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Article

Exploring the impact of nano-enhanced phase change materials on Trombe wall efficiency

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ABSTRACT

A novel Trombe wall design that incorporates highly thermally conductive materials along with nano-enhanced phase change material is presented. Performance analysis is conducted using finite element method simulations. A comparative study of NePCM and PCM in a room with a Trombe Wall revealed minor differences in thermal performance during January, February, and December, but a significant discrepancy in March due to higher solar radiation levels. The enhanced latent heat storage capability of NePCM contributed to a more sustained temperature increase during periods of intense solar radiation. Over seven months, NePCM demonstrated a 16% higher average energy gain compared to PCM, attributed to its improved thermal conductivity and heat transfer efficiency. These findings indicate that nano-enhanced phase change materials are more effective than their non-nano counterparts. The results indicate a substantial impact of the system, raising room temperatures to 22°C during the day and resulting in significant energy savings.

1. Introduction

Historically, numerous researchers have sought new energy sources in response to global energy crises. In this context, extensive studies have been conducted on alternative fuels and solutions that can replace fossil resources. To achieve sustainable development, countries require a reliable supply of clean and safe energy that minimizes environmental impacts [1]. Consequently, the exploration of renewable energy sources has become a crucial area of focus. This increasing interest in renewable energy has attracted considerable attention. Turkey, in particular, emphasizes the development of domestic and renewable energy sources, in line with the goals set forth in the National Energy Policy of 2017. As a testament to this commitment, Turkey has risen to the fifth position in Europe and twelfth globally in terms of installed renewable energy capacity. By the end of 2022, renewable sources accounted for 54% of Turkey's total installed energy capacity [2]. The global energy crisis and the urgent need for sustainable solutions have driven intensive research into renewable energy sources. Turkey, endowed with significant solar potential, has emerged as a key player in the renewable energy landscape. This study examines Turkey's impressive growth in solar energy, particularly in Istanbul, a city characterized by unique weather conditions. By analyzing statistical data from the International Renewable Energy Agency [3] and national energy ministries [4], this research investigates the critical role of solar energy in residential heating within the specific context of Istanbul. The building sector is responsible for 30-40% of global energy consumption, with nearly half of this energy allocated to heating and cooling systems to maintain indoor comfort [5,6]. This significant energy usage contributes substantially to global greenhouse gas emissions, highlighting the urgent need for reduction strategies. The United States aims to decrease building energy consumption by 70% by 2020 as part of federal policy initiatives [7], while China has set ambitious targets to cut energy usage in new constructions by 50% [8]. Furthermore, rising fossil fuel consumption and electricity demand underscore the necessity for more efficient building practices. Addressing these challenges is essential for mitigating environmental impacts and promoting sustainable energy practices. Various methods utilizing solar energy are implemented in construction, including passive walls with solar facades, natural ventilation systems, architectural solar roofs, solar chimneys, and Trombe walls [9,10]. Passive heating and cooling systems capture solar radiation and ambient temperature variations to store energy, which is then released into indoor spaces at optimal times. Trombe walls represent a pioneering approach in passive solar technology, effectively harnessing solar energy to provide space heating in buildings for several decades. These thermal mass walls, typically composed of masonry or concrete, absorb sunlight through a glass facade and subsequently release the stored heat into the interior space. Despite their potential, the thermal performance of Trombe walls can be hindered by various factors, including heat loss through conduction and convection, as well as their dependency on direct sunlight exposure. The well-established Trombe wall functions similarly to a solar thermal collector; it consists of a large wall with an external glazing area that stores solar energy within its mass for later use, particularly after sunset. Other passive systems include solar chimneys, unglazed transpired solar facades, and green walls—all designed to effectively harness natural energy sources. Trombe walls are also known as thermal or storage walls [11]. Trombe walls come in various forms, including classic Trombe walls, aquatic Trombe walls, water Trombe walls, zigzag Trombe walls, composite Trombe walls, solar compound walls, and the widely utilized PV Trombe wall [12]. In existing literature, the Trombe wall stands out as one of the most extensively studied passive systems with numerous configurations explored. In traditional designs, openings are integrated into the solid wall to enable air circulation. During winter months, circulation occurs internally; conversely, during summer months, an external connection is established to enhance ventilation rates [13]. A study by Abbassi et al. [14] examined the effectiveness of Trombe walls in Tunisia's climate and found that a 4 m^2 wall could reduce annual auxiliary heating energy needs by approximately 50%, while an 8 m^2 version could achieve a remarkable 77% reduction. Similarly, Bojic et al. [15] studied a residence in Lyon, France, demonstrating that a south-facing Trombe wall could decrease yearly heating consumption by up to 20%. These studies collectively highlight the versatility and efficiency of Trombe walls across various climates, making them a focal point for research in passive energy systems. Hu et al. [16] investigated the use of Venetian blinds placed between glazing and thermal mass walls and emphasized how blind tilt angles significantly influence natural convection within the air gap.

