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Research Article

Energy Efficiency in Buildings: Numerical Study of the Impact of Integrating Phase Change Materials Into the Walls

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Abstract. In order to improve the energy efficiency of lightweight envelopes, the solar energy storage using Phase Change Materials (PCMs) integrated into the walls is suggested as a passive solution, since PCMs are considered as one of the best materials for storing or releasing thermal heat as latent energy. For this specific reason a comparative study between structures with and without PCM has been developed to highlight the actual impact of the thickness, location and type of the PCM layer on the thermal behavior inside buildings and their impact on electricity consumption. An ASHRAE benchmark cases were chosen to validate the model. This numerical study was performed out using the "EnergyPlus V 9.0.1" building thermal simulation software, which accurately predicts the building's temperature, humidity and energy consumption profiles as well as several other parameters.

Keywords. Energy efficiency; Energy building; Zonal method; Phase change material; EnergyPlus; Conduction transfer function; Thermal Energy Storage (TES)

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1. Introduction

The high energy consumption and the industrial development during the recent years results in a growing Global energy demand and a decline of natural energy resources such as gas and oil. Primary energy consumption in Morocco follows the same global trend. Dominated

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by oil, it continued to grow almost exponentially between 1971 and 2016 [6]. The *total final consumption* (TFC) in 2016 increased five times compared to 1990, from 3.02 million tons of oil equivalent (Mtoe) in 1990 to 15.37 Mtoe in 2016.

The production of energy based on hydrocarbons, reduces available reserves, and pollutes our planet. Millions of tons of greenhouse gases are released into the atmosphere every year.The impact of fossil fuels on CO_2 emissions has increased over the last 26 years in Morocco, exceeding 55.37 million tons in 2015 [1, 4], however, one year later, CO_2 emissions decreased by about 70,000 tons after organizing the COP 22 conference in Marrakech [4].

As a result of such environmental challenges, humanity has been forced to reduce the consumption of carbon fuels without compromising the capacity of coming generations, by exploiting renewable energy sources, or even by changing our attitudes and reducing the quantity of energy we consume.

In the residential sector, vast amounts of energy are used for air-conditioning and released outside due to heat loss. Therefore, one of the solutions to reduce losses is to enhance the energy efficiency of buildings by improving their thermal insulation.

One feasible solution is the use of complex walls composed of a certain combination material. These walls are characterized by coupled physical phenomena such as thermal, aeraulic and hydric. In addition, their configuration allows the integration of insulating materials, such as *Phase Change Materials* (PCM).

PCMs are used to maintain an area within the thermal comfort level by controlling the temperature variation. They reduce the energy transfer in the wall by storing a part of the solar thermal energy as latent heat. The principle of the PCM is based on storing energy when it melts and then releasing it when it solidifies. The melting process occurs during daylight hours when the outdoor temperature is higher than the PCM's melting temperature range.Likewise, PCM solidification occurs overnight when the outdoor ambient temperature is less than the PCM's temperature melting range. Thus, when PCM is integrated into the building walls, the building's heat storage capacity increases and improves the interior thermal behavior. Consequently, it reduces the energy required for space cooling and heating, saving money as well as reducing CO_2 emissions.

PCMs can be integrated into almost every element of a building envelope. However, the most common methods are: inside walls, ceilings, floors, roofs, or into windows, through easy installation and for more efficient heat transfer [18].

Numerous studies have shown significant benefits related to thermal comfort, energy savings and reducing the activity of *Heating, Ventilation & Air-Conditioning* (HVAC) systems, when PCMs are integrated into buildings [21]. These benefits are obtained through appropriate design and a good selection of the PCMs.

Memon *et al*. [9] have performed a small-scale experiment on concrete containing paraffin macro-encapsulation for wall application. The results showed that the encapsulation reduced the interior room and panel surface temperatures by 4.7 °C and 7.5 °C, respectively. In addition, a 2.9 °C reduction in the interior temperature was observed in the prototype during the 10-day test.

Shi *et al*. [14] have studied the performance of macro-encapsulated PCMs embedded in wall concrete in Hong Kong's climate. The experimental results revealed that air temperature as well as indoor humidity levels were affected by the PCM, but that their effectiveness was highly dependent on the position of the PCM installed in the walls.

