Journal of Advanced Engineering Trends
ISSN : 2682 - 2091

Vol. 44, No. 1, January 2025

Influence of Embedding Paraffin Wax in Trombe Wall on Heating of Buildings

Rehab M. Helmi[1,*], Amr S. H. Abdallah[2], Mohamed S. Abd-Elhady[3,4] ,
Abdel Monteleb M. Aly[5]

[1] *Architectural Engineering Dep., Faculty of Engineering, Beni-Suef University, Beni-Suef, Egypt*
[2] *Architectural Engineering Dep., College of Engineering, Imam Mohammad Ibn Saud Islamic University (IMSIU), Riyadh, Saudi Arabia*
[3] *Mechanical Engineering Department, Faculty of Engineering, Beni-Suef University, Beni-Suef, Egypt*
[4] *Mechatronics Dep., Faculty of Engineering and Materials Science, German University in Cairo (GUC), Cairo, Egypt*
[5] *Architectural Engineering Dep., Faculty of Engineering, Assiut University, Assiut, Egypt*
** Corresponding author(s) E-mail: rehab_elkashf2005@yahoo.com*

ARTICLE INFO

Article history:
Received: 25 September 2024
Accepted: 3 January 2025
Online: 2 March 2025

Keywords:
Trombe wall,
Heating capacity,
Phase change material (PCM),
Paraffin wax.

ABSTRACT

The residential buildings sector in Egypt represents the largest sector that consumes energy, with a rate of 40.5%. The Trombe wall is a passive design technique that contributes to reducing energy consumption in buildings.The objective of this research is to improve the heating capacity of the Trombe wall by embedding a phase change material (PCM), i.e. Paraffin wax, in the wall. A test room was built in the new city of Beni-Suef, Egypt, to evaluate the performance of the modified Trombe wall, which is integrated with a PCM. The dimensions of the Trombe wall are 2 m × 2.7m, and is painted black, and a single pane of glass of thickness 6 mm is installed outside the wall, leaving an air gap of 30 cm. The indoor air temperature of the test room in the winter of 2023 was measured and compared in cases of (a) traditional wall, (b) traditional wall with PCM and (c) a Trombe wall integrated with PCM. It has been found that the maximum temperature difference between the indoors and outdoors temperatures in cases (a) and (b) were 4oC and 5.2oC, respectively, however, using a Trombe wall integrated with PCM, increased the temperature difference to 7.1oC. The period during which the room temperature was higher than the outside temperature in case of the Trombe wall was 20.5 h. It can be concluded that integrating a PCM in the Trombe wall resulted in a more stable and comfortable indoor climate.

1. Introduction

Buildings use almost one-third of all energy produced worldwide. Thus, they are the largest energy-consuming sector. Yet, according to Rabani et al., buildings are a significant source of carbon dioxide (CO2) emissions (Rabani et al. 2017). In Egypt, the residential building sector accounts for the majority of energy consumption, accounting for 40.5% of total electric energy consumed in the country (Egyptian Electricity Holding Company, report 2020-2021). It is inevitable to come out with alternatives and solutions that reduce energy consumption because residential buildings consume more energy than others (Fahmy et al. 2023). According to Bevilacqua et al., the Trombe Wall is a passive solar energy technique that, when implemented correctly, can reduce the requirement for heating energy and change the summertime behavior of buildings (Bevilacqua et al. 2019). The conventional Trombe wall design is based on the use of materials that possess high heat-storage capacities. These materials include concrete, stone, and brick. Khatib et al. stated that in order to enhance solar ray absorption, the Trombe wall's outer surface is painted black and there is an air gap between it and the glass cover (Khetib et al. 2021). The Operating principle of classic Trombe wall operation is that solar radiation heats the thick wall. In reaction, the wall warms the air in the room through radiation heat exchange and convection. To ensure the necessary air circulation, ventilation openings are used in both the upper and lower sections of the Trombe wall (Sergei et al. 2020).

One of the deficits of the Trombe wall is its low heat resistance. The phenomenon known as an inverse thermosiphon when a portion of the heat flux from the inside escapes to the outside during night or under protracted cloud cover. When the storage wall is colder than the air in the vented layer, as it often is at night during the winter, the air is cooled and re-entered into the room through the bottom venting hole, The room temperature drops as a result (Hu et al. 2017). The thermal storage capacity of the Trombe wall can be increased, hence increasing the quantity of solar energy that is stored and used, by adding a phase change material (PCM). PCM is frequently utilized for thermal energy storage in buildings due to its high latent heat and minimal volumetric change (Duan et al. 2021). PCM is mostly employed passively at the roof, ceiling, wallboard, window, floor, and solar chimney. PCM lessens the impact of heat transfer between the buildings and the outside environment, particularly during peak hours, by raising the thermal mass of these components. This lessens the peak heating or cooling load on a structure. Moreover, PCM lessens the effect of external temperature fluctuations on these crucial components of the building envelope, which lowers the variability in interior room temperature. It is therefore an effective approach to maintain the room temperature within its occupants' thermal comfort zone (Li et al. 2020).

There are two types of PCM materials: inorganic and organic. Salt hydrate derivatives are among the inorganic materials. Organic materials, which include fatty acids and paraffin, exhibit greater thermal stability than salt hydrates (Sergei et al. 2020). According to Elmarghany et al. (2022), high energy storage capacity, minimal volume expansion, high chemical stability, suitable pricing, non-toxicity, and non-corrosiveness are the qualities of a successful PCM. Further, the melting and solidification temperatures should be suitable (Elmarghany et al. 2022). The study used paraffin wax as a PCM because of its advantageous properties. However, there are certain disadvantages. These include limited heat conductivity, mild flammability, and incompatibility with plastic packaging (Memon 2014). Among the articles published on PCM integrated in buildings, the authors include PCM Trombe walls, PCM Wallboards and PCM building blocks together which are collectively called PCM walls. In fact, the principle is to make the PCM or PCM building blocks part of the wall structure, creating walls with high thermal inertia without the large mass associated with it (Cui et al. 2017). The objective of incorporating PCM into a Trombe wall is to increase the thermal inertial of the wall without increasing the mass of the wall extensively. The following is a review of the methods of incorporating PCMs into the Trombe wall and its influence on the performance of the wall, as well as incorporating PCMs into the building bricks.

