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Article

Analysis of Energy Efficiency Potential of Hollow Brick Building Envelope Filled with PCM

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ABSTRACT

The energy efficiency in the building sector is becoming a real issue to be handled to minimize the energy consumption and contribute to prevent the global warming influencing all the world. In this context different researchers have developed solutions to improve the use of solar energy in building envelopes. Phase change materials (PCM) have shown their ability to store energy during the day and release it during the night allowing indeed a significant reduction of energy load. The present paper aims for the performance analysis and energy saving potential of a building envelope composed by hollow brick filled with PCM considering different scenarios. This innovative material has been developed in previous studies considering just the material scale or the component scale, but the building scale has not been considered in enough studies, where it concerns just the use of PCM as a layer or a mortar. Results found by conducting a numerical simulation with difference finite method showed a good energetic performance when incorporating PCM into bricks envelope described by a reduction in temperature fluctuations by about 3°C on average and energy saving rate reaching 41% with the optimum disposition of the appropriate type of hollow brick materials.

KEYWORDS: hollow brick; PCM; numerical simulation; energy performance; building envelope

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INTRODUCTION

The need to enhance the energy efficiency of buildings is increasing day by day, where the concepts of zero energy and zero carbon building are presented [1], and the use of various techniques that prioritize renewable energies, especially solar energy, is being strongly emphasized. In this context, phase change materials have been employed through various possible methods for integration within buildings [2], either in the form of wall panels [3], ceiling panels [4], windows[5], or by incorporation into construction materials such as mortar [6], concrete [7], bricks [8], or in sunspaces [9]. Other means of utilizing PCMs in buildings have also focused on related systems such as the Trombe wall, heat pumps, and more.

According to Lee et al. [10], the integration of PCMs through encapsulation within construction materials has demonstrated its ability to minimize energy consumption and to improve occupant comfort. This is why this method has taken a significant place and has shown relevant results in studies already conducted by researchers. Sanna et al. [11] Conducted a testing and comparison of an active dry wall with PCM against a traditional dry wall, results found confirm that the use of PCM allows 40% of thermal saving in heat loss by building envelope. In another study, Kuzink et al. [12] developed a TRNSYS model for simulating the thermal behavior of exterior walls incorporating PCM panels. The model was validated using experimental results from the literature. The study concluded that PCMs were able to increase the thermal inertia of the studied building. The application of passive cooling using PCM panels was conducted by Chhugani et al. [13]. The potential energy gain was analyzed through dynamic thermal simulation of a cell using TRNSYS to address the issue of PCM cooling during the night by employing night ventilation. According to this study, the electrical energy demand was reduced by 30% through the integration of PCM panels compared to the reference cell without PCMs.

Zhu et al. [1] conducted a study to optimize the key factors influencing the annual thermal management of a Trombe wall integrated with PCMs. This innovative building envelope system enables better utilization of solar energy and natural ventilation, thereby enhancing occupants' thermal comfort. This study determined optimal values for six parameters by coupling the thermal transfer model from TRNSYS with the optimization software GenOpt. The results showed a 13.52% reduction in the total annual energy load of the optimized PCM-integrated Trombe wall compared to a traditional Trombe wall. Other studies have focused on evaluating the effect of using PCMs incorporated into construction materials. One such study by Arivazhagan et al. [14] analyzed the performance of concrete blocks integrated with PCMs for thermal management. An experimental study was conducted on a block of concrete to evaluate temperature fluctuations inside with and without PCM. The results showed a reduction of 3 °C for an optimal thickness of 12 mm of incorporated PCM. Al-yasiri et al. [15] experimentally assessed the thermal performance of concrete bricks filled with macro-encapsulated PCMs in the climate of Iraq. The behavior of three brick configurations, based on the number of capsules used, was compared to the reference brick. This led to the conclusion of an optimal solution that achieved maximum reduction in peak temperature and reduced thermal conduction transfer by up to 156% and 61% respectively. In another study by Arivazhagan et al. [10], a layer of PCM was added inside a concrete block to assess its thermal performance compared to the base block without PCM. The experimental study on a block revealed a reduction of

3 °C in the maximum air temperature achieved with the use of a 12 mm layer of PCM as the optimal thickness.

Tuncbilek et al. [16] conducted an analysis of the seasonal and annual performance of using PCMs incorporated into conventional bricks in the Marmara region of Turkey. A numerical model was developed at the scale of a brick to assess the impact on heating and cooling demand considering different PCM melting temperatures, quantities, and placements within the bricks. The results of this study demonstrated a 17.6% reduction in the annual thermal load under the optimal conditions identified.

Moving beyond the material scale, other studies like the study conducted by Mourid et al. [17], have transitioned to the building element scale to evaluate the performance of utilizing PCMs incorporated into construction materials. Yu et al. [18] prepared and characterized a PCM-diatomite composite material, with diatomite known for its good porosity, absorption, and purity. The composite was subsequently applied to a portion of an external wall in a test chamber to assess the thermal performance of the wall cladding blocks. The results showed a reduction in surface temperature compared to the use of traditional plastic insulation. In other studies conducted by Li et al. [19] and Wang et al. [20], PCM bricks were prepared and tested on the wall of a test cell to evaluate the thermal performance of using these bricks, which significantly reduced temperature fluctuations. The application of PCM panels was also carried out on the walls of a climate-controlled chamber, with results from R8 proving a temperature reduction of 32.4%.

Fraine et al. [21] evaluated the thermal and hydric performance of the PCM-diatomite composite incorporated into bricks, replacing expanded polystyrene (EPS) insulation. The analysis was based on a two-dimensional finite element model to assess the effect of using this composite on the indoor comfort level of buildings. The studied composite demonstrated good hygrothermal performance with a fill rate of 66% on the inner face of the brick, allowing for a reduction of up to 50% in temperature and humidity fluctuations indoors. Based on the aforementioned state of the art, it is evident that latent heat storage in PCMs incorporated into construction materials, particularly bricks or concrete blocks, has been studied primarily at the material or building element scale. However, its study at the scale of a real building has been undertaken just in few studies. In fact, this larger scale has only encompassed the application of PCM panels or mortar.

In the present study, the energy performance and potential thermal gain are evaluated for the use of a brick envelope incorporated with PCM. Subsequently, the optimal solutions for the use of a new innovative material developed by Souci and Houat [22] are examined at the building scale using dynamic thermal simulation with the finite difference method. Various configurations will be studied, considering two types of bricks incorporated with PCM. This involves a total of 14 configurations based on the arrangement, type, and filling of each brick within the walls of a residential building envelope. The Figure 1 represents the flowchart methodology of the present work.

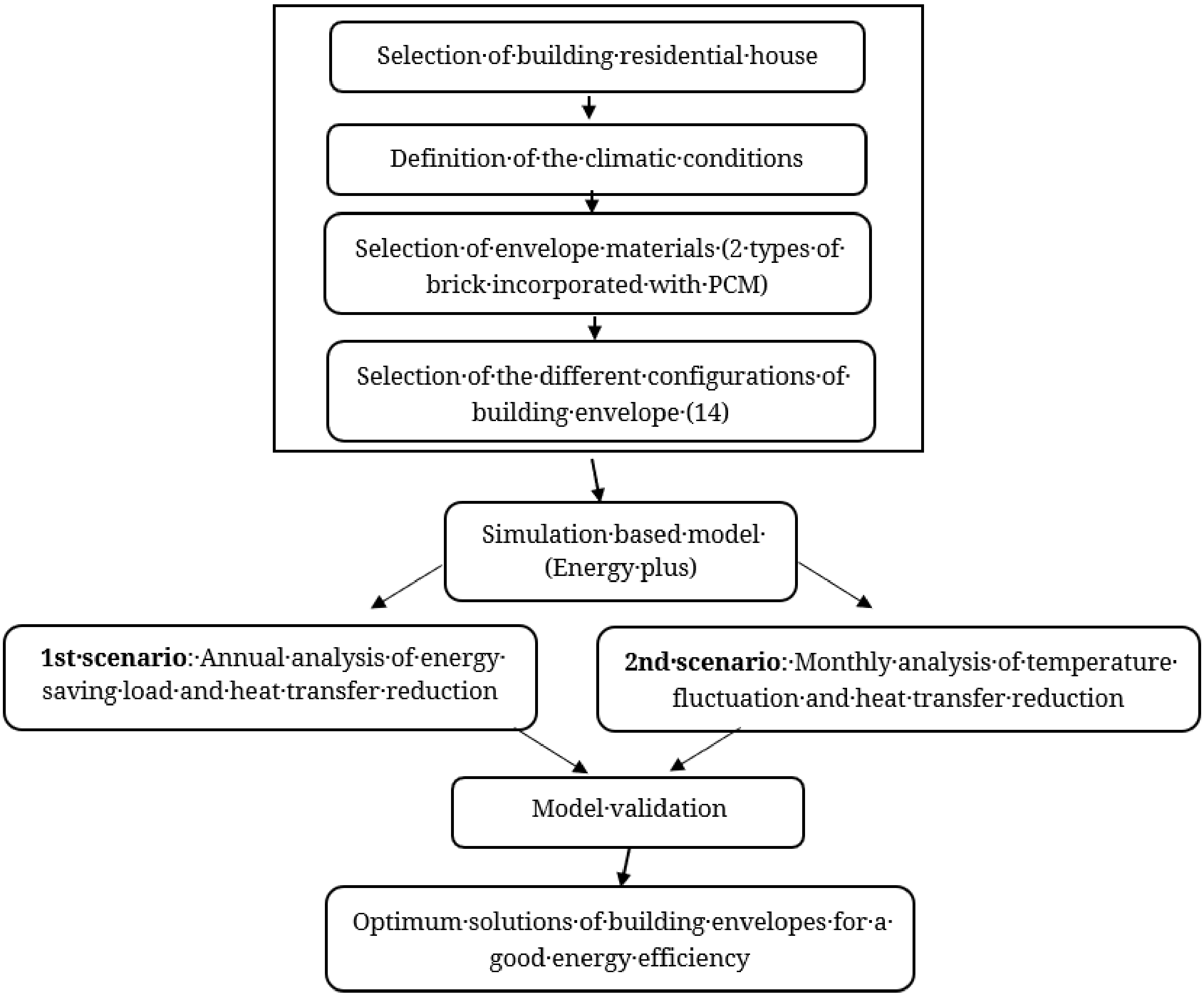


Figure 1. Flowchart methodology.