Zhong *et al*. [20] have performed an experimental work to investigate the thermal transfer efficiency in a window's glass containing PCM during summer days in China. The heat flow and temperature on the inner sides of the window filled with paraffin (PCMW) and without PCM (HW) were measured. The experimental resultsshowed that the maximum temperatures on the inner sides of the HW window were 2.6 °C to 2 °C greater than those of the PCMW; similarly, the maximum temperature was shifted by 2 h and 3 h during sunny and rainy summer days, respectively, which reduced the heat entering the building by approximately 18.3%.

Li *et al*. [8] have performed a numerical study to compare the thermal performance of different roofs integrating PCM for an habitat in China. The simulation results showed that the maximum roof temperature (with PCM) was shifted by 3 hours.

Saffari *et al*. [12] studied the effect of PCMs with different melting temperatures and thicknesses on the *heating, ventilation and air-conditioning* (HVAC) system of the building in Madrid, Spain. The study showed that PCMs can reduces annual energy consumption by about 10-15%.

Different methods have been adopted to quantify the performance of phase change materials integration into buildings. So far, Multiphysics modelling and full-building simulations have been considered as the best techniques for optimizing and evaluating building performance. In this paper, a numerical heat transfer model was developed using EnergyPlus to simulate PCM enhanced lightweight buildings in Morocco. The investigation has been carried out for the "Case-600 building model" prototype. The effects of some parameters (the emplacement, the melting temperature as well as the thickness of the PCM wallboards) on the energy saving have been studied and discussed for both cooling and heating. The impact of the PCM wall panels on the reduction of air-conditioning energy demand were also investigated.

2. Methodology

Numerical model

This parametric study was carried out using EnergyPlus 9.0.1 [17]. A standard case 600 building model (ASHRAE-140 case-600 ANSI/ASHRAE 2007) [3] was selected for the simulations [5]. As shown in Fig.1, the base test building is a single-zone rectangular case with internal dimensions of 8 m wide, 6 m long, and 2.7 m high [5]. The building has two windows (6 m^2 each) on the south wall, interior loads of 200 W (60% radiative, 40% convective), and a highly insulated slab to essentially eliminate thermal ground coupling [5]. Air infiltration has been regulated to 0.5 air-changes an hour [15]. The mechanical system of the building is an ideal system with a 100% convective air system and 100% efficiency with 0% duct losses and no capacity limitation [15]. The thermostat is adjustedwith a dead point, so heating takes place for temperatures below 20 °C and cooling for temperatures above 27 °C [15]. In this research, six paraffins with melting point ranging from 20-23 °C (PCM1) to 30-33 °C (PCM6) were installed only on the room's walls in two different positions. The position 1 (Figure 2) being the closest layer on the outside while the position 2 (Figure 3) being the closest layer on the inside. The characteristics of the walls, as well as the thermo-physical properties of the PCM are given respectively in Table 1, 2, 3 and 4.

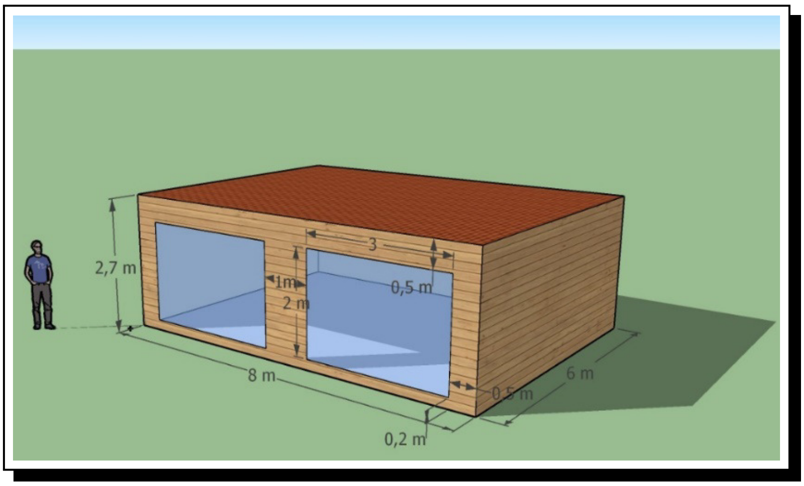

Figure 1. Building model geometry (Case 600)