1.1. Integrating Trombe wall with PCM

Several studies have explored the integration of phase change materials (PCMs) into Trombe wall to enhance their thermal performance. Zhu et al. (Zhu et al. 2019) conducted a simulation of a Trombe wall combined with a double-layer PCM board. They found that it reduced heating loads by 15% and peak cooling loads by 9% compared to a standard Trombe wall. The PCM room showed an average internal temperature 3.28°C lower in summer and 0.11°C higher in winter, compared to the reference room. Li et al. (Li et al. 2022) investigated a Trombe wall system with PCMs and compared its performance to conventional lightweight buildings and traditional Trombe walls. They concluded that placing PCM next to the inner wall surface achieved the lowest annual indoor discomfort. Zhou et al. (Zhou et al. 2018) introduced a ventilated Trombe wall with encapsulated active PCM wallboards, identifying optimal melting temperatures and thicknesses of PCM for boosting energy storage and release efficiency (ESRE) in both summer and winter climates in China. Mabrouki et al. (Mabrouki et al. 2023) combined a Trombe wall with PCM in a simulated single-room house, finding significant reductions in heating and cooling loads —30.13% for light storage walls and 25.45% for heavy storage walls. In a semi-oceanic climate, they determined that a 3 cm thick RT 28 HC PCM was most effective, reducing the annual load to 789.83 kWh. Duan et al. (Duan et al. 2021) tested PCM properties in a small-scale Trombe wall under laboratory conditions and found that the PCM integrated with the Trombe wall could increase indoor temperatures by 0.82°C to 1.88°C and 1.75°C to 3.27°C, depending on the temperature input mode. Kong et al. (Kong et al. 2022) developed a double-layered PCM Trombe wall and observed that it provided higher maximum temperatures in winter compared to room with single-layered PCM or without PCM and the normal double-layered PCM Trombe room. Samiev et al. (Samiev et al. 2022) conducted numerical and experimental study on the Trombe wall's thermal characteristics and found that using a Trombe wall in Uzbekistan could cut energy consumption used for heating by 36%, with specific energy consumption reduced to 56.6% when using the Trombe wall with PCM. Chaichan and Abaas (Chaichan and Abaas 2015) tested a Trombe wall with paraffin wax PCM in Baghdad's winter, demonstrating its effectiveness in heating buildings due to its high storage capacity and affordability. Leang et al. (Leang et al. 2020) evaluated the impact of PCM on a Trombe wall’s thermal performance across three climates and observed a 20% reduction in heating demand, with the PCM Trombe wall performing slightly better. Chaichan et al. (Chaichan et al. 2016) designed a Trombe wall combining sensible and latent heat storage methods using water and paraffin wax, concluding that this approach stores solar energy and heats buildings after sunset in an efficient manner. A summary of the above studies, which is about integrating a PCM into the Trombe wall, is presented in Table 1.

1.2. Integrating building bricks with PCM

Kumar et al. (Kumar et al. 2020) explored the integration of phase change materials (PCMs) into clay hollow bricks under Indian climatic conditions. They constructed two test rooms—one incorporating PCM and the other without—and examined their thermal behavior. Their study revealed that the Incorporation of PCM led to a 6°C reduction in room temperature during January. Rehman et al. (Rehman et al. 2021) investigated the effectiveness of utilizing dual PCMs year-round to enhance the thermal mass of brick walls. Their findings indicated that dual PCM configurations are effective for maintaining thermal comfort in both summer and winter conditions in Islamabad, Pakistan. Elmarghany et al. (Elmarghany et al. 2022) simulated two different models over a year to assess energy savings from integrating PCM into bricks. Their analysis indicated that PCM integration improves the thermal properties of building materials, with varying arrangements and types affecting performance. Tunçbilek et al. (Tunçbilek et al. 2020) conducted a study on the thermal performance of PCM-integrated bricks, focusing on optimal placement, quantity, and melting temperatures under Marmara region conditions in Turkey. They found that PCM-enhanced bricks significantly reduce heating and cooling loads, thus