Likewise, Hong et al. [17] focused on optimizing Venetian blinds integrated into Trombe walls; their findings indicated that an optimal distance of 9 cm between the blinds and glass was effective with a 14 cm air gap. Duan et al. [18] explored placing an absorber plate within the middle of the air gap rather than on the thermal mass wall surface; they demonstrated that this configuration outperformed conventional Trombe walls regarding both energy efficiency and interpretative aspects. Innovative designs for Trombe wall systems have also been explored. Rabani et al. [19] developed a Trombe wall that captures solar irradiation from eastern, western, and southern directions while covering half of the south-facing wall; this cost-effective system provided satisfactory thermal comfort due to its reduced surface area. Shen et al. [20] conducted a comparative analysis between classical and composite Trombe walls and highlighted superior performance for composite designs under cold and overcast weather conditions. Li et al. [21] researched thermal efficiency in PCM-integrated Trombe wall systems through comparative experiments conducted during summer months in hot and humid regions of China; results indicated that PCM-integrated designs exhibited better heat insulation properties compared to standard building envelopes and traditional Trombe wall designs. Recent advancements in materials science have introduced nanoparticles and phase change materials (NePCMs) as promising solutions to enhance the thermal efficiency of Trombe walls. Nanoparticles can significantly improve thermal conductivity, while PCMs are capable of increasing thermal storage capacity by absorbing and releasing heat during phase transitions. The integration of these materials into building energy systems has attracted increasing attention due to their potential to enhance energy efficiency, reduce carbon emissions, and improve occupant comfort. However, despite the growing interest in NePCMs, there remains a substantial gap in research regarding their application in Trombe walls specifically. This study aims to address this gap by investigating the incorporation of NePCMs into Trombe wall systems to enhance their energy efficiency. Through a theoretical analysis of thermal performance, this research seeks to contribute valuable insights into passive solar heating technologies and building energy efficiency strategies.

1.1 Trombe walls

A typical unvented Trombe wall consists of a south-facing masonry structure with a thickness ranging from 10 to 40 cm. The exterior surface of this wall is coated with a dark, heat-absorbing material and is covered by one or two layers of glass. These glass layers are spaced 2 to 5 cm away from the masonry wall, creating a small air gap between them. When sunlight enters through the glass, the dark surface absorbs heat, which is then stored within the wall and gradually conducted inward through the masonry. Using high-transmission glass enhances the solar heat gains captured by the masonry. Additionally, incorporating patterned glass can serve as an architectural feature that obscures the view of the dark concrete wall from outside while still allowing light to pass through. Trombe walls are architectural components designed for passive solar heat absorption, storage, and distribution. Typically made from high-mass materials such as concrete or stone, these walls collect solar radiation during the day and slowly release it into the interior at night, providing consistent and sustainable heating. However, their successful implementation relies on various factors, including orientation, thermal properties, and local climate conditions. The efficiency of Trombe walls across different scenarios has attracted interest from both researchers and building professionals. Different configurations are employed to adapt Trombe walls for various climates, purposes, and seasons, as illustrated in Figure 1 [22].

Several types of Trombe walls exist, including classic and modified designs, zigzag Trombe walls, solar water walls, solar trans walls, solar hybrid walls, Trombe walls with phase change materials (PCM), composite Trombe walls, fluidized Trombe walls, and photovoltaic (PV) Trombe walls [23]. A conventional Trombe wall, also known as a standard Trombe wall, features glass and an air gap that separates it from the outdoor environment [24]. The concept of the Trombe wall was first patented by Edward Morse, an American engineer, in 1881 but gained widespread recognition thanks to Felix Trombe and architect Jacque Michel [25], leading to its common designation as a Trombe wall. Figure 2 shows a PV-Trombe wall equipped with photovoltaic cells that enhance thermal comfort while contributing to electricity generation [26].