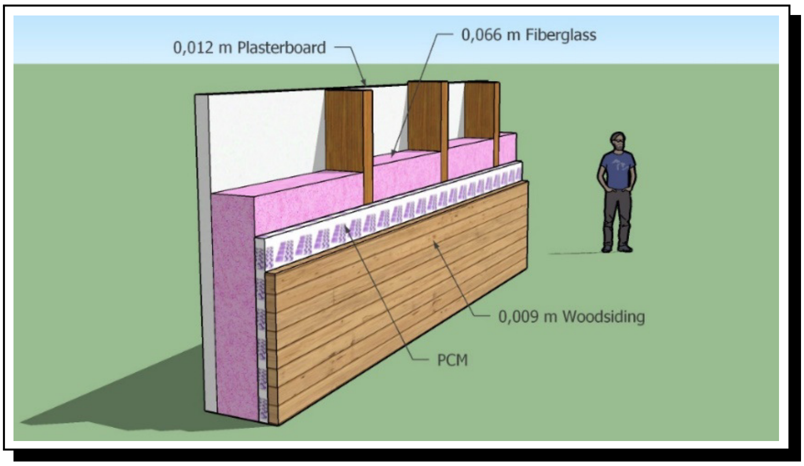

Figure 2. Wall construction materials (PCM in position N°1)

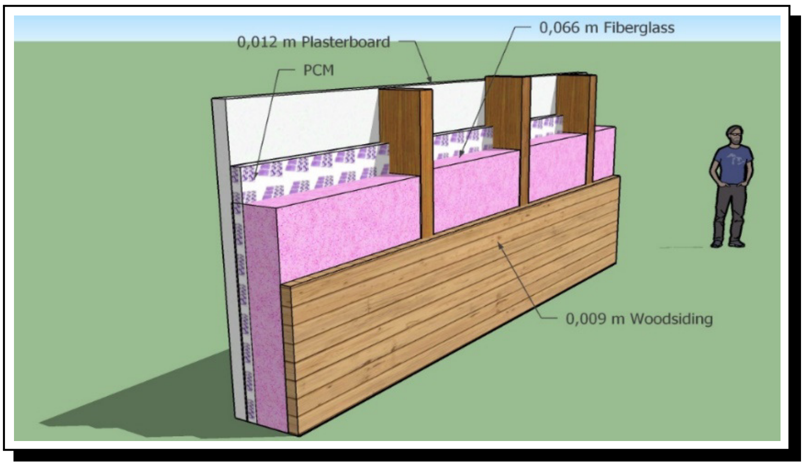

Figure 3. Wall construction materials (PCM in position N°2)

Wall construction:

Table 1. The materials used for the wall construction of the prototype [5]

Element	Conductivity ($Wm^{-1}K^{-1}$)	Thickness (m)	U ($Wm^{-2}K^{-1}$)	Thermal resistance (m^2KW^{-1})	Density capacity (kgm^{-3})	Thermal ($Jkg^{-1}K^{-1}$)
Int. Surface Coeff			8.2900	0.121		
Plasterboard	0.16	0.012	13.333	0.075	950	840
Fiberglass Quilt	0.04	0.066	0.6060	1.650	12	840
Wood Siding	0.14	0.009	15.556	0.064	530	900
Ext. Surface Coeff			29.300	0.034		

Roof construction:

Table 2. The Materials Used for the Roof Construction of the Prototype [5]

Element	Conductivity ($Wm^{-1}K^{-1}$)	Thickness (m)	U ($Wm^{-2}K^{-1}$)	Thermal resistance (m^2KW^{-1})	Density capacity (kgm^{-3})	Thermal ($Jkg^{-1}K^{-1}$)
Int. Surface Coeff			8.29	0.121		
Plasterboard	0.16	0.01	16	0.063	950	840
Fiberglass Quilt	0.04	0.1118	0.358	2.794	12	840
Roof Deck	0.14	0.019	7.368	0.136	530	900
Ext. Surface Coeff			29.3	0.034		

Floor construction:

Table 3. Materials Used for the Floor Construction of the Prototype [5]

Element	Conductivity ($Wm^{-1}K^{-1}$)	Thickness (m)	U ($Wm^{-2}K^{-1}$)	Thermal resistance (m^2KW^{-1})	Density capacity (kgm^{-3})	Thermal ($Jkg^{-1}K^{-1}$)
Int. Surface Coeff			8.29	0.121		
Timber Flooring	0.14	0.025	5.6	0.179	650	1200
Isolation	0.04	1.003	0.04	25.075		

Window Properties:

Extinction coefficient	0.0196/mm	N° of windows	2
Individual glazing conductance	333 $Wm^{-2}K^{-1}$	Individual window thickness	3.175 mm
External surface coeff	21.00 $Wm^{-2}K^{-1}$	Air gap thickness	13 mm
Internal surface coeff	8.29 $Wm^{-2}K^{-1}$	Index of refraction	1.526
Glass conductivity	1.06 $Wm^{-1}K^{-1}$	Glass conductivity	1.06 $Wm^{-1}K^{-1}$
Normal transmission coefficient of the glass pane	0.8615		
Combined Convective and Radiative Coeff of the Gap	6.2969 $Wm^{-2}K^{-1}$		

Table 4. Thermo-Physical Properties Range of All Six Materials [11]

Materials	PCM 1	PCM 2	PCM 3	PCM 4	PCM 5	PCM 6
Specific heat capacity (J/kg K)	1662					
Density (kg/m^3)	942					
Thermal conductivity (W/m K)	0.213					
Milting point [°C]	20-23	21-24	22-25	25-28	26-30	30-33

2.1 EnergyPlus PCM Model

The one-dimensional finite difference conduction solution (CondFD) algorithm was selected to simulate the phase change process, the performance of this algorithm has been underlined by many works including the National Renewable Energy Laboratory (NREL) [16] and also the experimental data of Kuznick and Virgon [2]. The (CondFD) algorithm uses an implicit finite-difference (FD)model combined with an enthalpic function to calculate precisely the energy of the phase change.

$$C_p \rho \Delta x \frac{T_{i,j+1} - T_{i,j}}{\Delta t} = \frac{1}{2}\left(\lambda_{i+1,i}\frac{T_{i+1,j+1} - T_{i,j+1}}{\Delta x} + \lambda_{i-1,i}\frac{T_{i-1,j+1} - T_{i,j+1}}{\Delta x}\right), \tag{2.1}$$

where

$$\lambda_{i+1,i} = \frac{\lambda_{i+1} + \lambda_i}{2}, \quad \lambda_{i-1,i} = \frac{\lambda_{i-1} + \lambda_i}{2},$$

ρ: density (kg/m^3), C_p: specific heat capacity (kJ/kg K), Δx: layer thickness (m), T_i: temperature (K), i: current node under modelling, $i+1$: node next to the inside of the construction, $i-1$: node next to the outside of the construction, λ: thermal conduction coefficient ($kWm^{-1}K^{-1}$), $j+1$: new timestep, j: current timestep, Δt: calculation timestep (s), h: enthalpy (kJ/kg).

For the phase change material and due to the iteration scheme used, the enthalpies of the nodes change with each iteration, so equation (2.1) is coupled to an equation which links enthalpy to temperature (HTF) [7]. Where HTF is the enthalpy-temperature function, it uses the data entered by the user torelate enthalpy and temperature. This function is used to develop a specific heat equivalent to each time step. Therefore, C_p, will be written in the form [7].

$$h_i = \mathrm{HTF}(T_i), \tag{2.2}$$

$$C^j_{p,\mathrm{eq}} = \frac{h_{i,j+1} - h_{i,j}}{T_{i,j+1} - T_{i,j}} = \frac{h_{i,\mathrm{new}} - h_{i,\mathrm{old}}}{T_{i,\mathrm{new}} - T_{i,\mathrm{old}}}. \tag{2.3}$$

2.2 Weather data

The EPW Casablanca Nouasser weather data file [19] was used as Casablanca's, which belongs to the climatic zone number 1. The typical average daily outdoor dry bulb temperatures all year round is given in Figure 4.

The weather files to be used are taken from the EnergyPlus website (`http://www.energyplus.gov`). The meteorological information corresponds to the period between 1983 and 1997.