METHODS AND MATERIALS

Problem Description

In the present work, the energy saving potential of hollow brick envelope filled with PCM is analyzed using different scenarios and configurations. For this purpose we considered a residential building with one floor of 77.8 m² of area as the case study. The Figure 2 and the Table 1 present the view of the building and a description of the building conditions respectively.

(a) **(b)**

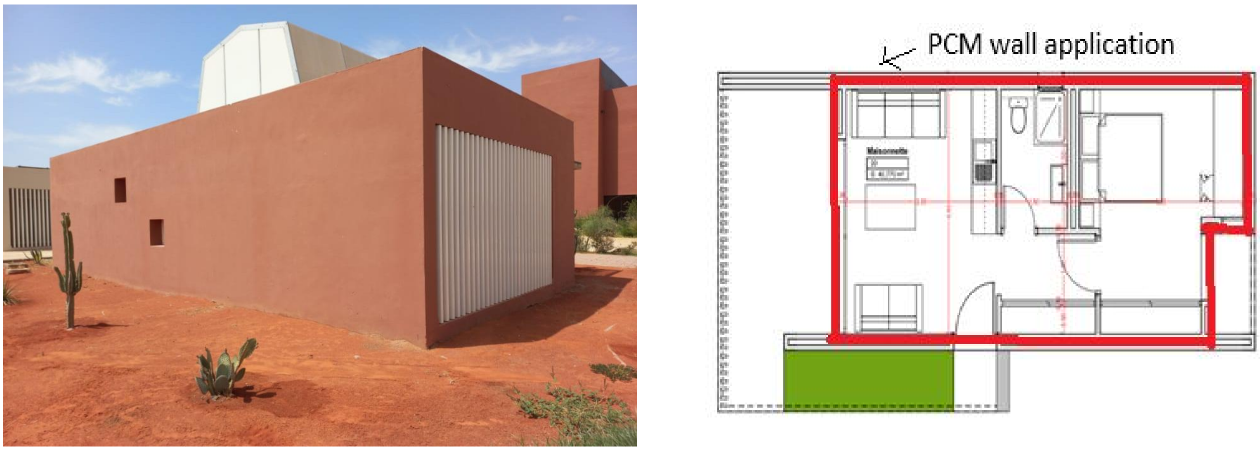


Figure 2. (**a**) Photo of the real building, (**b**) Plan view of the building case study.

Table 1. Building conditions [23].

Designation	**Case study**
Building type	Residential house
Floor area m²	77.8 m²
Number of floors	1
Windows	15 mm (double layered glass of 6 mm with air gap
Location	Benguerir city–Morocco

Climatic Conditions

Climatic conditions are a crucial factor that must be considered to achieve accurate results for the configurations under investigation. Our research was conducted in Benguerir city climate. This city is located in Morocco and is characterized by a warm sub-arid climate appointed by Bsh according to Koppen Geiger classification [24]. The Table 2 and the Figure 3 show the climatic specifications of the city considered. This zone is known for its consistently high temperatures throughout the year. This environmental characteristic prompts us to contemplate the potential utilization of solar energy in these region.

Table 2. Climatic specifications of Benguerir city according to Koppen-Geiger [23].

Climate	**Country**	**City**	**Longitude**	**Latitude**	**Elevation (m)**	**Average highest annual temperature (°C)**	**Average lowest annual temperature (°C)**
Bsh	Morocco	Benguerir	7.94	32.24	468	26.1	11.1

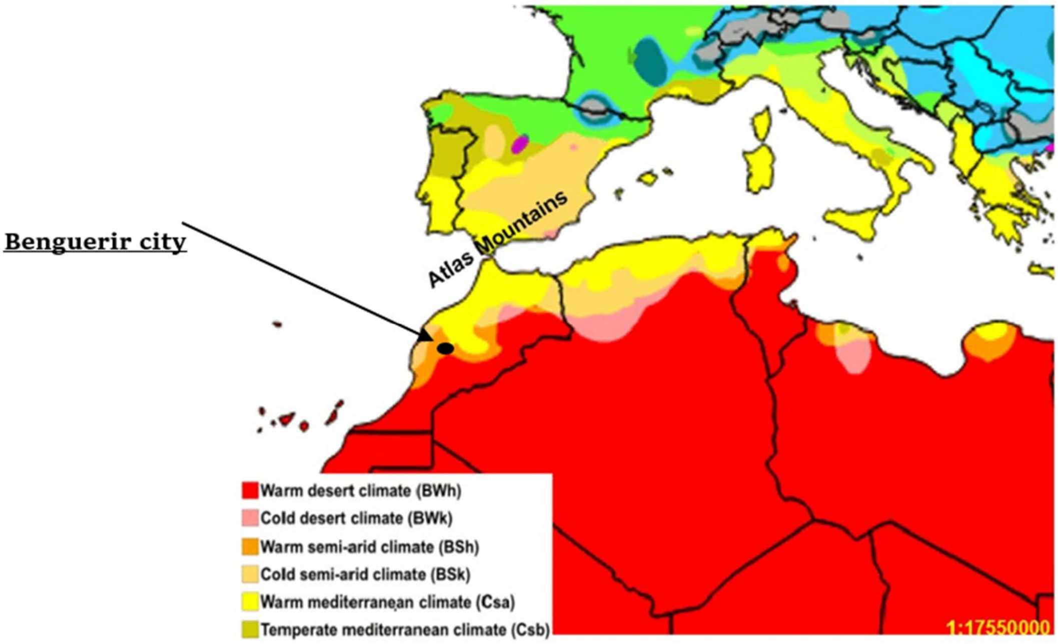


Figure 3. Classifications of climatic zones according to Koppen-Geiger.

Description of Materials

The envelope studied is composed of two types of red hollow brick which is commonly used in the majority of constructions in Morocco. It has a parallelepiped form with different sizes described in Figure 4 and Table 3. It's proposed to fill the paraffin (*n*-octadecane) as a phase change material into the cavities of these bricks. The thermo-physical characteristics of the PCM, bricks and the bricks filled with PCM are summarized in Table 4 based on the study conducted by S.Houat et al. [22]. They developed a numerical simulation with finite difference method to analyze the thermo-physical properties of this new material (hollow brick filled with PCM) applied in a wall scale. They found that it could increase significantly the thermal inertia of walls and then the energy efficiency of buildings.

The present study is based on the analysis of energy saving and thermal comfort using 14 different configurations of envelope's walls composed by the two types of hollow brick, filled or not by PCM as described in the Figure 5 below.

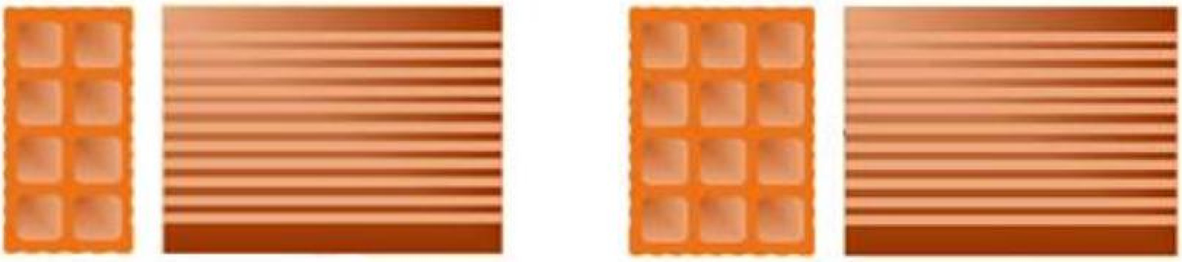


Figure 4. Two types of hollow brick wall, left: type1 (8 hollows) and right: type 2 (12 hollows).

Table 3. Bricks characteristics.

Characteristic	Brick type 1	Brick type 2
thickness	10 cm	15 cm
length	30 cm	30 cm
width	20 cm	20 cm
Internal holes number	8	12
Cavities dimensions	3.5 × 3.5 cm^2	3.5 × 3.5 cm^2

Table 4. Thermo-physical properties of materials.