1.2 Solar radiation in Istanbul

Turkey has a vast land area well-suited for capturing solar energy, attributed to its favorable geographical position. The country lies between latitudes 36° and 42° N. Historical data gathered by the Turkish State Meteorological Service from 1971 to 2000 indicates a significant solar potential across the nation. On average, Turkey has 2,573 hours of sunshine annually (approximately 7 hours per day) and an average total radiation of 1,474 kWh/m^2 per year (or about 4 kWh/m^2 daily). Figure 3 illustrates the global irradiation levels for Turkey [27].

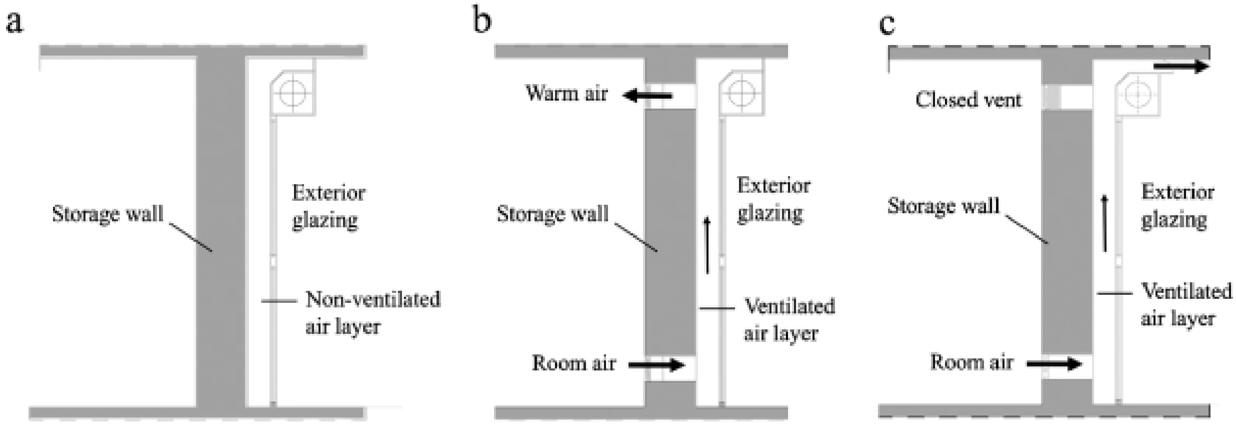

Figure 1. Operating schemes: non-ventilated solar wall (a); Trombe wall in winter mode with air thermo-circulation (b); Trombe wall in summer mode with cross ventilation [22]

Figure 2. Schematic diagram and photograph of PV-Trombe wall for winter heating [26]

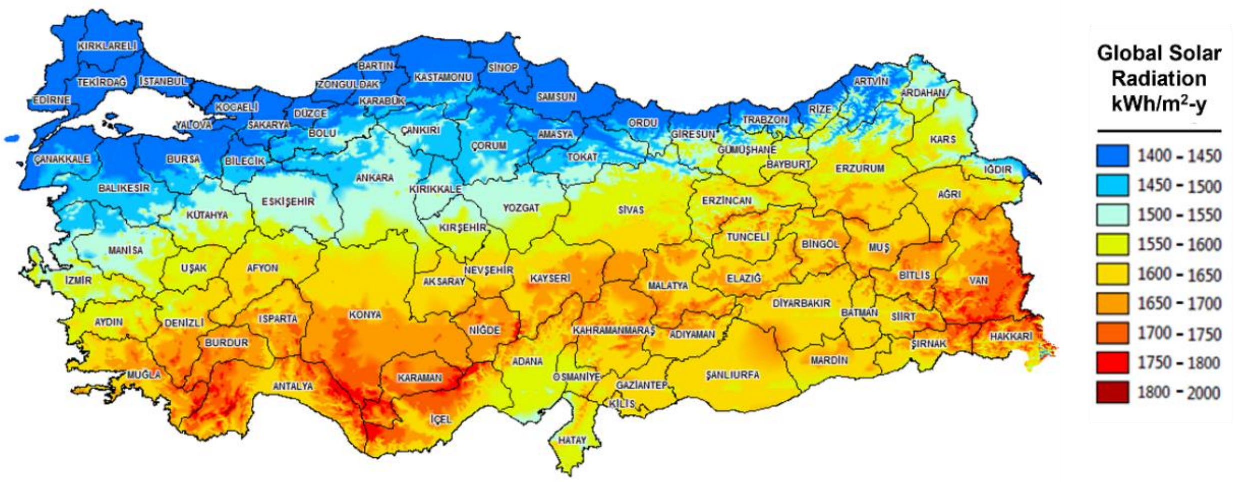

Figure 3. Global irradiation levels for Turkey [27]