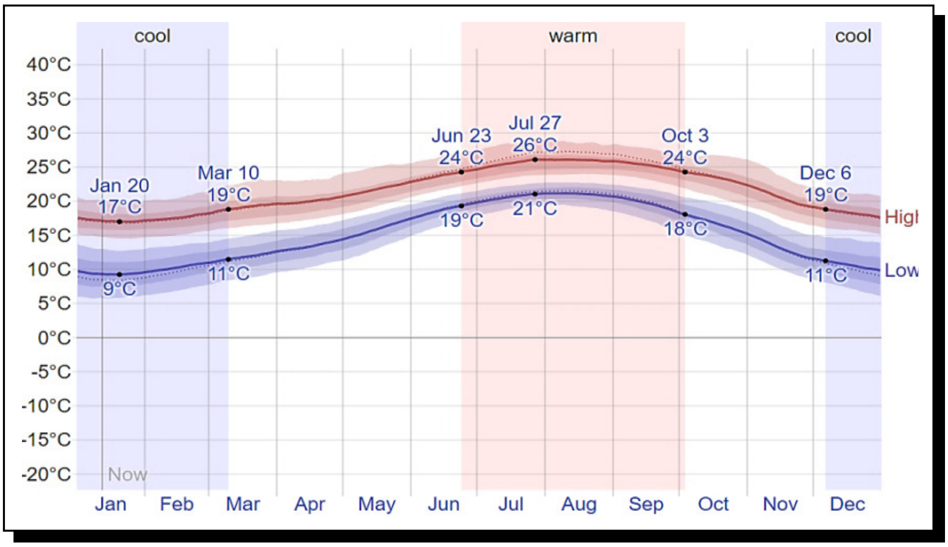

Figure 4. The annual temperature variation of Casablanca

3. Results and Discussion

3.1 Effect of the PCM melting temperature and its location

The model's wall has been simulated with a 25 mm PCM layer at two locations, as shown in Figure 2 and 3, by varying the PCM types. The Annual air conditioning energy consumption for both locations have been plotted in Figures 5 and 6, respectively.

PCM in position 1

wherein the case of the PCM in position 1, it can be seen that the annual air-conditioning energy increases with the melting point of the material. The lowest consumption is observed for PCM 1, while the maximum consumption corresponds to PCM6 (Figure 5, Table 5). This is due to the high thermal storage capacity, which rises with PCM'smelting temperature. As mentioned before, PCMs allow the storage of solar energy during the day which stabilizes the internal temperature, and leads to a reduction of the daily electricity consumption. This stored thermal energy will be released during the night, and as the storage capacity is higher, the heat released by the PCM is greater, allowing the HVAC system to start cooling the area and increase electricity consumption. In other words, consumption is reduced during the day but increased at night. One of the alternatives to address this problem is the use of natural cooling via PCM-based heat exchangers.

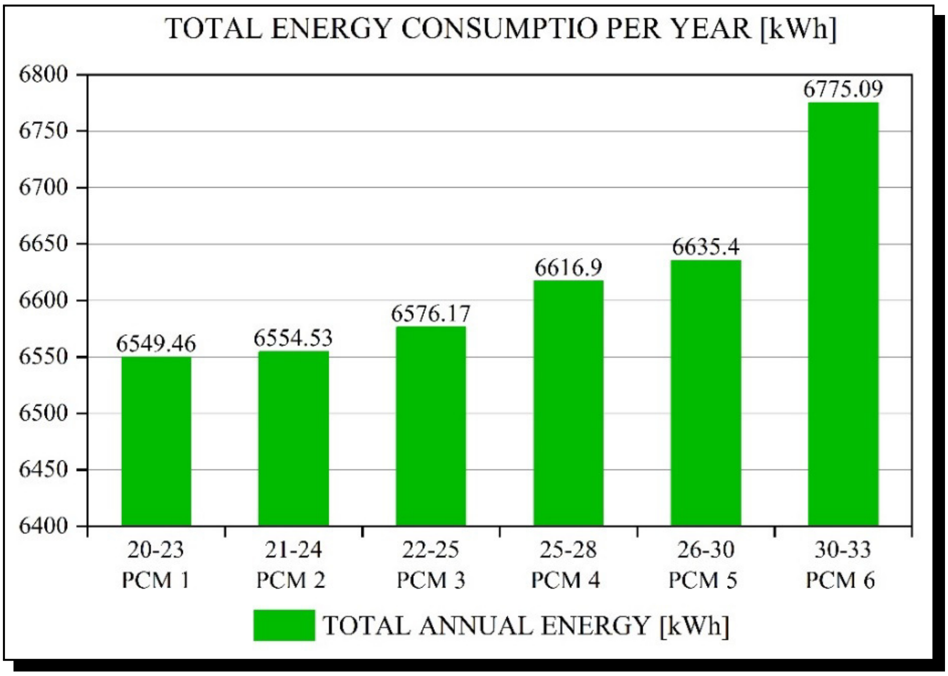

Figure 5. Annual air-conditioning energy as a function of PCM melting point (Position 1)

