Application of the gypsum board with PCM in other buildings with more thermal mass would provide less energy savings than the highlighted in the analyzed relocatable lightweight building.

Throughout the use of computational software now it is possible to evaluate several weather conditions at the same time. This means that now it is possible to assess several materials using their thermal properties and have a better idea about the thermal material performance. The previous evaluation of building materials with thermal properties, such as PCM could provide substantial evidence about the economic and environmental improvements, in terms to persuade potential implementations that are currently discarded because of their high cost of production.

Acknowledgements

The authors acknowledge to CONICYT/FONDAP Nº 15110019. This work has been partially funded by the Spanish government (ENE2015-64117-C5-1-R (MINECO/FEDER) and ENE2015-64117-C5-3-R (MINECO/FEDER)). The authors would like to thank the Catalan Government for the quality accreditation given to their research group (2014 SGR 123). The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° PIRSES-GA-2013-610692 (INNOSTORAGE) and from the European Union's Horizon 2020 research and innovation programme under grant agreement No 657466 (INPATH-TES). Alvaro de Gracia would like to thank Ministerio de Economía y Competitividad de España for Grant Juan de la Cierva, FJCI-2014-19940. Paula Marin thanks fellowship CONICYT-PCHA/doctorado nacional/2015-21151359.

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