With a population exceeding 80 million, Turkey is facing a rising demand for energy, leading to a continuous increase in energy consumption. In 2022, Turkey's per capita energy consumption reached 3,360 kWh [28]. According to the Turkey Energy Efficiency Development Report, approximately 20% of the country's energy and around 22% of total electricity consumption is utilized in households. Of this energy usage, about 60% is allocated to heating in buildings [29]. The average cooling requirement for a typical building in Istanbul is approximately 33.52 kWh/m^2 per year, while the heating requirement is around 84.49 kWh/m^2 per year [30]. Alarmingly, over 75% of this energy is currently supplied through imports, a figure that continues to rise annually. Therefore, it has become increasingly urgent to diversify energy sources by focusing on both domestic non-renewable and renewable resources. Among these alternatives, solar energy stands out as a crucial option with significant potential that remains largely untapped in Turkey. The nation has an average of 200 sunny days each year, providing a solid foundation for developing a comprehensive solar energy strategy. The primary objective of this research is to evaluate the performance of a Trombe wall system integrated into a room within Istanbul. Located at a latitude of 40.58° N, longitude of 29.05° E, and an elevation of 39 meters, Istanbul is one of Turkey's most densely populated urban areas in the northwestern part of the country.

Figure 4 presents data on global solar radiation and sunshine hours for Istanbul. In Istanbul, the average annual global solar radiation is recorded at 1,612 kWh/m^2 per year, with an average annual sunshine duration of 2,446 hours. These values are relatively low compared to many other cities in Turkey. To promote solar energy utilization, the Istanbul Metropolitan Municipality's Geographic Information System (GIS) Directorate has developed the Istanbul Solar Energy Potential Map. A snapshot from this map is shown in Figure 5 [31].

2. Methodology

2.1 Material selection

n-Octadecane, a paraffin-based organic phase change material (PCM), was selected for the present study due to its advantageous properties for industrial applications. The key factors influencing this choice include:

- Thermal Comfort Range: n-Octadecane has a phase change temperature that closely aligns with the optimal range for thermal comfort in indoor environments. This characteristic allows it to effectively absorb and release thermal energy within a temperature range conducive to human comfort.
- High Thermal Conductivity: Compared to other organic PCMs, n-Octadecane exhibits relatively high thermal conductivity. This property facilitates efficient heat transfer both within the material and between the PCM and its surrounding environment.