Material	Density (kg/m^3)	Thermal conductivity (W/(m.K))	Heat capacity (J/(kg.K))
PCM (solid)	865	0.358	1934
PCM (liquid)	780	0.148	2196
Hollow brick without PCM	1600	0.7	840
Brick type 1 filled with PCM	1240	0.5	2465
Brick type 2 filled with PCM	1240	0.47	2465

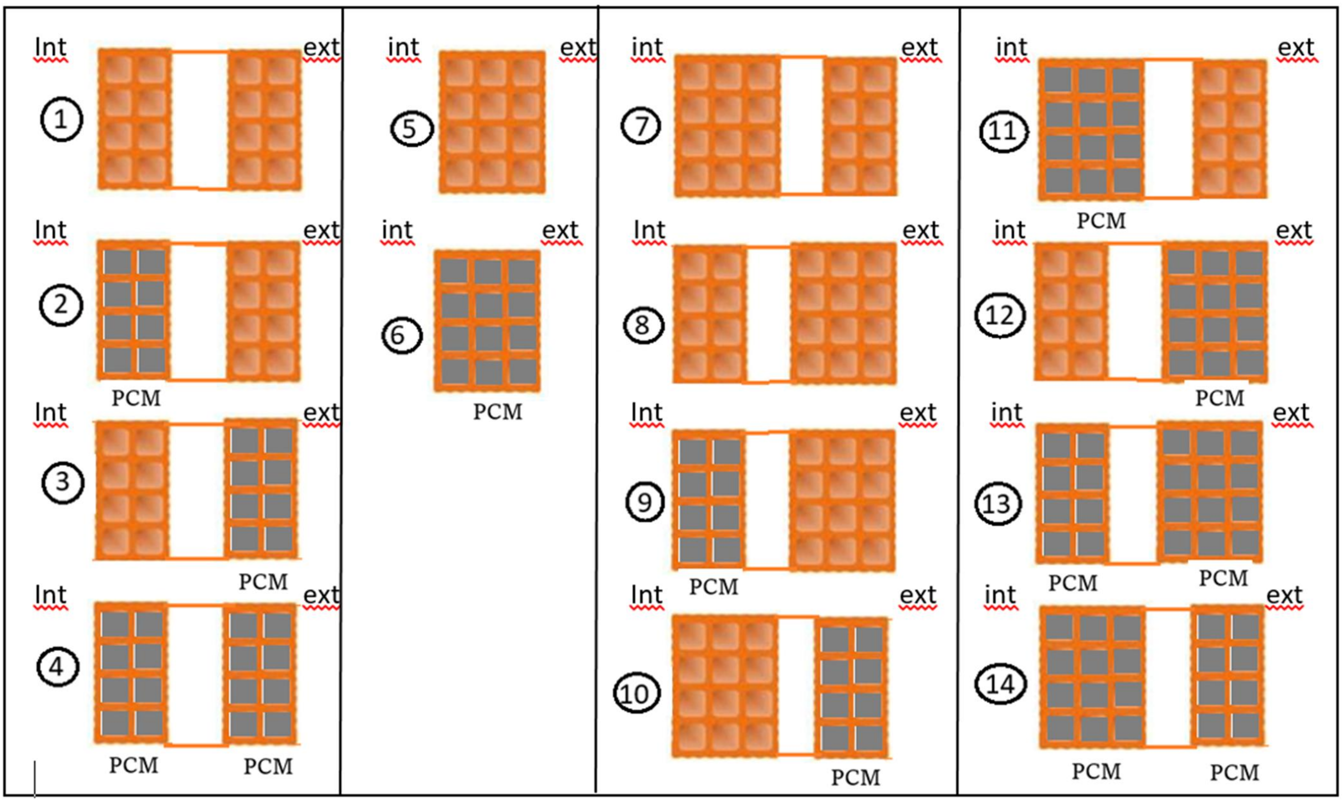


Figure 5. Configurations of envelope's walls.

Simulation Method

The above-mentioned case study involved dynamic thermal simulation conducted using EnergyPlus 8.9 software [25], which was accessed through the Design Builder user interface. The selection of EnergyPlus was based on its growing prominence as a robust tool for analyzing energy simulations, which has been successfully validated in various scenarios and configurations involving Phase Change Materials (PCM).

The simulation based model was conducted using the specified data already selected to check how the building would behave under actual operating conditions, and to analyze the monthly and annually thermal behavior.

This software employs a one-dimensional conduction finite difference method, known as CondFD, customized to match the thermo-physical characteristics of PCM materials. The algorithm is built upon the concept of the enthalpy-temperature function and employs a fully implicit finite difference approach to precisely account for the energy associated with phase changes. This algorithm discretizes the building envelope into discrete nodes to calculate heat storage properties as shown in the Figure 6.

The enthalpy-temperature function, described by Equation (1) and elucidated in Figure 4, plays a pivotal role in this algorithm's calculations. Where the thermal conductivities are calculated by the Equations 2 and 3. Here's how the algorithm operates: during each iteration, the temperature-dependent specific heat capacity (C), as outlined in Equation 4, is continuously updated based on the effective heat capacity derived from the enthalpy-temperature function.

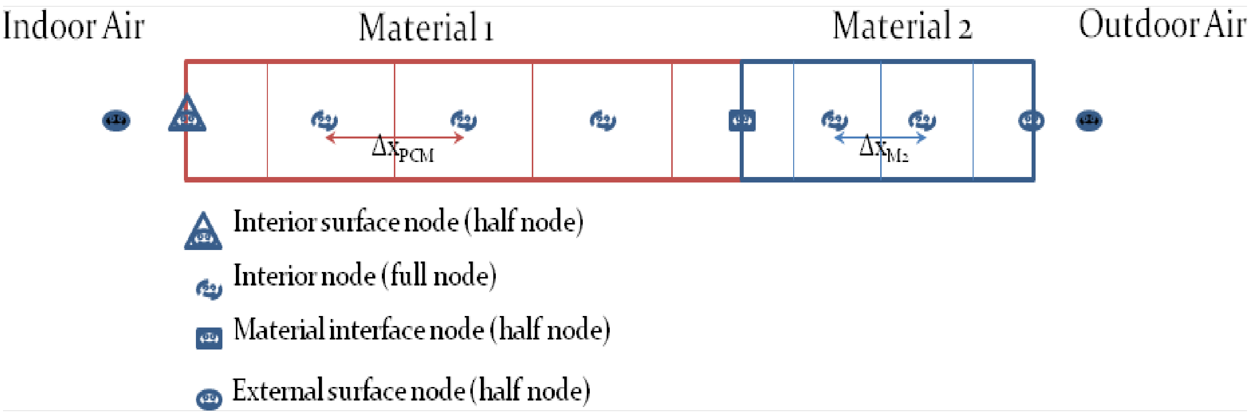


Figure 6. Node depiction for conduction finite difference method.

In accordance with European standards [23], the thermal comfort range was established between 20 °C and 26 °C, while the setback temperatures for heating and cooling were set at 18 °C and 28 °C, respectively.

$$C\rho\Delta x\frac{T_i^{j+1}-T_i^j}{\Delta t}=(k_w\frac{(T_{i+1}^{j+1}-T_i^{j+1})}{\Delta x}+k_E\frac{(T_{i-1}^{j+1}-T_i^{j+1})}{\Delta x}) \quad (1)$$

$$k_w=\frac{(k_{i+1}^{j+1}+k_i^{j+1})}{2} \quad (2)$$

$$k_E=\frac{(k_{i-1}^{j+1}+k_i^{j+1})}{2} \quad (3)$$

$$C_p = \frac{(h_i^j - h_i^{j-1})}{(T_i^j - T_i^{j-1})} \quad (4)$$

where:
C: specific heat capacity
ρ: density (kg/m^3)
Δx: Finite difference layer thikness (m)
Δt: Calculation time step (s)
T: node temperature (K)
i: node being modeled
i−1 and i+1—adjacent nodes towards inner and outer sides of building respectively
j+1 and j−1: simulation time step and previous time step respectively
k_W: thermal conductivity for the interface between i node and i+1 node
k_E: thermal conductivity for the interface between i node and i−1 node

Model Validation

The conduction finite difference method used with PCM has been developed and validated in different research studies. Cabeza et al. [26] used comparative testing, analytical verification and empirical validations to validate this method. Experimental data have been used also by other researches to validate this method [27]. Tabares-Velasco et al. [28] have studied the impact of using PCM on the comfort conditions of two buildings, they validated their results by comparing them numerically and experimentally. In another study conducted by Sage Lock et Sailor [29], the model has been validated with monitored data from real scale. All these studies have shown the effectiveness of the CondFD method in performing accurate simulations of PCM integration into buildings.

In our situation, we have followed the model's procedures as outlined by the guidelines provided by Tabares-Velasco et al. [28]. And the model developed was validated against experimental results conducted by 22. The Figure 7 below shows the experimental setup presented by Kumar et al. [27] where two identical test rooms were constructed of (3 m × 3 m × 3.65 m) as dimensions in a warm and humid climate of Chennai city of India. One room was equipped with brick wall without PCM and the other one was equipped with brick wall filled with encapsulated PCM. Two temperature sensors with a data logger was used to measure the average atmospheric temperature inside the rooms. According to the experimental results of the indoor temperature calculate in January, the study found a maximum drop of temperature of 6 °C indicating that the difference found between experimental and numerical results are less than 2 °C. In the present study the maximum fluctuation in January is about 4 °C which confirm the reliability of our model. Hence the model developed in the present research can be used to perform the energy efficiency of buildings integrated with PCM.