Table 1: Influence of incorporating a PCM with Trombe wall

Ref.	PCM application	Type of study	Location and Region	Objectives	Results and Conclusion
(Zhu et al. 2019)	**Double-layered PCM panel.**	**Numerical**	**Wuhan, China.**	**● Introduction of a new Trombe wall combined with a dual-layered PCM panel to attain indoor thermal comfort in both summer and winter.**	**● The integration of PCM with the Trombe wall enhances thermal comfort by minimizing internal temperature variations in comparison to the traditional Trombe wall design.**
(Li et al. al. 2022)	**A single layer of XPS- PCMs composite board with a PCM.**	**Numerical and Experimental**	**Changsha, China.**	**● Simulation and evaluation of thermal comfort in Trombe wall system with added PCM to determine the best wall structure for regions with cold winters and hot summers, as well as to choose the appropriate PCM for various climate conditions.**	**● The Trombe wall, when combined with PCM placed near the inner surface of the wall, showed the lowest annual duration of indoor discomfort and integrated indoor discomfort degree-hour.**
(Zhou et al. 2018)	**PCM double wall panels include an external PCM wall panel and an internal PCM wall panel with active hot/cooled water piping.**	**Numerical**	**Hot summer and cold winter region of China.**	**● Proposition a new ventilated Trombe wall integrated with an encapsulated active PCM wallboard to assessment the thermal performance and energy performance, as well as to choose the appropriate PCM for various climate conditions.**	**● The researchers discovered the ideal melting temperature and thickness for PCM that could greatly enhance ESRE while cooling and heating.**
(Mabrouki et al. 2023)	**Aluminum plates with micro-encapsulated PCMs make up the paraffin utilized in the simulation.**	**Numerical**	**Ifrane city, Morocco, with a semi-oceanic climate.**	**● Studying the impact of various factors on the heating and cooling load of the PCM Trombe wall through integration with PCM.**	**● The findings indicated that the yearly burden on light storage walls dropped by 30.13%, while for heavy storage walls, it decreased by 25.45%.** **● The optimal PCM for a Trombe wall had a 3 cm thickness, resulting in an annual load reduction to 789.83 kWh.**
Duan et al. 2021)	**A stainless steel container containing an encapsulated PCM (a mixture of 55% decanoic acid and 45% lauric acid).**	**Experimental**	**China.**	**● Improving the thermal performance of the Trombe wall.**	**● The integration of a Trombe wall with PCM can result in raising the indoor air temperature by 0.82°C - 1.88°C in the low-temperature input mode and 1.75°C - 3.27°C in the high-temperature input mode.**
(Kong et al. 2022)	**External and internal wallboards of PCM, Phase change microcapsules were made from paraffin, expanded perlite and styrene-acrylic emulsion.**	**Numerical**	**Tianjin, China.**	**● Achieving indoor thermal comfort and energy efficiency can be accomplished by suggesting a PCM Trombe wall with a double-layer design.**	**● The internal thermal environment is effectively improved and controlled by the double-layer PCM Trombe wall.**
(Samiev et al. 2022)	**Installing the Trombe wall with PCM (organic RT24).**	**Numerical and Experimental**	**Uzbekistan.**	**● To assess the potential for energy savings while employing the Trombe wall, a numerical and experimental investigation of the wall's thermal properties should be conducted (with and without a PCM).**	**● During the heating period, energy consumption will be reduced by 36% when using the Trombe wall.** **● By incorporating a Trombe wall with PCM, the specific energy consumption can be lowered to 56.6% during the heating season.**
(Chaichan and Abaas 2015)	**Aluminum pipes filled with paraffin wax.**	**Experimental**	**Baghdad-Iraq.**	**● A study was carried out to improve the heat storage capability of a Trombe wall by integrating paraffin wax as a phase change material (PCM).**	**● The potential for heating Iraqi buildings in winter was demonstrated through using the proposed Trombe wall.**
(Leang et al. 2020)	**Microencapsulated PCM.**	**Numerical**	**Three different climate conditions (Paris, Lyon and Nice).**	**● Influence of PCM incorporation on the thermal performance of a Trombe wall composite storage wall.**	**● The findings indicated that the heating energy demand decreased by around 20%, specifically 20.45% for a Trombe wall and 19.90% for a PCM Trombe wall, in comparison to a house lacking a Trombe solar wall.**
(Chaichan et al. 2016)	**The space between the plate and the bottle was filled with paraffin wax.**	**Experimental**	**Baghdad-Iraq.**	**● Develop a novel Trombe wall that integrates the two methods of heat storage (SHS and LHS).** **● The study's objective was to ascertain the amount of energy provided to the Trombe wall, as well as the duration required for charging and the real-world factors affecting its performance.**	**● The test outcomes demonstrated the effectiveness of this wall in retaining solar energy. This wall can be utilized during the winter to help heat residences after the sun has set.**

Table 2: Influence of incorporating a PCM with building bricks of wall

Ref.	PCM application	Type of study	Location and Region	Objectives	Results and Conclusion
(Kumar et al. 2020)	**PCM is encapsulated in an aluminum foil packet.**	**Numerical and Experimental**	**Chennai city, India.**	**● Investigated the thermal performance of PCM by incorporating it into clay hollow bricks and analyzing the thermal behavior of the chambers. ● The Design Builder software was used to conduct simulations, and the results of the simulations were then compared to the experimental results.**	**● The addition of the PCM led to a decrease of up to 6°C in room temperature in January and a decrease of less than 2°C in July.**
(Rehman et al. 2021)	**Double layer PCM.**	**Numerical and Experimental**	**Islamabad, Pakistan.**	**● Organic and inorganic PCMs are being evaluated to take advantage of their diverse thermophysical properties. ● Conducting a lab experiment to assess how two layers of PCM integrated with concrete respond to thermal changes.**	**● The findings indicated that the dual PCM configuration is appropriate for use in buildings to ensure the thermal comfort of the occupants during both summer and winter.**
(Elmarghany et al. 2022)	**Paraffin wax PCM filled inside plastic tubes.**	**Numerical and Experimental**	**Egypt.**	**● An evaluation was conducted over a one-year period to assess the energy conservation achieved by using phase change materials in the construction of bricks. ● Explored the process of estimating energy by utilizing commercially available red bricks that are filled with PCM.**	**● The thermal properties of the building materials are improved through the incorporation of PCM into the block, as indicated by the results.**
(Tunçbilek et al. 2020)	**Brick filled with PCM.**	**Numerical**	**Marmara region, Turkey.**	**● Investigation into the thermal efficiency of conventional bricks combined with PCM. ● Investigation into the best placement, amount, and melting point of PCM.**	**● Integrating PCM with a suitable melting temperature into bricks has the potential to decrease heating and cooling demands. ● Incorporating PCM into bricks led to a 17.6% decrease in annual energy demand.**
(Wang et al. 2016)	**SSPCMs with a particle size of 0.5–5mm and was constituted of HDPE, expanded graphite and paraffin, (The SSPCMs-bricks).**	**Experimental**	**Hot summer and cold winter region in Shanghai.**	**● The thermal performance of a composite wall containing PCM was compared to that of a conventional wall.**	**● The thermal performance of a wall constructed with PCM is outstanding all year round. ● The use of PCM wall can result in a 10 to 30% decrease in heating load. Additionally, it can lead to a reduction of 24.32% in the cooling load during summer conditions.**

improving occupant comfort. Wang et al. (Wang et al. 2016) compared the thermal performance of composite PCM walls to traditional walls and found that PCM walls offered superior performance year-round, reducing heating loads by 10% to 30% and cooling loads by 24.32% in summer. Table 2 presents a summary of previous studies of PCM incorporation in brick.

Although there are studies that investigated the incorporation of PCM into Trombe wall in different ways that were mentioned previously, as well as studies that combined PCM with bricks. Most of these researches combined PCM either as layers, wallboards or capsules with the Trombe wall and installed them either inside or outside the wall component of the Trombe wall or both. However, these studies did not deal with the incorporation of the Trombe wall with PCM by filling the holes of clay bricks with PCM under the climatic conditions of Egypt. The objective of this paper is to improve the heating capacity of the Trombe wall by filling the perforated clay bricks forming the wall with a PCM. A test room was built to evaluate the influence of the modified Trombe wall, which was combined with a phase change material, i.e. paraffin wax, on heating of the room.