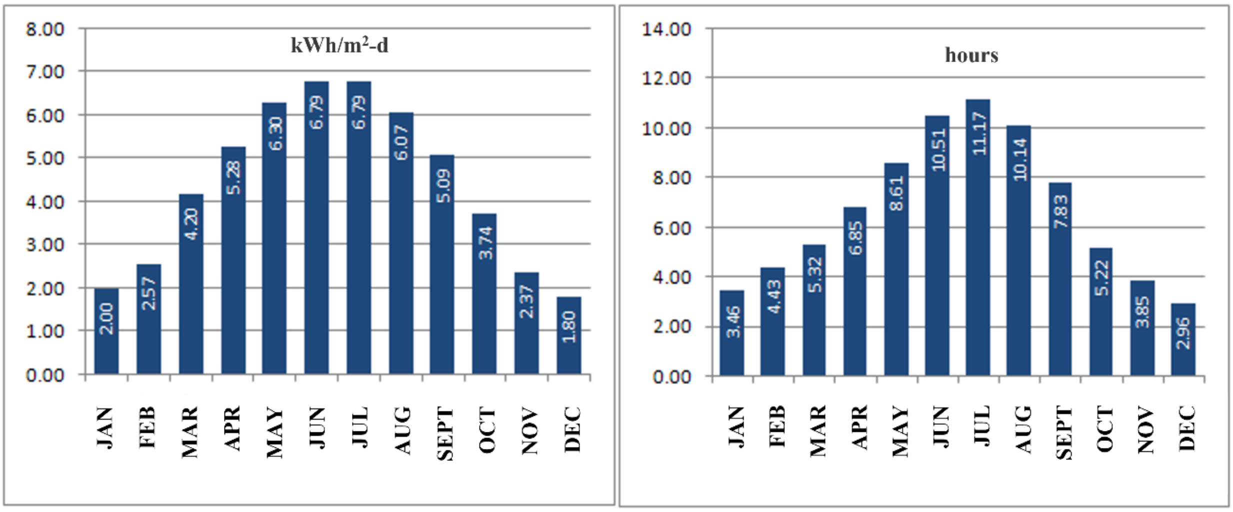

Figure 4. Monthly averaged daily global solar radiation and sunshine duration hours in Istanbul [27]

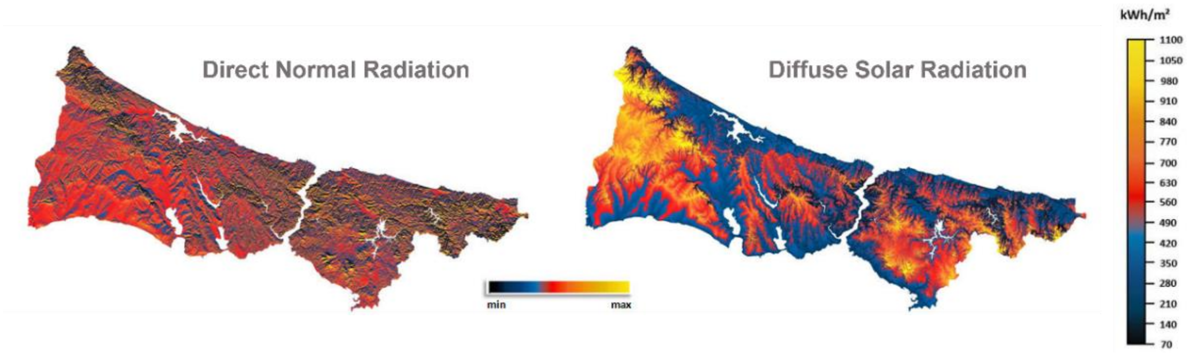

Figure 5. Istanbul Solar Energy Potential Map [31]

- Latent Heat Storage Capacity: n-Octadecane possesses a significant latent heat of fusion, enabling it to store a substantial amount of thermal energy per unit mass during its phase transition. This maximizes its potential for energy storage.

In the study, n-Octadecane ($C_{18}H_{38}$) was chosen as the primary PCM due to its melting point of 28°C, which is well-suited for maintaining thermal comfort in occupied spaces. This property allows n-Octadecane to effectively store and release thermal energy within the desired temperature range. To enhance the PCM's performance the nano-enhancement expandable graphite (EG), a carbon-based compound, was selected for its compatibility with n-Octadecane. Both materials share graphite as a common source, ensuring chemical compatibility and minimizing potential adverse interactions within the composite.

2.2 Trombe wall construction

The Trombe wall was designed with two essential components:

- Highly Thermal Conductive Encapsulation: The outer layer was constructed using pyrolytic graphite, a highly ordered form of graphite known for its exceptional thermal conductivity (approximately 1800 W/m·K in-plane). This high conductivity ensures efficient heat transfer from the solar-heated exterior surface to the PCM layer within the wall.
- Energy Storage Substance (PCM): The core of the Trombe wall consisted of the PCM layer containing n-Octadecane, with or without nano-enhanced EG for comparative analysis. During daylight hours, the PCM absorbed thermal energy from the sun-heated pyrolytic graphite and released it back into the room as temperatures dropped, thereby providing passive heating during colder periods.

2.3 Room construction

The surrounding room walls were constructed from concrete, selected for its robust thermal mass, which helps regulate fluctuations in room temperature. Additionally, a glass window was incorporated into the design to allow direct solar radiation onto the Trombe wall, optimizing its potential for thermal gain. Detailed properties of the materials used in this system are summarized in Table 1 for reference.