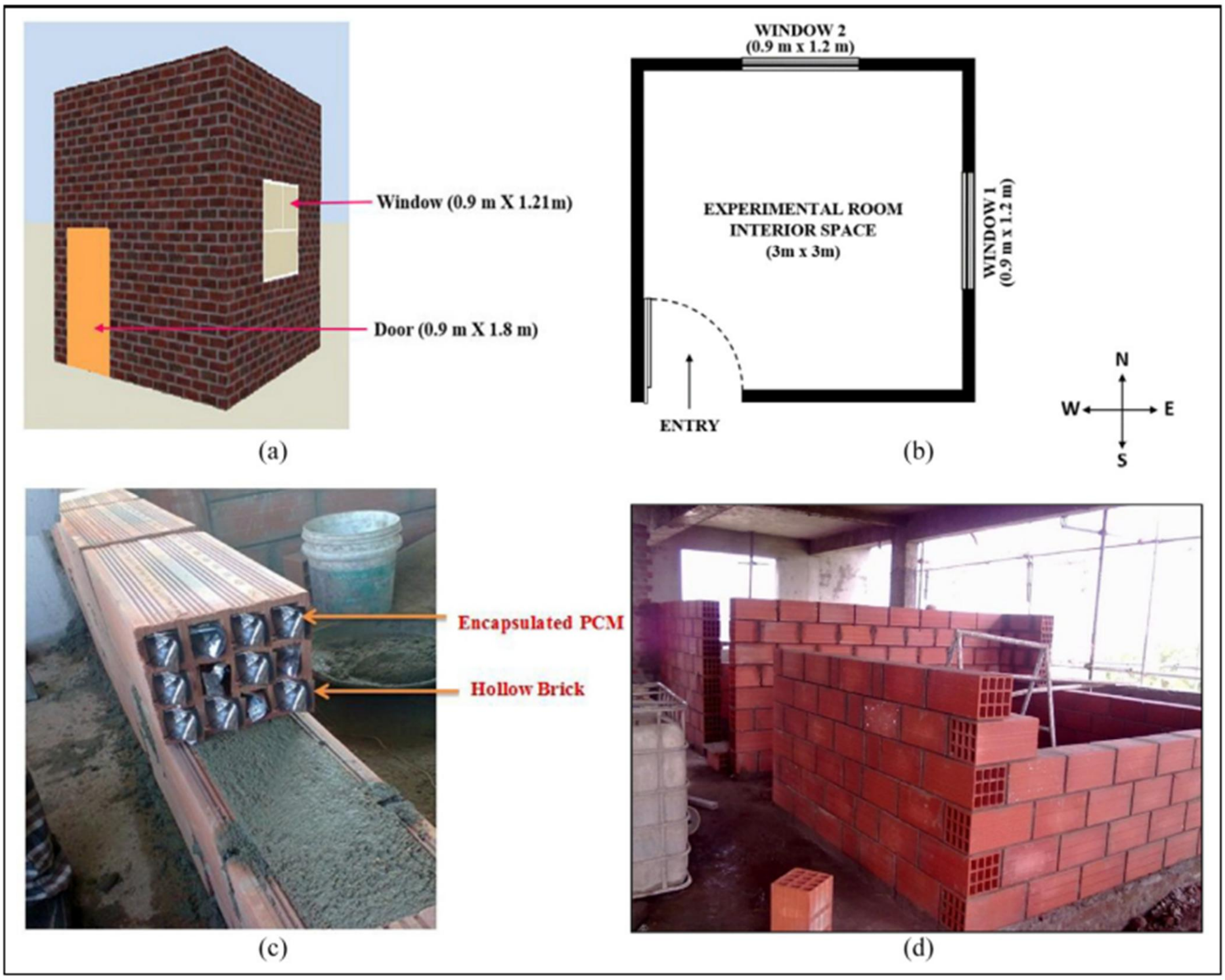


Figure 7. Description of the experimental setup.

RESULTS AND DISCUSSION

In this section the potential of energy saving using PCM filled into bricks is evaluated using two different scenarios. The first one concerns an annual analysis of the heat flux transfer and energy load of heating and cooling to conclude with the optimum energy saving reduction and heat transfer ratio.

The second scenario is related to a representative month analysis of heat transfer ratio and reduction of temperature fluctuations when using PCM filled into bricks.

First Scenario: Annual Analysis of Energy Saving Load and Heat Transfer Reduction

The annual analysis of energy load has been conducted by performing the simulation for each configuration of wall composition. Results of total annual energy load are presented in the Figure 8.

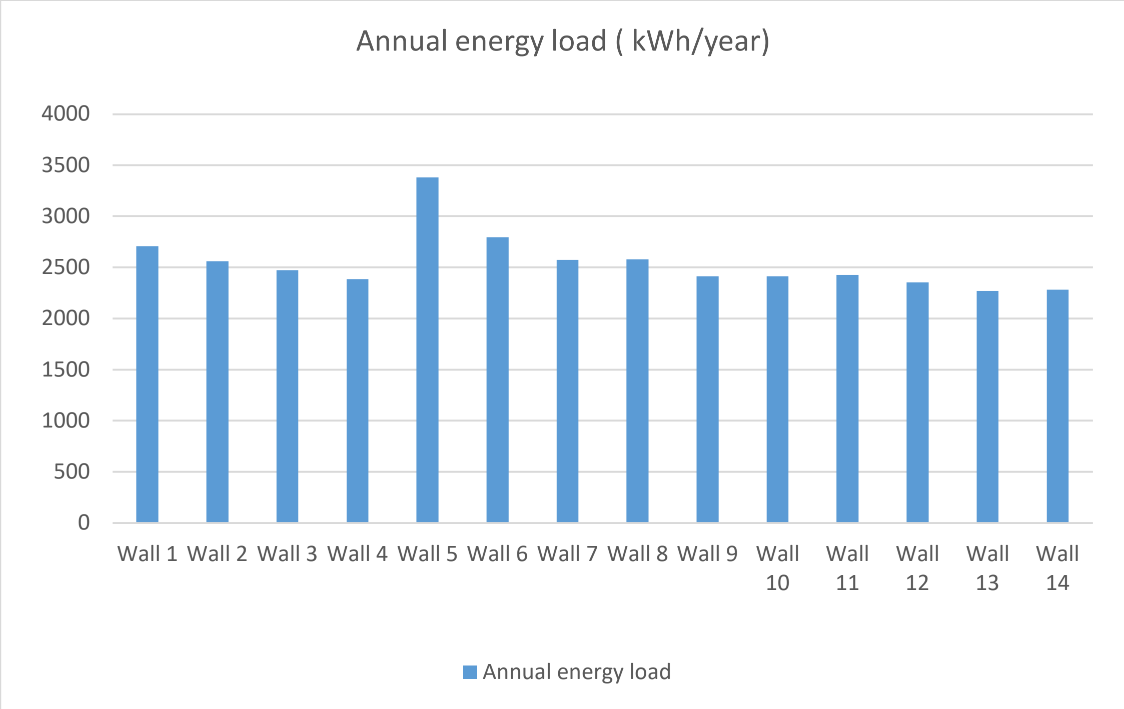


Figure 8. Annual energy load.

The energy consumption reduction ECR calculated with Equation 5 is calculated to evaluate the real and direct impact of each configuration compared to another one. Results are presented in Figure 9.

$$ECR = \frac{EC\ (no\ PCM) - EC\ (PCM)}{EC\ (no\ PCM)}\ x\ 100\% \quad (5)$$

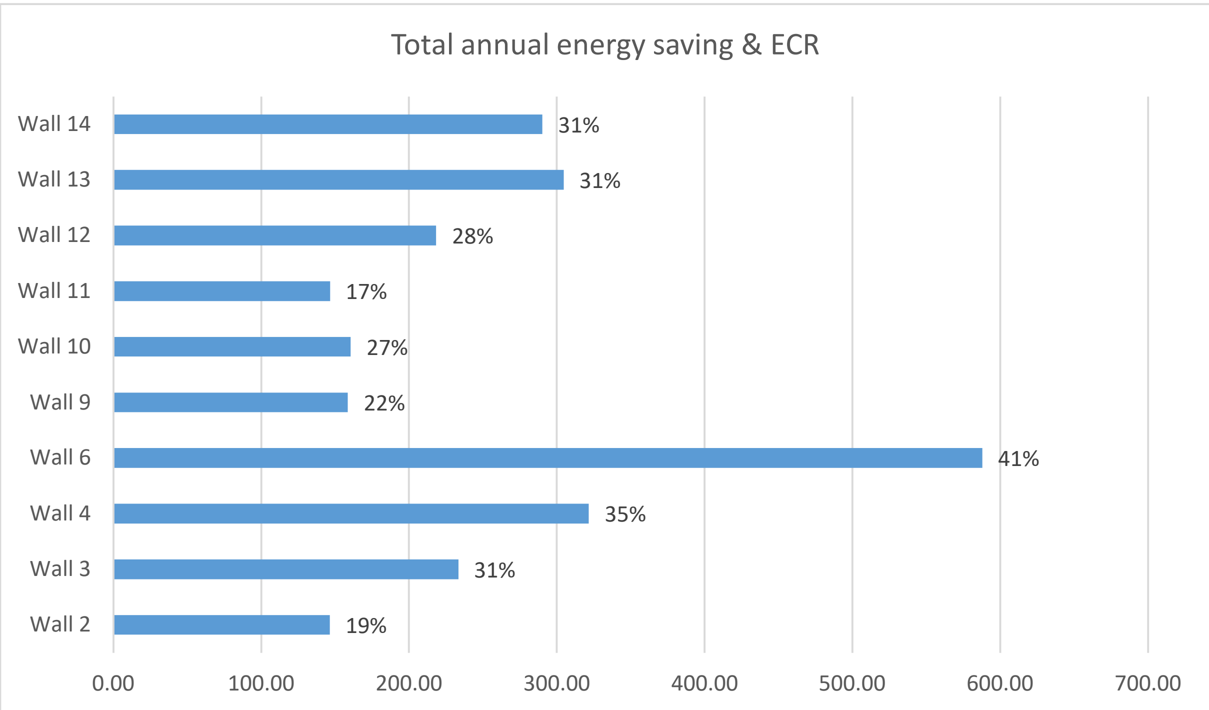


Figure 9. Total annual energy saving and ECR.