2. Experimental Setup

2.1. Test room

A test room was built in the new city of Beni-Suef, Egypt. The average annual temperatures for the Beni-Suef city range between 37°C, i.e. the highest maximum in June and July, and 5.6°C, which is the lowest minimum in January (Ministry of Housing, Utilities and Urban Communities, New Beni Suef City Authority 2015). A photo and sketch of the test room are shown in Fig. 1. The test room is 6.4 m by 4.2 m and the height of the room is 2.7 m. The door of the test room is installed in the Eastern wall and the Trombe wall is installed in the south wall, two windows have been installed on the northern wall to boost ventilation and air circulation within the room. The test room was built to evaluate the influence of the Trombe wall, which is integrated with a phase change material (PCM), on the heating of the room. The external dimensions of the Trombe wall are 2 m in length and 2.7 m in height, as shown in Fig. 2. The room was built with common bricks and the structural system consists of load-bearing walls made of hollow clay bricks with a thickness of 25 cm. The ceiling is made of reinforced concrete. The room is attached to a bathroom with internal dimensions of 3.7 m x 1.4 m. The internal dimensions of the room for which field measurements were made are 4.25 m x 3.7 m. The thermophysical properties of the building materials for the test room are shown in Table 3.

2.2. Experimental methodology

Three experiments were conducted to evaluate the influence of embedding a PCM material in the Trombe wall on the heating performance of the wall. In the first experiment, the test room is built from traditional walls, i.e. without Trombe wall. Measurements of the outside temperature and indoor temperature in the test room were taken in the winter of 2023 for a period of 24 hours from 7:00 am on January 13 until 7:00 am on January 14. In the second experiment, hollow clay bricks has been added at the center of the south wall of the test room, such that the overall dimension of the bricks is 2 m x 2.4 m, and a PCM, i.e. Paraffin wax, has been added to the bricks. Paraffin wax has been melted, and then poured in the holes of the clay bricks, and then left for a period of time until the wax hardened inside the brick's holes, as shown in Fig. 3. Then, the bricks were used in the southern wall of the test room, as shown in Fig. 2.a. The hollow bricks have been painted externally in black in order to improve the absorptivity of the surface. The thermal properties of the PCM are given in Table 4. Building walls from hollow bricks that is filled with paraffin wax is expensive and consumes time if compared to just building the wall from traditional hollow bricks.

In the third experiment, the southern wall has been changed into a Trombe wall by adding a glass cover over the hollow clay bricks that has been added previously to the southern wall, as can be seen in Fig. 2. Two openings have been made in the hollow clay brick, in order to promote the air circulation inside the test room. The dimensions of each opening are 0.75 m x 0.25 m, and the position of the openings is shown in Fig. 2. The glass cover is transparent glass of thickness 6 mm. The air gap between the glass cover and the hollow bricks is 30 cm, and the hollow bricks are

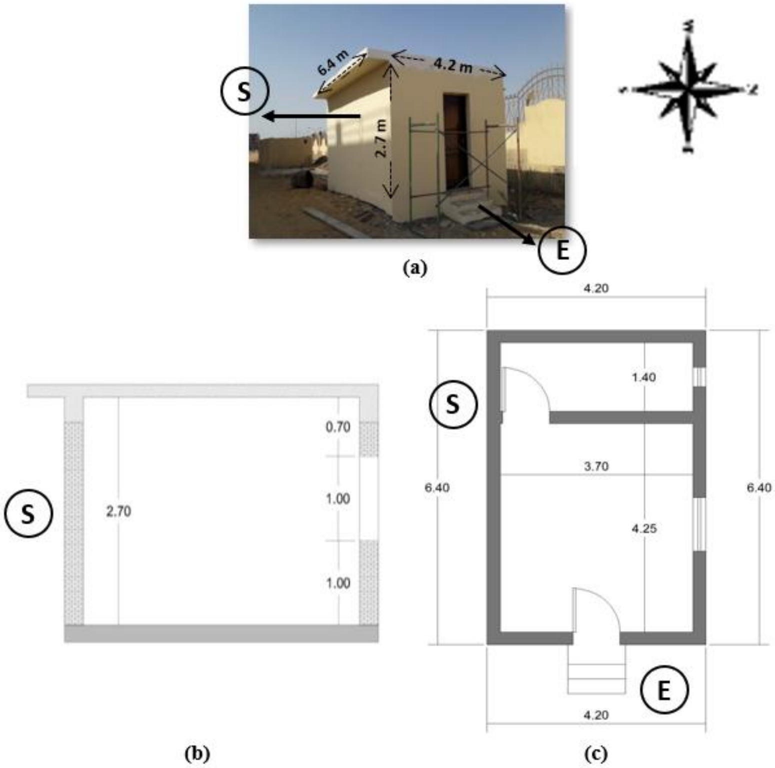

Figure 1: (a) A photo, (b) cross sectional elevation and (c) plan of the test room. All dimensions are in m.

filled with wax as in the previous experiment, i.e. the second experiment. In all of the performed experiments the indoor and outdoor temperatures were measured every 5 minutes from 7 am till 7 am next day, and then the results were analyzed and compared to evaluate the performance of the modified Trombe wall. The research methodology is summarized in Fig. 4.

2.3. Testing conditions

1- All windows and doors of the test room were closed during the measuring period.

2- There is no human activity, equipment or artificial lighting in the room.

3- The bottom and the top holes of the Trombe wall were opened for 24 hours during the measuring period.

4- Indoor and outdoor temperature measurements were taken by calibrated digital temperature sensors, i.e. Elitech RC-51H, of an accuracy of ±0.5ºC. The indoor temperature was measured by placing the temperature sensor in the middle of the room and at a height of 1 m, while the outdoor temperature was measured by placing the temperature sensor outside the test room and very close to the Northern wall.

3. Experimental results and discussion

3.1. Indoor and outdoor temperatures of the test room in case of traditional walls

The outdoor and indoor temperatures were measured for the test room in the winter of 2023 for a period of 24 hours from 7:00 am on the 13th of January to 7:00 am on the 14th of January, and the results are shown in Fig. 5. The temperatures were taken every 5 minutes, and it was found that the maximum outdoor temperature was 19.3°C and the minimum temperature was 9.1°C, while the maximum indoor room temperature was 17.7°C and the minimum temperature was 12.8°C. The temperature difference between the indoor temperature and the outdoor temperature is also presented in Fig. 5. The highest temperature difference between the indoor and the outdoor temperatures was 4°C at 7:00 am, and the lowest difference was -4.1°C at 10:00 am. The indoor temperature was lower than the outdoors in the period from ٨:00 am to ٥:00 pm, i.e. during daylight, and it is higher than the outdoor temperature in the period from ٥:00 pm to 8:00 am, i.e. almost after sunset, as can be seen in Fig. 5. It can be concluded that the time during which the room temperature is lower than the ambient temperature, which will be named as the cold period, is 9 h, while the period in which the room temperature is higher than the ambient temperature, which will be named as the hot period, is 15 h. The walls of the test room absorb and store the incident solar energy during the daylight, i.e. from 8 am till 5 pm, which leads to a low temperature inside the test room compared to the ambient air. However, after sunset, the outside air temperature decreases below the room’s wall temperature, such that the walls start to radiate the heat stored within the walls causing heating of the test room and the temperature of the room becomes higher than the ambient air at night.