The subject of this study is a small room with an approximate area of 15.5 m^2, which includes four external walls, a roof, and a ground floor. A window is situated on the south side, adjacent to the Trombe wall (TW). The configuration of the room featuring the Trombe wall is depicted in Figure 6, showcasing a unique setup regarding both its placement and operational mechanism. The TW is constructed from a highly thermally conductive material (pyrolytic graphite) and utilizes phase change material (PCM) for energy storage. This innovative design presents several advantages, making it an intriguing subject for examinations. Firstly, it does not include any ventilation gaps, setting it apart from other types of Trombe walls documented in the literature. Secondly, it functions as a hybrid system that allows the wall to transfer heat into the room while storing some energy in the PCM for use during nighttime. The dimensions and configuration of the TW considered in the calculations are shown in Figure 7. The thermal and mechanical properties of the materials used in the TW are summarized in Table 2. Although the Trombe wall is primarily intended for use during the eight cold months in Istanbul, analyses and calculations were conducted for all twelve months. Weather and solar data specific to Istanbul for each month are detailed in Table 3.

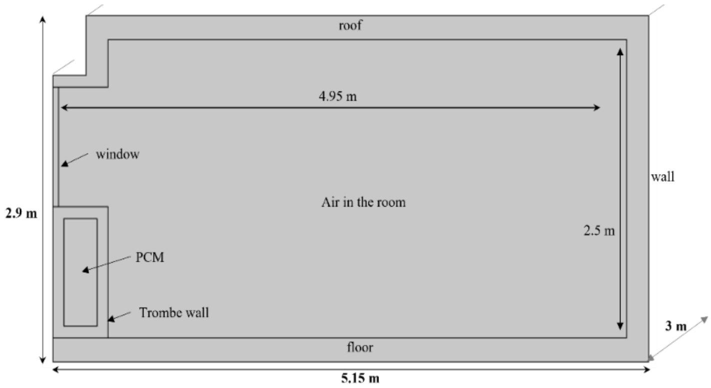

Figure 6. Dimensions and configuration of the analyzed Trombe wall

Table 1. Material properties [32]

Property	Pyrolytic Graphite	PCM (n-octadecane)	NePCM (n-octadecane/EG)	Concrete Wall	Glass Window
Density (kg/m³)	2100	814	-	2300	2203
Specific heat (J/kgK)	850	2660	-	880	703
Thermal conductivity (W/mK)	1800	0.36	1.11	1.8	1.38
Melting point (°C)	-	28	23	-	-
Latent heat (kJ/kg)	-	244	196.8	-	-

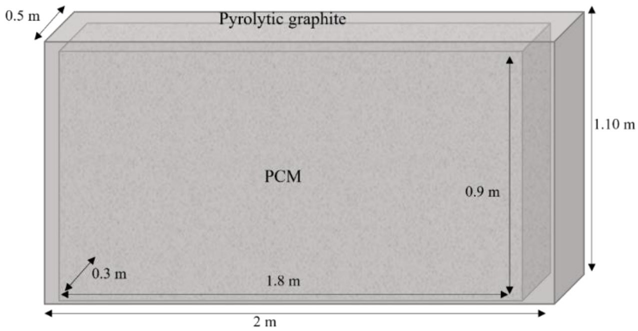

Figure 7. Dimensions of the Trombe wall

Table 2. Properties of TW materials [32, 33]

Thermal and Mechanical Property	Pyrolytic Graphite	PCM (paraffin)
Density (kg/m³)	2100	912
Specific heat (J/kgK)	850	2310
Thermal conductivity (W/mK)	1800	0.21
Melting point (°C)	-	31.9

Table 3. The weather and solar data specific to Istanbul

Months	DNI (W/m²)	Sunshine (hrs./day)	Ambient temperature, T_a, (°C)	Wind speed, v, (m/s)	h (W/m²K)
Jan	491.33	3.46	6.00	4.81	24
Feb	493.12	4.43	6.10	4.81	24
Mar	671.05	5.32	7.70	4.36	22
Apr	655.18	6.85	12.00	4.03	21
May	621.95	8.61	16.70	3.97	21
Jun	549.14	10.51	21.40	4.28	22
July	516.70	11.17	23.80	4.78	24
Aug	508.83	10.14	23.80	4.78	24
Sep	552.55	7.83	20.10	4.92	24
Oct	609.00	5.22	15.70	4.36	22
Nov	523.25	3.85	11.70	4.25	22
Dec	516.89	2.96	8.20	4.83	24

The weather data, including solar radiation (DNI) and sunshine hours, were averaged for each day of a specific month for these calculations, while convective heat loss due to wind was calculated using Equation (1), as described by Hong et al. [34].