In order to evaluate the impact of using PCM filled into hollow bricks, we considered three comparisons of the 14 configurations dispatched as shown in the Table 5 according to their similarity composition with and without filled PCM as follows:

- Comparison 1: Building with wall 1 as a baseline to be compared with buildings with wall 2, wall 3 and wall 4.
- Comparison 2: Building with wall 5 as a baseline to be compared with building with wall 6.
- Comparison 3: Building with wall 7 or 8 as a baseline to be compared with buildings with wall 9, wall 10, wall 11, wall 12, wall 13 and wall 14.

Table 5. Description of comparisons types.

Comparison N	Baseline wall without PCM	Wall with PCM
1	1	2/3/4
2	5	6
3	7 or 8	9/10/11/12/13/14

We can note clearly that the annual energy load decreases significantly in the three comparisons. Building with wall 4 envelope need 321 kWh annually less than the one with wall 1 envelope which confirms that the use of PCM filled into the double brick envelope of type 1 is more efficiently preceded by its use in the brick placed in the exterior side (wall 3) with 233 kWh of energy saving. These results are described by 35% and 31% of energy consumption reduction obtained with the use of wall 4 and wall 3 respectively.

Concerning the second comparison between envelope with wall 5 and wall 6, the annual energy load is the highest when we use just the brick type 2 without PCM as an envelope. The energy saving found by introducing filed PCM into a simple wall composed by bricks of type 2 is about 587 kWh which represent 41% of energy consumption reduction.

In the third comparison between envelopes composed by a double brick layer of type 1 and type 2 with or without filled PCM, we found that the use of PCM incorporated into the double brick (wall 13 and wall 14) offers 31% of energy consumption reduction. As mentioned in the previous paragraph, the use of PCM is more efficient with brick of exterior side (wall 12 and wall 10) rather than the ones placed in the interior side (wall 9 and wall 11). Which is affirmed by 28% of energy consumption rate compared to 17%.

According to these three comparisons we can note that the optimum envelope types are composed by wall 4, wall 6 and wall 13. But when we analyze the total annual energy load of each one we found that it reaches the minimum with wall 13 compared to the others enchained with wall 4. These two walls compositions approve the beneficial impact of using filled PCM in the double layer bricks.

Envelope with wall 6 isn't efficient as the one with wall 4 and wall 13 even if the ECR is higher because this last one is calculated based on its comparison with the use of wall 5 only. But when we analyze also the total annual energy load we find clearly that it consumes an important amount of energy compared to the other walls. These results are confirmed also with the study conducted by Qu et al. [30] which exhibit a considerable energy saving reaching 34.8% when integrating PCM into building envelopes under Chinese climate.

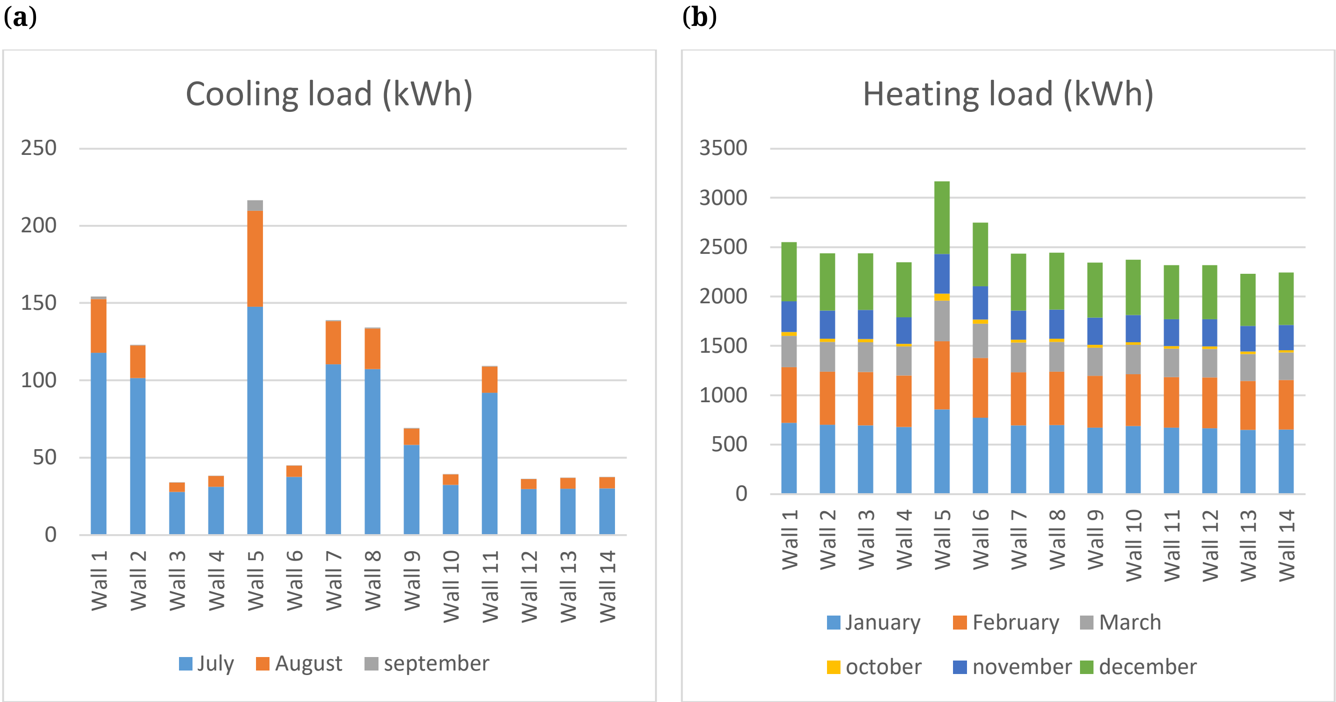


Figure 10. (**a**) Annual cooling load, (**b**) Annual heating load.

Figure 10 depicts the allocation of energy load between cooling and heating loads for every configuration of wall composition envelopes. Based on these findings, it is evident that July and August are the primary months with the highest cooling load consumption, while September, April, and May exhibit negligible energy load. Concerning the heating load, we can note that December, January and February are the first consumers compared to the rest of winter months. These results confirm that envelope with wall 13 is more appropriate for heating purpose by 2230 kWh of energy consumption in winter months, and the one with wall 3 is more appropriate for cooling purpose because it consumes only 34 kWh in the summer season.

In order to evaluate the impact of using PCM into bricks in each configuration of wall compositions studied, it's required also to determine the heat flux ratio HTR defined by the Equation 6 below. Where E_{PCM} presents the heat transfer from the walls composed by bricks filled with PCM and $E_{without\ PCM}$ corresponds to the heat transfer from the walls composed by bricks without PCM.

$$\mathrm{HTR} = \frac{E_{PCM}}{E_{without\ PCM}} \quad (6)$$

(a) (b) (c)

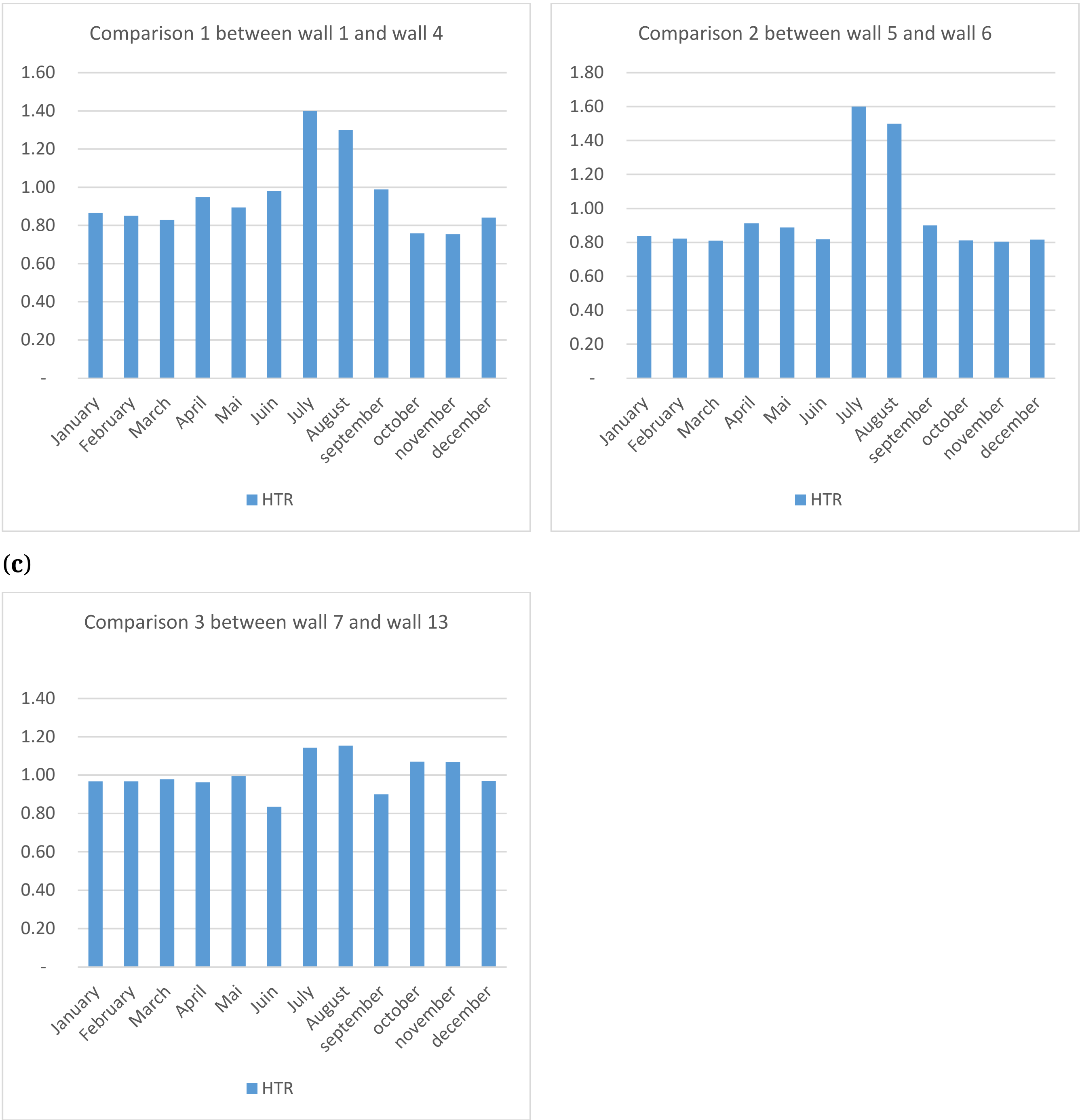


Figure 11. Heat transfer ratio value. (**a**) Comparison 1 between wall 1 and wall 4, (**b**) Comparison 2 between wall 5 and wall 6, (**c**) Comparison 3 between wall 7 and wall 13.