3.2. Indoor and outdoor temperatures of the test room in case of a traditional wall with PCM

The outdoor temperature and the temperature inside the test room were measured in the winter of 2023 for a period of 24 hours, from 7:00 am on the 12th of February to 7:00 am on the next day.

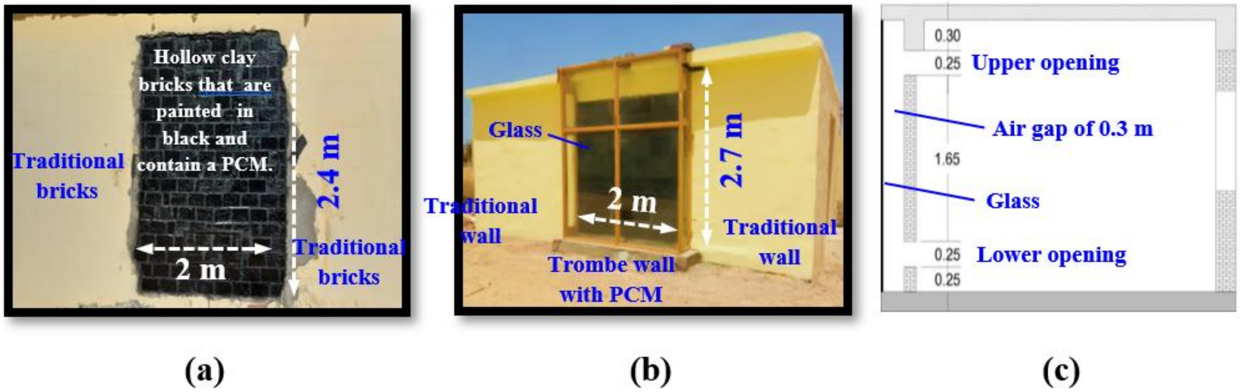

Figure 2: A photo of the south wall of the test room integrated with (a) hollow clay bricks that contain PCM, (b) Trombe wall and (c) sketch of the Trombe wall

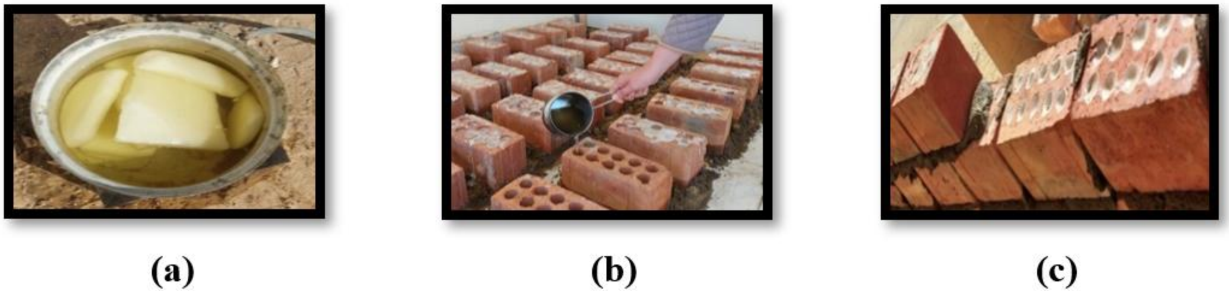

Figure 3: Steps of filling hollow clay bricks with Paraffin wax; (a) melting of wax, (b) pouring the molten wax in the holes of the bricks and (c) leaving the wax for a while to cool down and solidify

A PCM has been embedded to a portion of the south wall of the test room, which is 2 m wide and located in the center of the wall, and the height of that portion is equal to the height of the South wall, as can be seen in Fig. 6. This portion of the wall has been painted black using a black paint spray, in order to improve its absorptivity. The temperatures were taken every 5 minutes, and the results are shown in Fig. 6, such that the maximum outdoor temperature was 20.1°C and the minimum was 6.9°C, while the maximum indoor room temperature was 16.7°C and the minimum was 11.4°C. The temperature difference between the indoor and the outdoor temperatures is also presented in Fig. 6, such that the highest temperature difference was 5.2°C at 3:34 am and the lowest difference was -7.8°C at 10:29 am. The indoor temperature was lower than the outdoor temperature in the period from 8:00 am to 4:00 pm, i.e. the cold period, and it is higher than the outdoor temperature in the period from 4:00 pm to 8:00 am, which is the hot period. It can be concluded that the cold period of the test room is 8 hours and it is during the daylight, and the hot period is at night and it is for 16 hours. The PCM absorbs and stores the incident solar energy during the day, such that when the temperature of the PCM increases above the melting point, the PCM melts and stores the incident solar energy in the form of latent heat of fusion. However, at night the ambient temperature drops below the melting temperature of the PCM, such that the molten PCM solidifies and radiates the stored latent heat outdoors as well as indoors, such that the room temperature rises above the ambient temperature. Adding a PCM to the south wall of the test room decreased the cold period by 1 h and increased the hot period by 1 h, if compared to the non PCM case. It can be concluded that adding a PCM to the south wall of the test room has a marginal influence on the thermal performance of the room if compared to the traditional wall case, i.e. without a PCM.