Table 5. Heating& Cooling Annual Energy Consumption (Position 1)

Melting Range [°C]		Annual Heating	Annual Cooling Energy [kWh]	Total Annual Energy [kWh]
PCM 1	20-23	784.15	5765.31	6549.46
PCM 2	21-24	797.09	5757.44	6554.53
PCM 3	22-25	821.04	5755.13	6576.17
PCM 4	25-28	850.38	5766.52	6616.90
PCM 5	26-30	854.96	5780.44	6635.40
PCM 6	30-33	897.35	5840.09	6737.44

PCM in Position 2

For the second wall-type where the PCM is placed in position 2, we observe that the annual air-conditioning energy decreases with the melting temperature of the material until reaching a minimum for the melting temperature between 26-30 °C corresponding to PCM 5, and then gradually increases, as indicated in Figure 6.

The lowest consumption was observed for PCM 5, while the maximum consumption was observed between 20-23 °C corresponding to PCM 1.

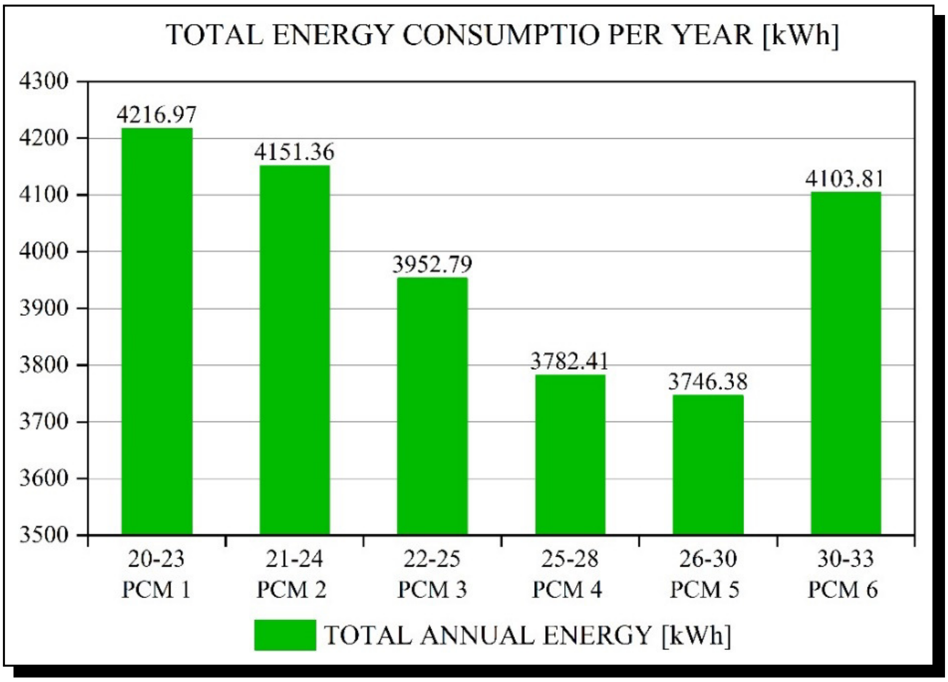

Figure 6. Annual air-conditioning energy as a function of PCM melting point (Position 2)

Table 6. Annual Energy Consumption for Heating, Cooling (position 2)

Melting Range [°C]		Annual Heating Energy [kWh]	Annual Cooling Energy [kWh]	Total Annual Energy [kWh]
PCM 1	20-23	27.85	4189.12	4216.97
PCM 2	21-24	17.25	4134.11	4151.36
PCM 3	22-25	27.69	3925.1	3952.79
PCM 4	25-28	53.56	3728.85	3782.41
PCM 5	26-30	73.67	3672.71	3746.38
PCM 6	30-33	120.25	3983.56	4103.81

4. Conclusion

As a conclusion, it can be said that PCM 5 with a melting temperature range of 26-30 °C in position 2 (as the inner most layer) is the most suitable material for the Casablanca weather characterized by an average annual temperature of between 18 and 32 °C.

The location of the PCM in the innermost layer (Position N°2) improves the performance by allowing a better transfer of energy with the indoor air. As a result, the HVAC system peak load would be reduced and shifted more than as the outermost layer (Position N°1). This is consistent with previous experimental and numerical research realized for a single-zone in the United States and Iran [10, 13].