In cases where the Heat Transfer Ratio (HTR) falls below one, it indicates that incorporating PCM into the brick envelope will reduce the ratio of heat transfer. As depicted in Figure 11, the HTR values for all configurations are consistently below one in all months of the year except for July and August.

These outcomes can be attributed to the reality that in the summer period, PCM have the ability to assimilate heat, thereby managing indoor temperatures and augmenting heat exchange. Conversely, during winter season, these materials can store and subsequently emit heat, effectively curbing heat dissipation and potentially diminishing heat transfer. The reduction of heat transfer ratio is about 25%, 20% and 17% respectively for the three comparisons. These results are in line with the findings of Jia et al. [31] who studied the thermal behavior improvement of hollow bricks integrated with phase change materials (PCM) and thermal insulation materials (TIM). They found that the introduction of thermal interface material (TIM) into all the voids led to a notable decrease of 29.7% in the mean heat flow across the inner surface. Conversely, the application of phase change material (PCM) within the inner cavities resulted in a marginal increase of 6.1% in the same heat flow.

Second Scenario: Monthly Analysis of Temperature Fluctuation and Heat Transfer Reduction

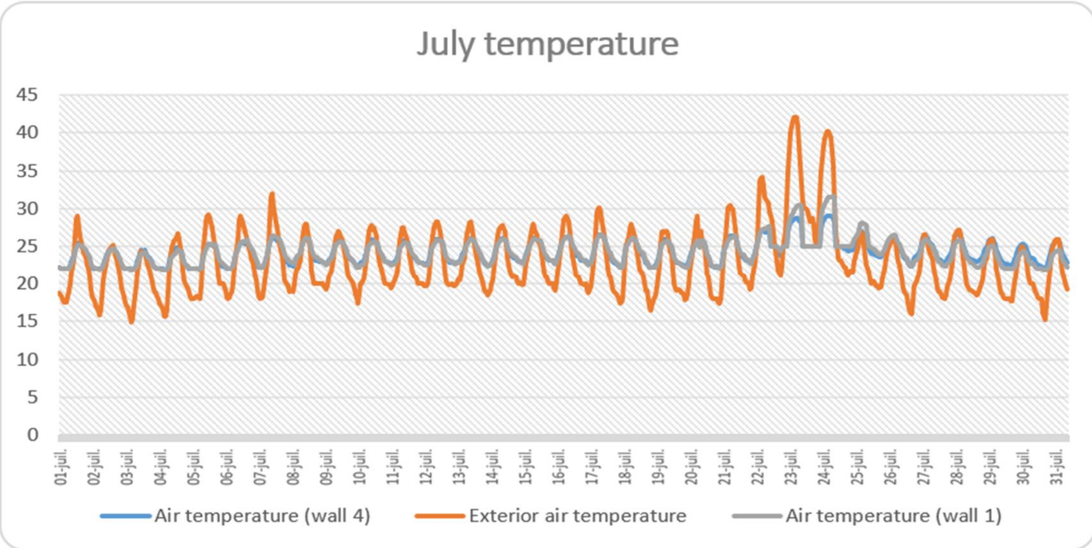
In this second scenario analysis, the monthly assessment of heat transfer ratio has been carried out by simulating the 14 wall composition configurations.

In order to evaluate the reduction of temperature fluctuations, we have chosen two typical months; July as a summer month and January as a winter month. The analysis has been done initially for the wall 4 and the wall 1 because the envelope with wall 4 has shown a good energy saving consumption according to the previous scenario analysis.

The findings, depicting the monthly temperature fluctuations have been showcased in Figure 12. From these results we note that the use of filled PCM into bricks envelopes diminishes the temperature fluctuations by about 1 °C to 5 °C in July and about 1 °C to 4 °C in January which confirm the beneficial impact of using PCM into envelopes. These results align with those of Kumar et al. [27], this research studied experimentally and numerically the effect of PCM integration in hollow brick envelope in two different climate humid and warm. The findings depicted that the temperature drop varies from 6 °C to 2 °C.

The behavior of air temperature in the both Configurations of wall 1 and wall 4 could be explained by the fact that in winter months the PCM affects primarily the minimum inside temperature to stabilize the temperature fluctuations by storing solar energy. We can note also that the maximum temperature reached in January is about 21 °C for the two wall. In this case heat storage of PCM doesn't have a significant impact on the maximum temperature because the goal is to maintain warmth within the comfort range in the colder winter.

(**a**)



(**b**)

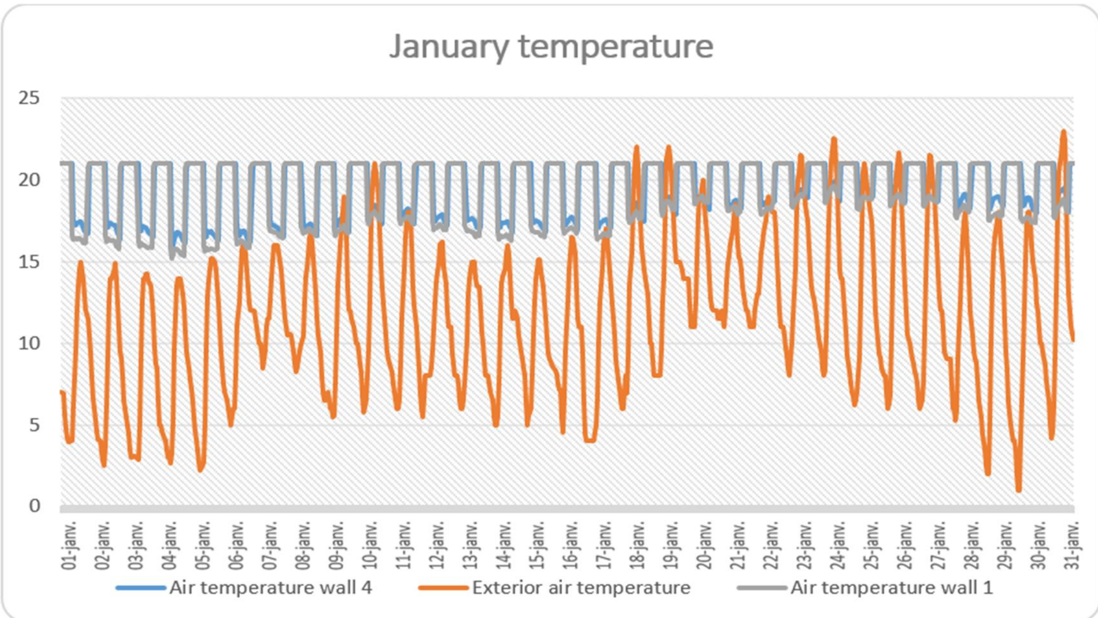


Figure 12. Temperature fluctuations (for wall 1 and wall 4) in typical months: (**a**) July, (**b**) January.

Then we analyze the temperature fluctuation in the same months but considering a comparison between the wall 8 and the wall 13. Results found in the Figure 13 show that the use of PCM integrated in brick envelope's wall diminish the temperature fluctuations by about 0.5 °C to 2.6 °C in July and by about 0.3 °C to 1 °C in January which confirm that the use of PCM regulate the indoor temperature in all cases with variables degrees according to different parameters. In this case of comparison the temperature drop is more interesting in summer season with a significant reduction of interior temperature.

As mentioned in the first scenario, the evaluation of heat transfer ratio is important to analyze the impact of using filled PCM into bricks envelopes. By using the same Equation 6 we calculated the heat transfer ratio in two typical months July and January for the three comparisons mentioned in the first scenario paragraph. Based on the findings presented in Figure 9, it's evident that the use of PCM in the walls can have different effects on heat transfer in summer and winter, explained by the increase in heat transfer ratio in July and its decrease in January.