$$h_{wind} = 5.7 + 3.8v_{wind} \quad (1)$$

where v_{wind} represents wind speed.
Simulation of the system was performed regarding time dependent Finite Element Method. Simulation model is calculating the heat load with respect to the effect of the conduction, convection and radiation heat transfer rates as given below.

$$dQ = (q''_{cond} + q''_{conv} + q''_{rad})dt \quad (2)$$

In the FEM, the Navier-Stokes equations are used which govern conservation of mass, momentum, and energy as given trough Eq (3) to Eq (7).
For the conduction calculations in the system following equations are used.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla q = Q \quad (3)$$

$$q = -k\nabla T \quad (4)$$

For the laminar flow of air which is Newtonian in the room and the gravity calculations, equation below was used.

$$\rho \frac{\partial u}{\partial t} + \rho(u\nabla)u = \nabla[-pI + K] + F + \rho g \quad (5)$$

Where,

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \quad (6)$$

$$K = \mu(\nabla u + (\nabla u)^T - \frac{2}{3}\mu(\nabla u)I \quad (7)$$

I is the identity tensor, ρ is the density, u is the velocity vector , p is the pressure, μ is the dynamic viscosity, C_p is the specific heat capacity at constant pressure, T is the absolute temperature, q is the heat flux vector, Q contains the heat sources, k is the Thermal conductivity, F is the buoyancy force and g gravitational acceleration.
Ambient radiation to the surface was calculated as below.

$$-nq = \varepsilon\sigma(T_{amb}^4 - T^4) \quad (8)$$

ε is the emissivity of the surface, σ is Stefan-Boltzmann constant, $T_{amb}$is the ambient temperature, n is the surface normal vector.
Phase change interface calculations were performed regarding the equations below. In stationary and time-dependent studies, the temperature is set to the phase change temperature, T_{pc}, on the interface:

$$T = T_{pc} \quad (9)$$

In addition, in time-dependent studies, the Stefan condition defines the phase change interface velocity v_n from the conductive heat flux jump across the interface, q, the latent heat of phase change from solid to fluid, $L_{s\to f}$, and the solid density, ρ_s:

$$v_n = \frac{q}{\rho_s L_{s\to f}} \quad (10)$$

With,

$$q = -k_s \nabla T_s + k_f \nabla T_f \quad (11)$$

Where k_s and T_s are the solid heat coefficient and temperature, k_f and T_f are the fluid heat coefficient and temperature of PCM.
A portion of the solar energy entering the room heats the air, helping to achieve a comfortable temperature of 22°C. Additionally, some of this energy is stored in the Trombe wall for use at night. The energy stored within the Trombe wall can be calculated using the following equation:

$$Q_{TW} = m_{TW} \times c_{TW} \times T_{TW} \quad (12)$$

where T_{TW} is the temperature of Trombe wall, m_{TW} is the total mass, c_{TW} is the total specific heat which are calculated as below:

$$m_{TW} = m_{pg} + m_{pcm} \quad (13)$$

where m_{pg} and m_{pcm} are the mass of pyrolytic graphite and PCM respectively.

$$c_{TW} = \left(\frac{m_{pg}}{m_{TW}}\right) \times c_{pg} + \left(\frac{m_{pcm}}{m_{TW}}\right) \times c_{pcm} \quad (14)$$

where c_{pg} and c_{pcm} are the specific heat of pyrolytic graphite and PCM respectively.

The increased temperature, T_r, by the utilization of energy, Q_{TW} is given as below:

$$T_r = 18 + Q_{TW}/(m_a c_a) \quad (15)$$

where m_a is mass and c_a is specific heat of air.

The fundamental thermal model for the room-Trombe wall system is depicted in Figure 8, providing a schematic representation of thermal transfer within the system.

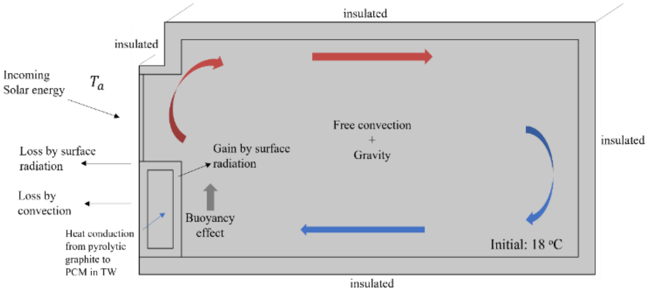

Figure 8. Thermal model for the room-Trombe wall system

Several assumptions were made based on thermal transfer principles:

- The thermal physical properties used in this model are considered constant.
- Pyrolytic graphite exhibits high thermal conductivity in-plane but low conductivity through-plane; it is assumed to be utilized as an in-plane conductive material.