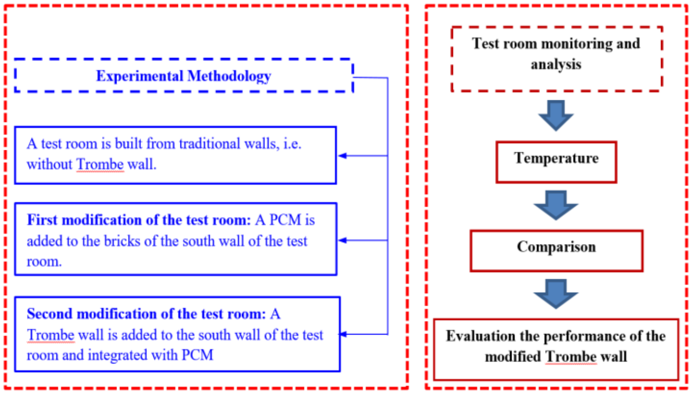

Figure 4: Research methodology

Table 3. The thermophysical properties of building materials for the test room

Ref.	Building materials	Specific heat (kJ/kg)	Thermal conductivity (W/m°C)	Density (kg/m3)
(Energy planning system, 1998)	Hollow clay brick	835	0.55 - 0.65	1850 - 2000
(Energy planning system, 1998)	Concrete slab (ceiling)	653	0.93	2300
(Energy planning system, 1998)	Common plaster (coating)	835	0.75	2100
(Ministry of Housing 2006)	Floor (ceramic tiles)	-	1.6	2000

Table 4: The thermal properties of the paraffin wax used in the experiments

Ref.	PCM Material	Melting temperature (°C)	Latent heat of fusion (kJ/kg°C)	Thermal conductivity (W/m°C)	Density (kg/m^3)	
					Solid	Liquid
(Swami et al. 2018)	Paraffin wax C23–24	45–48	170	0.21	912	769

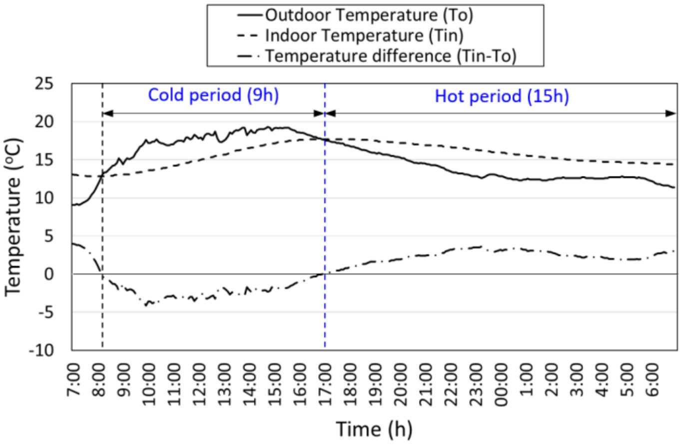

Figure 5: The indoor and the outdoor temperatures of the test room on the 13th of January 2023 in case of no Trombe wall, i.e. traditional wall

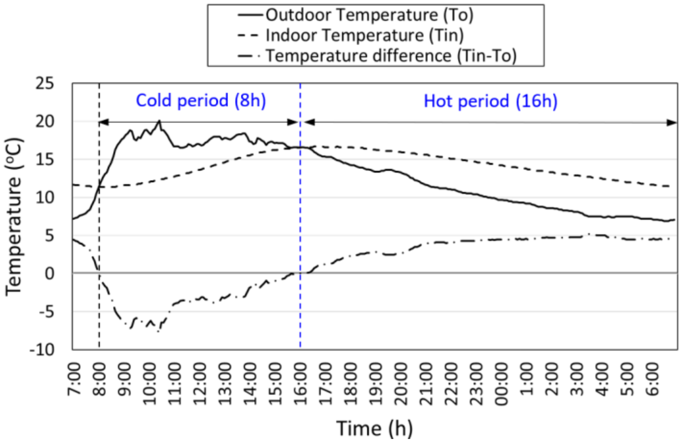

Figure 6: The indoor and the outdoor temperatures of the test room on the 12th of February 2023 in case of a traditional wall embedded with PCM

3.3. Indoor and outdoor temperatures of the test room in case of a Trombe wall integrated with PCM

A Trombe wall has been added to the middle portion of the South wall, which has been painted in black and in which a PCM has been embedded, as can be seen in Fig. 2. The width of the Trombe wall is 2 m and the height is equal to the height of the South wall. The thickness of the glass plate used in the Trombe wall is 6 mm, and the distance between the glass plate and the wall of the Trombe wall is 30 cm. An upper and a lower opening in the wall of the Trombe wall have been made, with dimensions of 75 cm width and 25 cm height. The outdoor temperature and the temperature inside the test room were measured in the winter of 2023 for a period of 24 hours, from 7:00 am on the 14th of March to 7:00 am on the next day. The temperatures were measured every 5 minutes, and the results are presented in Fig. 7. The maximum outdoor temperature was 25.5°C and the minimum temperature was 11°C, while the maximum indoor room temperature was 25.7°C and the minimum temperature was 17.2°C. The temperature difference between the indoor temperature and the outdoor temperature is also presented in Fig. 7. The highest temperature difference between the room temperature and the outdoor temperature was 7.1°C at 1:00 am, and the lowest difference was -4.2°C at 9:37 am. The indoor temperature was lower than the outdoor temperature in the period from 8:00 am to 11:30 am, i.e. the cold period, and it is higher than the outdoor temperature in the period from 11:30 am to 8:00 am next day, which is the hot period, as can be seen in Fig. 7. It can be deduced that the warming up period of the test room, i.e. the cold period, in case of using a Trombe wall is 3.5 h, and the hot period is 20.5 h. It can be concluded that using a Trombe wall has decreased the cold period and increased the hot period in comparison to using a traditional wall or using a traditional wall embedded in it a PCM.

The incident solar radiation is trapped in the air gap between the glass surface and the wall of the Trombe wall during the daylight, and that energy is stored afterwards in the PCM embedded in the building blocks of the Trombe wall. When the temperature of the Trombe wall becomes higher than the room temperature, heat is transferred from the Trombe wall to the test room by convection via the openings in the Trombe wall and also by radiation causing heating of the room. Heat loss from the Trombe wall to the ambient air is minimized due to the glass cover of the Trombe wall, which diminishes heat transfer by radiation to outdoors and also minimizes heat transfer by convection. The heat energy stored in the Trombe wall depends on the amount of PCM embedded in the building blocks of the Trombe wall, and that heat energy determines the hot period. The combination of the Trombe wall with a PCM improved the thermal performance of the wall, which is consistent with some of the aforementioned studies (Duan et al. 2021; Chaichan and Abaas 2015). The period in which the room temperature is higher than the outside temperature in case of using a traditional wall or a traditional wall embedded in it a PCM were 15 h and 16 h, while in case of the Trombe wall is 20.5 h. The proposed design of the Trombe wall, which is embedding a phase change material, i.e. paraffin wax, in the building bricks of the wall increased the solar energy storage capacity of the wall, consequently increased the hot period, i.e. the time at which the wall transfers heat to the room and causes heating of the room.