(a)

(b)

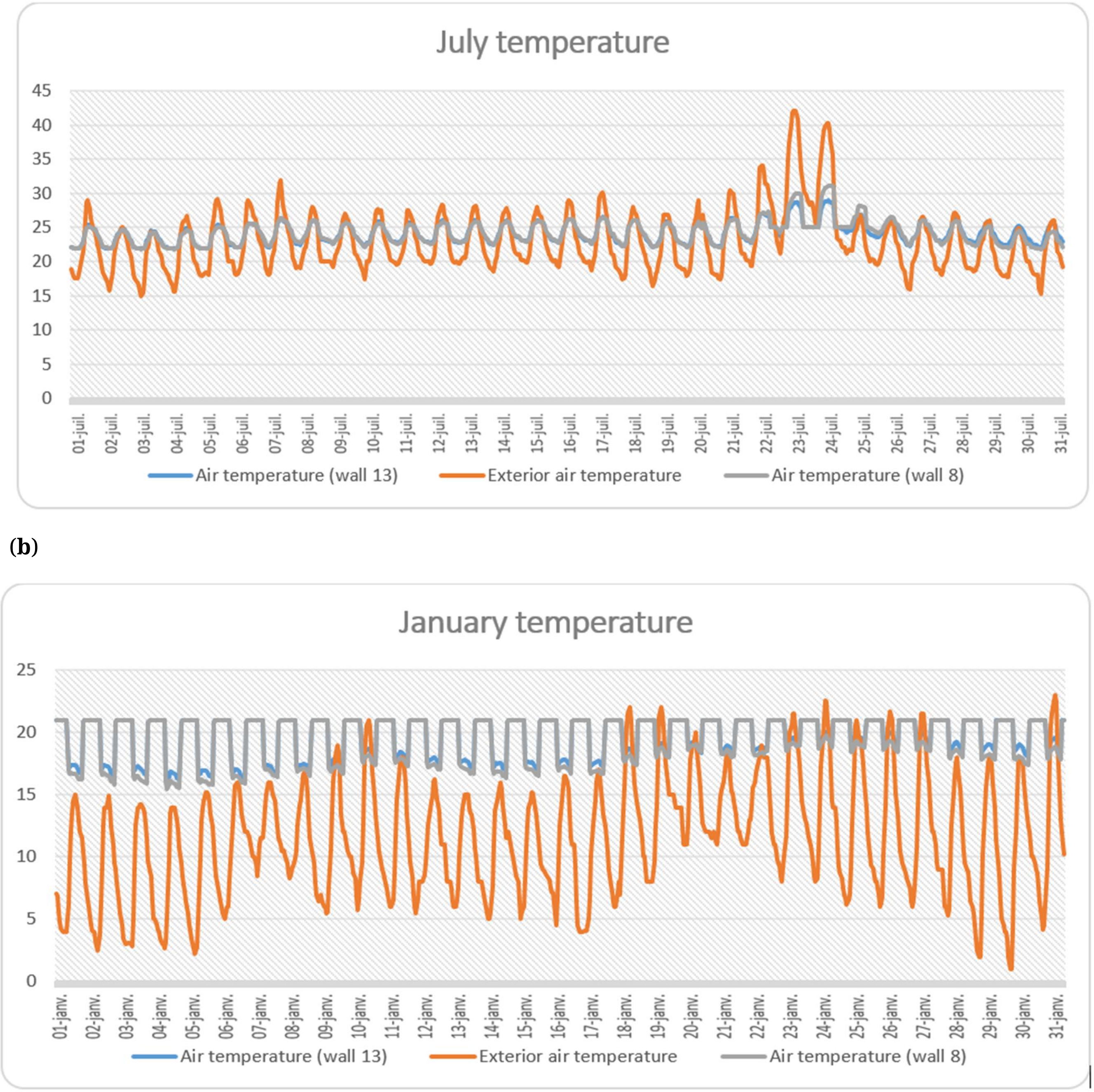
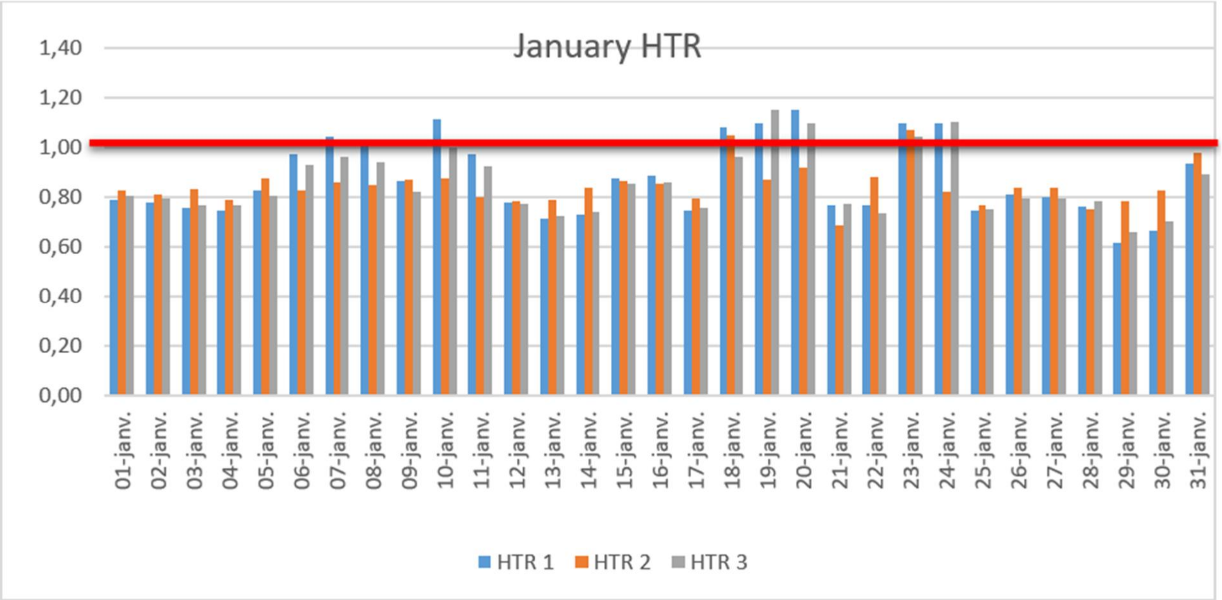


Figure 13. Temperature fluctuations (for wall 8 and wall 13) in typical months: (**a**) July, (**b**) January.

(a)



(b)

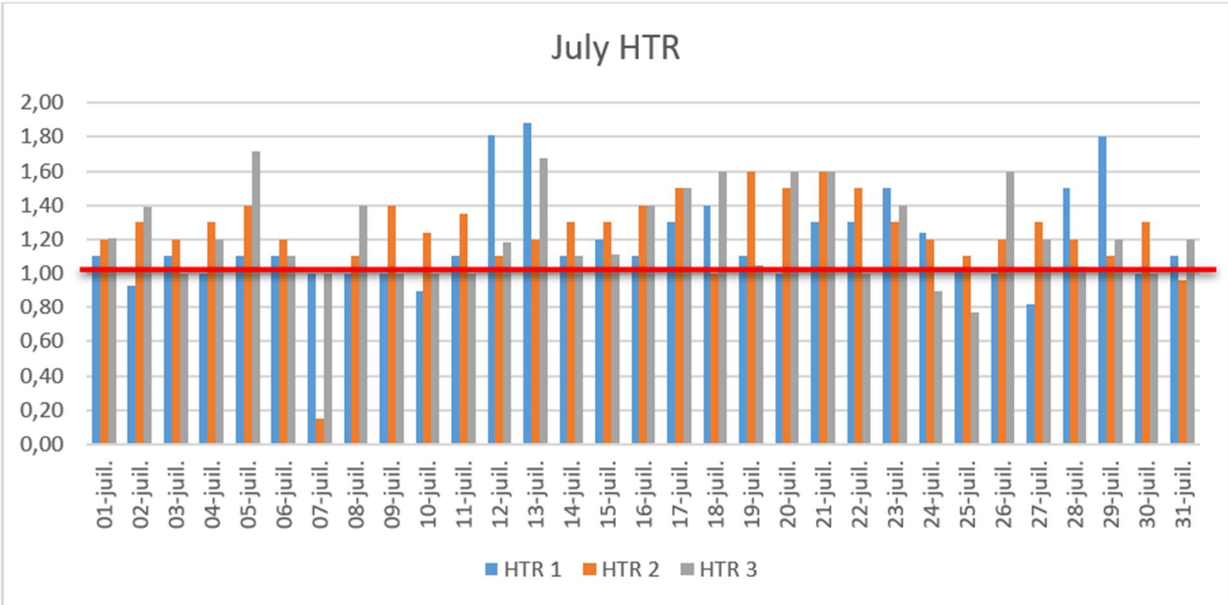


Figure 14. HTR value in the two typical months: (**a**) January and (**b**) July.

In the first graph of Figure 14 it can be observed that the HTR is globally less than one which means that the heat transfer decreases when using PCM into bricks of building envelopes. In January the outdoor temperature is colder than the desired indoor temperature. The PCMs store heat during the day, and release it gradually at night when the outdoor temperature is colder. This can reduce heat loss through the walls and thus leads to a decrease in the heat transfer ratio. Additionally, PCMs act as a thermal buffer, delaying the transfer of heat into the building, which can help maintain a more stable indoor temperature and reduce heat losses.

In summer, the outdoor temperature is generally higher than the desired indoor temperature. If the PCMs are designed to be activated by high temperatures, they can absorb excess heat from the sun and hot climate. This heat absorption can lead to an increase in the heat transfer ratio through the walls. PCMs entering the melting phase absorb latent heat at a constant temperature, which can prevent excessive indoor temperature rise. This can be particularly beneficial for regulating indoor temperature and reducing the need for active cooling systems.

The Table 6 below show a comparison of the results found in the present study with other research.

Table 6. Comparison studies.