5. Effect of PCM Thickness

The effect of the PCM thickness on the annual air-conditioning consumption has been investigated with different thicknesses from 1,5 cm to 10 cm, using PCM 5.

In Figure 7, It can be seen that the annual air-conditioning energy decreases as the thickness of the PCM layer decreases, since more PCM means more thermal stored energy. The consumption reaches his minimum equal to 3687.62 kWh for the 0.045 m thickness. Beyond 0.045 m, we note that there is no big variation in the total consumption. Therefore, there is no need to waste more money on more PCMs.

Based on these results we conclude that the most efficient thickness for a minimum energy use falls between 0.030 m and 0.050 m.

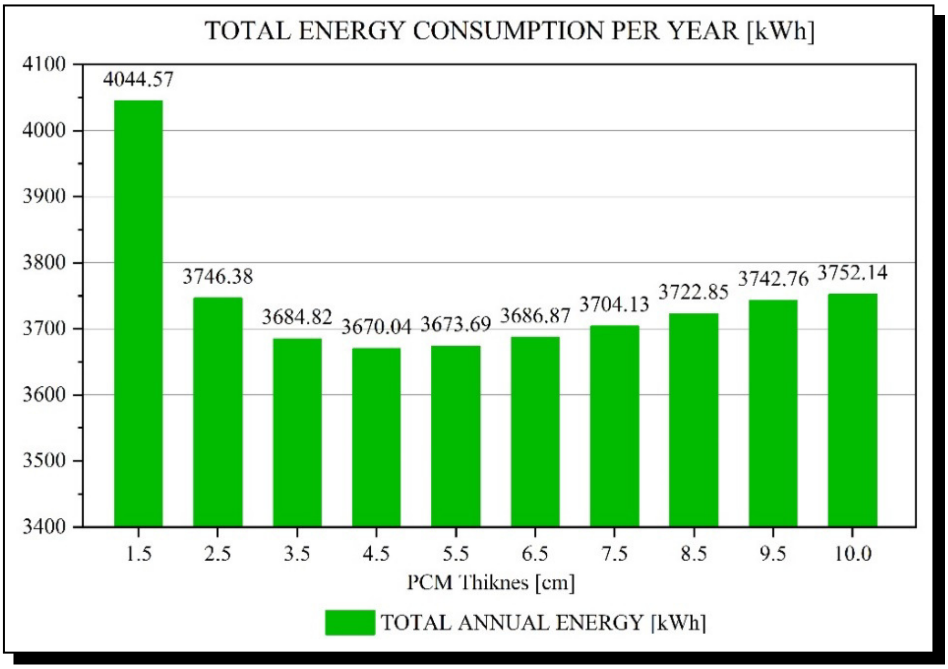

Figure 7. Annual air-conditioning energy variation as a function of PCM layer(Heating + Cooling)

In the remainder of this work, we will take 0.045 m as the standard thickness for the PCM layer in the rest of the simulations, as indicated in Table 7.

Table 7. Annual Energy Consumption for Heating, Cooling and Total (Position 1)

Melting point [°C]		Thermal capacity [$Jkg^{-1}K^{-1}$]	Density [kgm^{-3}]	Thermal conductivity [Wm^{-1} K^{-1}]	Thickness of PCM [m]
PCM 5	26-30	1662	942	0,213	0.045

5.1 Comparison of power consumption of cases with and without PCM layer

In this section, we will compare the power consumption used for air conditioning in two cases with and without a layer of PCM 5. Figure 8 indicates the power consumption of both cases. When using the PCM, the total energy used for heating and cooling was divided by more than half (53%) compared to the case without PCM. 99% of energy is saved for heating and 44% for cooling energy.