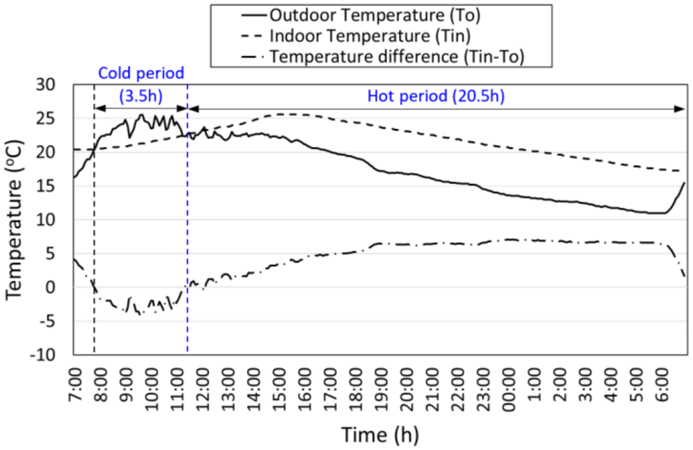

Figure 7: The indoor and the outdoor temperatures of the test room on the 14th of March 2023 in case of a Trombe wall integrated with PCM

3.4. Discussion of Results

The temperature difference, ΔT, between the indoor room temperature, Tin, and the outdoor temperature, To, were compared in case of (a) no Trombe wall, i.e. traditional wall, (b) traditional wall with PCM and (c) a Trombe wall integrated with PCM. The average temperature difference along the different periods of the day for the different tested cases are presented in Fig. 8. The Trombe wall embedded with PCM has resulted in increasing the temperature difference between the room temperature and the outside air more than in case of using a traditional wall embedded with or without a PCM, e.g. the Trombe wall has resulted in increasing the temperature difference between the room temperature and the outside air from 6 pm to 1 am to be 6.3ºC, while in case of using a traditional wall with PCM is 3.6ºC and in case of a traditional wall without a PCM is 2.4ºC. Embedding a PCM in the building bricks of the test room walls is not as efficient as embedding the PCM in the Trombe wall, and that is due to the glass cover of the Trombe wall which decrease the heat energy loss by radiation and convection. Embedding the PCM in the building bricks of the Trombe wall improves the heating performance of the wall, which is a new technique to improve the heating capabilities of the Trombe wall, however, it is an expensive building method compared to the traditional methods in which the PCM is just a sheet placed either on the outer surface or the inner surface of the Trombe wall.

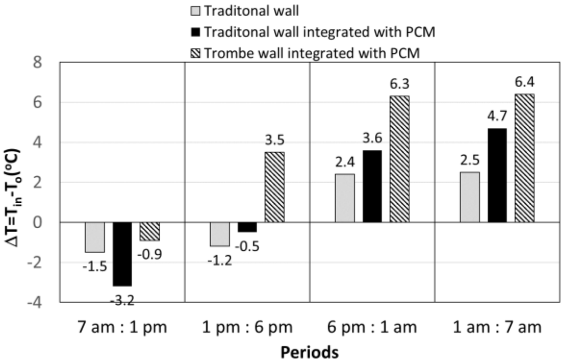

Figure 8: The average maximum difference between the indoor and the outdoor air temperature

4. Conclusions

This study focuses on improving the thermal performance of the Trombe wall, by embedding a phase change material (PCM) in the building bricks of the Trombe wall. The PCM used in this study is paraffin wax. A test room was built in the new city of Beni-Suef, Egypt, to evaluate the performance of the modified Trombe wall. The indoor air temperature of the test room in the winter of 2023 was measured and compared in cases of (a) no Trombe wall, i.e. traditional wall, (b) traditional wall with PCM and (c) a Trombe wall integrated with PCM. It has been found that:

1. The Trombe wall embedded with a PCM has resulted in increasing the temperature difference between the room temperature and the outside air more than in case of using a traditional wall embedded with or without a PCM.
2. Embedding PCM in the building bricks of the Trombe wall has decreased the cold period and increased the hot period of the test room in comparison to using a traditional wall or using a traditional wall embedded in it a PCM.
3. Embedding a PCM in the building bricks of the test room walls is not thermally efficient as embedding the PCM in the Trombe wall and that is due to the glass cover of the Trombe wall which decreases the heat energy loss by radiation and convection.

Embedding the PCM in the building bricks of the Trombe wall is an expensive building method compared to the traditional techniques in which the PCM is just a sheet placed either on the outer surface or the inner surface of the Trombe wall.

Conflict of Interest

The authors declare no conflict of interest.

Nomenclature

ESRE	Energy Storage and Release Efficiency
LHS	Latent Heat Storage
PCM	Phase Change Material
SHS	Sensible Heat Storage
T_{in}	Indoor Temperature (°C)
T_o	Outdoor Temperature (°C)
ΔT	Average temperature difference between the indoor and the outdoor temperature (°C) $\Delta T = T_{in} - T_o$

References

1. Bevilacqua, P., Benevento, F., Bruno, R. and Arcuri, N. (2019). "Are Trombe walls suitable passive systems for the reduction of the yearly building energy requirements?." Energy, vol. 185, pp. 554-566.

2. Chaichan, M. T., Abaas K. I., and Al-zubaidi, D. S. M. (2016). "A Study of a Hybrid Solar Heat Storage Wall (Trombe Wall) Utilizing Paraffin Wax and Water." Quest Journals, vol. 2, pp.1-7.

3. Chaichan, M. T., and Abaas K. I. (2015). "Performance Amelioration of a Trombe Wall by Using Phase Change Material (PCM)." International Advanced Research Journal in Science, Engineering and Technology, vol. 2, pp. 1-6.

4. Cui, Y., Xie, J., Liu, J., Wang, J. and Chen, S. (2017). "A Review on Phase Change Material Application in Building." Advances in Mechanical Engineering , vol. 9(6), pp.1-15.