Work	ECR (%)	Reduction of HTR	Temperature fluctuations
Reference [22]	--	--	2 °C to 6 °C
Reference [25]	34.80%	--	2 °C to 5 °C
Reference [26]	--	29.70%	--
Reference [32]	11%	11%	--
This work	28%	21%	1° C to 4 °C

CONCLUSION

In conclusion the present paper analyzes the impact of incorporating PCM into hollow bricks envelope's building considering two different scenarios and 14 wall compositions. In the first scenario an annual analysis has been done to evaluate the energy saving and the heat transfer ratio for the different configurations. And in the second scenario a monthly analysis of heat transfer ratio and temperature fluctuations has been carried out for two typical months of winter and summer considering the optimum wall composition found in the first scenario. The most important findings are:

- The configuration involving wall 13 and wall 4 demonstrates the lowest values of total annual energy consumption with. These two wall compositions provide further evidence for the positive influence achieved by employing filled PCM within the double layer bricks.
- The use of PCM filled into double bricks layers of building envelope ensure a maximum energy saving rate of 41%, 35% and 31% respectively for single brick of type 2 filled with PCM (wall 6), double bricks of type 1 filled with PCM (wall 4), and double bricks of type 1 and 2 from interior to exterior filled with PCM (wall 13).
- The envelope featuring wall 13 proves more suitable for winter heating, exhibiting a reduction of 2230 kWh in energy consumption during colder months. Conversely, the envelope containing wall 3 is better suited for cooling, as it only consumes 34 kWh during the summer season.
- The analysis of the heat transfer ratio (HTR) of each wall along the year shows that the heat transfer rate decreases with the use of PCM in

winter and increases in summer. These results are confirmed with the monthly analysis of HTR in July and January. In summer, PCMs can absorb heat to regulate indoor temperature, potentially increasing heat transfer. In winter, they can store and release heat to reduce heat losses, potentially decreasing heat transfer.

- The incorporation of filled PCM into brick envelopes reduces temperature fluctuations by approximately 1 °C to 5 °C in July and around 1 °C to 4 °C in January.

DATA AVAILABILITY

All data generated from the study are available in the manuscript.

AUTHOR CONTRIBUTIONS

Yousra M'hamdi designed the study, made the simulations, analyzed the results and wrote the paper. Khadija BaBa validated the study simulations and analysis. Mohammed Tajayouti helped in writing the paper and validation of results.

CONFLICTS OF INTEREST

The author declares that there is no conflict of interest.

REFERENCES

1. Salvalai G, Pfafferott J, Jacob D. Validation of a low-energy whole building simulation model. Available from: https://www.researchgate.net/profile/Graziano-Salvalai/publication/265264650_VALIDATION_OF_A_LOW-ENERGY_WHOLE_BUILDING_SIMULATION_MODEL/links/548a9f1d0cf225bf669c8345/VALIDATION-OF-A-LOW-ENERGY-WHOLE-BUILDING-SIMULATION-MODEL.pdf. Accessed 2023 Oct 18.
2. Liu L, Hammami N, Trovalet L, Bigot B, Habas JP, Malet-Damour B. Description of phase change materials (PCMs) used in buildings under various climates: A review. J Energy Storage. 2022;56:105760.
3. Zhu N, Deng R, Hu P, Lei F, Xu L, Jiang Z. Coupling optimization study of key influencing factors on PCM trombe wall for year thermal management. Energy. 2021;236:121470.
4. Wang H, Lu W, Wu Z, Zhang G. Parametric analysis of applying PCM wallboards for energy saving in high-rise lightweight buildings in Shanghai. Renew Energy. 2020;145:52-64.
5. Wieprzkowicz A, Heim D. Modelling of thermal processes in a glazing structure with temperature dependent optical properties-An example of PCM-window. Renew Energy. 2020;160:653-62.
6. M'hamdi Y, Baba K, Tajayouti M, Nounah A. Parametric analysis of the use of PCM in building energy performance Avialable from: https://link.springer.com/book/9783031439216. Accessed 2023 Oct 18.

7. Shen Y, Liu S, Zeng C, Zhang Y, Li Y, Han X, et al. Experimental thermal study of a new PCM-concrete thermal storage block (PCM-CTSB). Constr Build Mater. 2021;293:123540.
8. Saxena R, Rakshit D, Kaushik SC. Experimental assessment of Phase Change Material (PCM) embedded bricks for passive conditioning in buildings. Renew Energy. 2019;149:587-99.
9. Uludaş MÇ, Tuncbilek E, Yıldız Ç, Arıcı M, Li D, Krajčík M. PCM-enhanced sunspace for energy efficiency and CO_2 mitigation in a house in mediterranean climate. J Build Eng. 2022;57:104856.
10. Lee KO, Medina MA, Raith E, Sun X. Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management. Appl Energy. 2015;137:699-706.
11. Sanna A, Di Giuda G, Chiara Tagliabue L. Towards a New Ethics in Building. Available from: https://rivistatema.com/sito/wp-content/uploads/2023/06/d-2-288-TEMA-Vol9-No1-2023_10.30682tema0901n_EDITORIAL_SANNA-et-al.pdf. Accessed 2023 Oct 18.
12. Kuznik F, Virgone J, Johannes K. Development and validation of a new TRNSYS type for the simulation of external building walls containing PCM. Energy Build. 2010;42(7):1004-9.
13. Chhugani B, Yasin M, Klinker F, Weinlaeder H, Weismann S, Reim M. Performance analysis and energy saving potential of room integrated PCM wallboards for passive cooling application. IOP Conf Ser Earth Environ Sci. 2019;290(1):012142.
14. Arivazhagan R, Prakash SA, Kumaran P, Sankar S, Loganathan GB, Arivarasan A. Performance analysis of concrete block integrated with PCM for thermal management. Mater Today. 2020;22:370-4.
15. Al-Yasiri Q, Szabo M. Effect of encapsulation area on the thermal performance of PCM incorporated concrete bricks: a case study under Iraq summer conditions. Case Stud Constr Mater. 2021;15:e00686.
16. Tunçbilek E, Arıcı M, Bouadila S, Wonorahardjo S. Seasonal and annual performance analysis of PCM-integrated building brick under the climatic conditions of Marmara region. J Therm Anal Calorim. 2020;141:613-24.
17. Mourid A, El Alami M, Kuznik F. Experimental investigation on thermal behavior and reduction of energy consumption in a real scale building by using phase change materials on its envelope. Sustain Cities Soc. 2018;41:35-43.
18. Yu H, Li C, Zhang K, Song Y, Wang M. Preparation and thermophysical performance of diatomite-based composite PCM wallboard for thermal energy storage in buildings. J Build Eng. 2020;32:101753.
19. Li L, Yu H, Liu R. Research on composite-phase change materials (PCMs)-bricks in the west wall of room-scale cubicle: Mid-season and summer day cases. Build Environ. 2017;123:494-503.
20. Wang X, Yu H, Li L, Zhao M. Experimental assessment on a kind of composite wall incorporated with shape-stabilized phase change materials (SSPCMs). Energy Build. 2016;128:567-74.

21. Fraine Y, Seladji C, Aït-Mokhtar A. Effect of microencapsulation phase change material and diatomite composite filling on hygrothermal performance of sintered hollow bricks. Build Environ. 2019;154:145-54.
22. Souci OY, Houat S. Numerical study of thermos physical properties of a hollow brick filled by the PCM. J Mater Environ Sci. 2017;8:2213-20.
23. M'hamdi Y, Baba K, Tajayouti M, Nounah A. Energy, environmental, and economic analysis of different buildings envelope integrated with phase change materials in different climates. Sol Energy. 2022;243:91-102.
24. Peel MC, Finlayson BL, McMahon TA. Climate types over North Africa based on the Köppen-Geiger climate classification system, 1980–2016. Available from: https://www.researchgate.net/figure/Climate-types-over-North-Africa-based-on-the-Koeppen-Geiger-climate-classification-system_fig1_341192742. Accessed 2023 Oct 18.
25. U.S. Department of Energy. Engineering Reference. Available from: https://energyplus.net/assets/nrel_custom/pdfs/pdfs_v22.1.0/EngineeringReference.pdf. Accessed 2023 Oct 18.
26. Cabeza LF, Castellon C, Nogues M, Medrano M, Leppers R, Zubillaga O. Use of microencapsulated PCM in concrete walls for energy savings. Energy Build. 2007;39(2):113-9.
27. Kumar S, Arun Prakash S, Pandiyarajan V, Geetha NB, Antony Aroul Raj V, Velraj R. Effect of phase change material integration in clay hollow brick composite in building envelope for thermal management of energy efficient buildings. J Build Phys. 2020;43(4):351-64.
28. Tabares-Velasco PC, Christensen C, Bianchi M. Verification and validation of EnergyPlus phase change material model for opaque wall assemblies. Build Environ. 2012;54:186-96.
29. Sage-Lauck JS, Sailor DJ. Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building. Energy Build. 2014;79:32-40.
30. Qu Y, Zhou D, Xue F, Cui L. Multi-factor analysis on thermal comfort and energy saving potential for PCM-integrated buildings in summer. Energy Build. 2021;241:110966.
31. Jia C, Geng X, Liu F, Gao Y. Thermal behavior improvement of hollow sintered bricks integrated with both thermal insulation material (TIM) and Phase-Change Material (PCM). Case Stud Therm Eng. 2021;25:100938.
32. Abu-Hamdeh NH, Melaibari AA, Alquthami TS, Khoshaim A, Öztop HF, Karimipour A. Efficacy of incorporating PCM into the building envelope on the energy saving and AHU power usage in winter. Sustain Energy Technol Assess. 2021;43:100969.

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