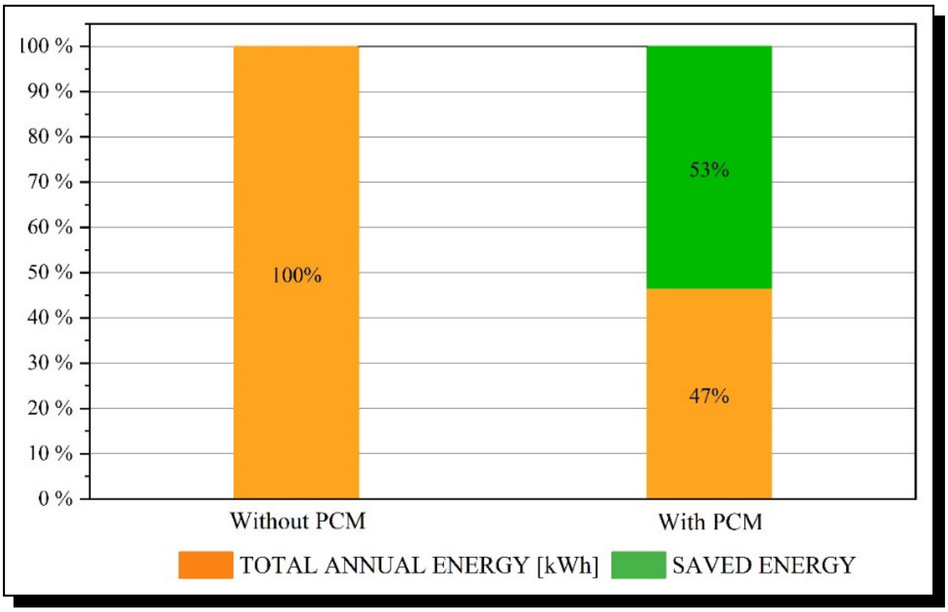

Figure 8. Comparison between the energy consumed for both scenarios, without and with PCMs

We also show the effect of complex walls on the temperature of the site and for this purpose we have compared the temperature of the air inside the cell -with and without PCM-. In Figure 9, we note that the temperature fluctuation is delayed or shifted when the PCM layer is present throughout the simulation. This phenomenon is the main characteristic of the PCM which, during sunny days, absorbs solar radiations and stores the energy as latent heat in order to delay the temperature rise. Then, during the night, the PCM will start to release the stored energy to delay the lowering of the temperature once the temperature drops.

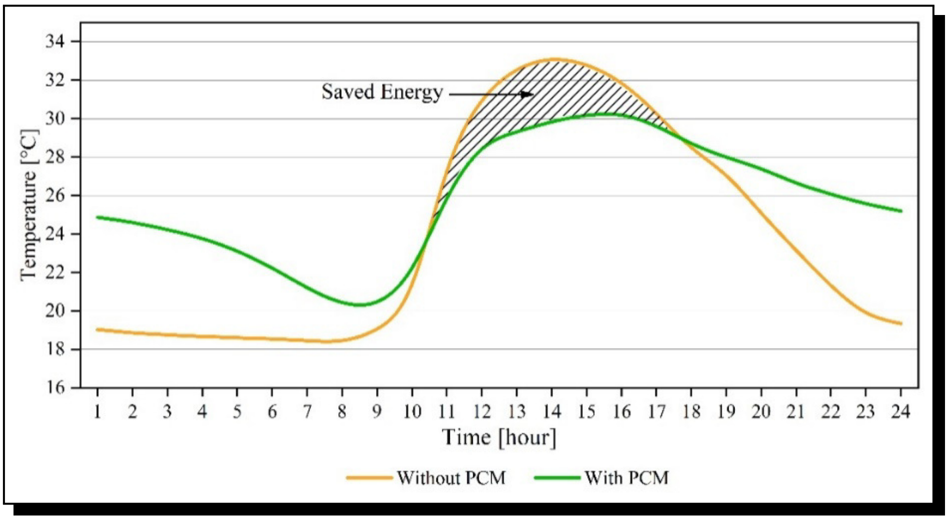

Figure 9. Temperature profile inside the cabinet during 24h

6. Conclusion

This work is part of the use of passive solutions to achieve high energy performance in the building field. One of the proposed solutions is the integration of Phase Change Materials (PCM) in the walls. These materials are designed to release and store thermal energy in latent heat form.

A comparative study -between structures with and without PCMs- has been elaborated in order to highlight the real impact of PCMs on the thermal behavior inside buildings and to see the gain in energy consumption and thermal comfort using PCMs.

In the first part of this parametric study, we simulated six scenarios of paraffin-type PCMs with different melting temperatures placed in two locations in the walls of a benchmark building. While in the second part, we studied the effect of the PCM thickness on the energy use of the building.

The results have revealed that the integration of PCMs in the building envelope can reduce fluctuations in indoor temperature. According to the results it can be concluded that the optimal material for Casablanca weather is characterized by a melting range between 26-30 °C and a thickness between 4 cm and 5 cm located at a position close to the interior proves to be the most efficient case with 54% saving in energy use.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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