5. Duan, S., Li, H., Zhao, Z. and Wang, L. (2021). "Investigation on Heating Performance of an Integrated Phase Change Material Trombe Wall Based on State Space Method." Journal of Energy Storage, vol. 38, pp.102460.

6. Duan, S., Wang, L., Zhao, Z. and Zhang, C. (2021). "Experimental Study on Thermal Performance of an Integrated PCM Trombe Wall." Renewable Energy, vol. 163, pp. 1932-1941.

7. Egyptian Electricity Holding Company. n.d. “The Annual Report 2020-2021.”

8. Elmarghany, M. R., Radwan, A., Shouman, M. A., Khater, A. A., Salem, M. S. and Abdelrehim, O. (2022). "Year-Long Energy Analysis of Building Brick Filled with Phase Change Materials." Journal of Energy Storage, vol. 50, pp. 104605.

9. Energy planning system. (1998). Architecture and Energy Guidebook.

10. Fahmy, S. B., Zamzam, M., Khalil T., Abdalla, Y., Loeffler, T., Abd-Elhady, M.S. (2023). "Influence of the Hot Water Mass Flow Rate on Heating of Radiant Floors of Green Buildings." Journal of Building Physics.

11. Hu, Z., He, W., Ji, J. and Zhang, S. (2017). "A Review on the Application of Trombe Wall System in Buildings." Renewable and Sustainable Energy Reviews, vol. 70, pp. 976-987.

12. Khetib Y., Alotaibi, A. A., Alshahri, A. H., Cheraghan, G., Sharifpur, M. and Meyer,J. P. (2021) "Study on the effect of hole size of trombe wall in the presence of phase change material for different times of a day in winter and summer." Processes, vol. 9.

13. Kong, X., Li, J., Fan, M., Li, W. and Li, H. (2022). "Study on the Thermal Performance of a New Double Layer PCM Trombe Wall with Multiple Phase Change Points." Solar Energy Materials and Solar Cells, vol. 240, pp. 111685.

14. Kumar, S., Prakash, S. A., Pandiyarajan, V., Geetha, N. B., Raj,V. A. A. and Velraj, R. (2020). "Effect of Phase Change Material Integration in Clay Hollow Brick Composite in Building Envelope for Thermal Management of Energy Efficient Buildings." Journal of Building Physics, vol. 43(4), pp. 351-364.

15. Leang, E., Tittelein, P., Zalewski, L. and Lassue, S. (2020). "Impact of a Composite Trombe Wall Incorporating Phase Change Materials on the Thermal Behavior of an Individual House with Low Energy Consumption." Energies, vol. 13(18), pp. 1-32.

16. Li, J., Zhang, Y., Zhu, Z., Zhu, J., Luo, J., Peng, F. and Sun, X. (2024). "Thermal Comfort in a Building with Trombe Wall Integrated with Phase Change Materials in Hot Summer and Cold Winter Region without Air Conditioning." Energy and Built Environment, vol. 5, pp.58-69.

17. Li, Y., Nord, N., Xiao, Q. and Tereshchenko, T. (2020). "Building Heating Applications with Phase Change Material: A Comprehensive Review." Journal of Energy Storage, vol. 31, pp. 101634.

18. Mabrouki, A., Karim, Y. B., Hassani, H. O., Jamali, Y. and Khaldoun, A. (2023). "A Study of a Passive Heating Design Employing a Trombe Wall with PCM: A Numerical Investigation of the Semi-Oceanic Climate in Morocco." Materials Today: Proceedings, vol. 72, pp. 3626-3631.

19. Memon, S. A. (2014). "Phase Change Materials Integrated in Building Walls: A State of the Art Review." Renewable and Sustainable Energy Reviews, vol. 31, pp. 870–906.

20. Ministry of Housing, Utilities and Urban Communities, New Beni Suef City Authority, General Administration of Environmental Affairs. 2015. “Environmental Characterization of the New City of Beni-Suef.”

21. Ministry of Housing, Utilities & Urban Communities and Housing & Building National Research Center (HBRC). 2006. The Egyptian Code to Improve Energy Efficiency in Buildings, ECP 306 - 2005.

22. Rabani, M., Madessa, H. B. and Nord, N. (2017). "A State-of-Art Review of Retrofit Interventions in Buildings towards Nearly Zero Energy Level." Energy Procedia, vol. 134, pp. 317-326.

23. Rehman, A. U., Sheikh, S. R., Kausar, Z. and McCormack, S. J. (2021). "Numerical Simulation of a Novel Dual Layered Phase Change." Energies, vol. 14(13).

24. Samiev, K. A., Mirzaev, M. S. and Ibragimov, U. X. (2022). "Annual Thermal Performance of a Passive Solar Heating System with a Trombe Wall with Phase Change Materials." IOP Conference Series: Earth and Environmental Science, vol. 1070(1).

25. Sergei, K., Shen, C. and Jiang, Y. (2020). "A Review of the Current Work Potential of a trombe wall." Renewable and Sustainable Energy Reviews, vol. 130, pp. 109947.

26. Swami, V. M., Autee, A.T. and Anil, T R. (2018). "Experimental Analysis of Solar Fish Dryer Using Phase Change Material." Journal of Energy Storage, vol. 20, pp. 310-315.

27. Tunçbilek, E., Arıcı, M., Bouadila, S. and Wonorahardjo, S. (2020). "Seasonal and Annual Performance Analysis of PCM-Integrated Building Brick under the Climatic Conditions of Marmara Region." Journal of Thermal Analysis and Calorimetry, vol. 141, pp. 613-624.

28. Wang, X., Yu, H., Li, L. and Zhao, M. (2016). "Experimental Assessment on the Use of Phase Change Materials (PCMs)-Bricks in the Exterior Wall of a Full-Scale Room."Energy Conversion and Management, vol. 120, pp. 81–89.

29. Zhou, Y., Yu, C. W. F. and Zhang, G. (2018). "Study on Heat-Transfer Mechanism of Wallboards Containing Active Phase Change Material and Parameter Optimization with Ventilation." Applied Thermal Engineering, vol. 144, pp. 1091–1108.

30. Zhu, N., Li, S., Hu, P., Lei, F. and Deng, R. (2019). " Numerical investigations on performance of phase change material Trombe wall in building." Energy, vol. 187, p. 116057.