Boundary conditions of the simulation model are given below.

- Room is a closed system that has no fluid in or out from the system.
- Outlet temperature and heat flux inlet from solar radiation is taken according to the weather data.
- Initial temperature and pressure of the room is taken as 18°C and 1 atm.
- All the walls of the room except Trombe wall and window are insulated.
- Heat flux from solar radiation is applied to window and Trombe wall.
- No slip condition is applied to the walls.
- Acceleration of gravity is assumed as constant.
- Pressure point constraint point is taken the left corner of the room.
- Given the minimal nano-enhancement present in the n-octadecane/EG composite (NePCM), its density is considered equivalent to that of pure n-octadecane.

3. Results and discussion

This section presents the simulation results obtained from the two-dimensional Finite Element Method (FEM) model. The simulations were conducted for the seven coldest months of the year: January, February, March, April, October, November, and December. The initial simulation utilized NePCM, specifically a combination of n-octadecane and expandable graphite (EG), yielding promising results. Temperature readings for the Trombe wall, PCM, and the room were recorded and are illustrated in Figure 9.

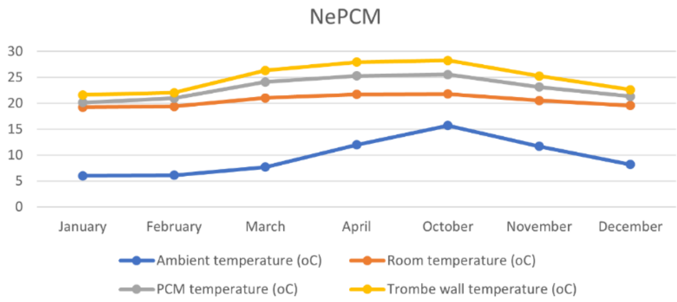

Figure 9. First simulation temperature data

The initial room temperature was set at 18°C. In Figure 9, the blue line represents the average ambient temperature. The simulations, which incorporated weather and solar radiation data, revealed an increase in room temperature over the simulation period. December, January, and February recorded the lowest average room temperatures at 19.57°C, 19.23°C, and 19.40°C, respectively. This increase can be attributed to the Trombe wall's high thermal conductivity. The heating effect of the Trombe wall extended beyond the room itself, resulting in an increase in the temperature of PCM as well. The PCM serves as a thermal energy storage medium, absorbing heat until the room temperature drops below that of the Trombe wall. During these periods, the stored energy in the PCM is released to provide additional heating to the room. The sunshine duration for each month was factored into the simulation, with corresponding temperature distributions shown in Figure 10.

To further investigate the impact of nano-enhancement on phase change materials (PCMs), a second simulation was conducted using n-octadecane PCM without any nano-enhanced components. This simulation employed the same weather data for Istanbul as used in the NePCM scenario. To ensure consistency, the Trombe wall design, room layout, and material characteristics were identical to those in the first simulation. This approach allows for a controlled comparison between NePCM and standard n-octadecane PCM performance under identical environmental conditions and physical constraints. The primary goal was to isolate and evaluate the specific effects of nano-enhancement on the thermal behavior of the PCM and its interaction with the Trombe wall system. Figure 11 shows the second simulation temperature data.

The results indicated a positive correlation among the temperatures of the room, PCM, and Trombe wall. The Trombe wall consistently exhibited higher temperatures than both the room and PCM, likely due to its superior thermal conductivity that facilitates efficient heat transfer from the wall to both areas. The months of December (19.56°C), January (19.15°C), and February (19.28°C) recorded the lowest average room temperatures. This trend can be attributed to a combination of lower ambient temperatures during these months and an increased thermal demand for heating. Overall, these simulations demonstrate how both standard n-octadecane and its nano-enhanced counterpart perform under winter conditions, highlighting significant differences in thermal behavior that could influence future designs of passive solar heating systems using Trombe walls.

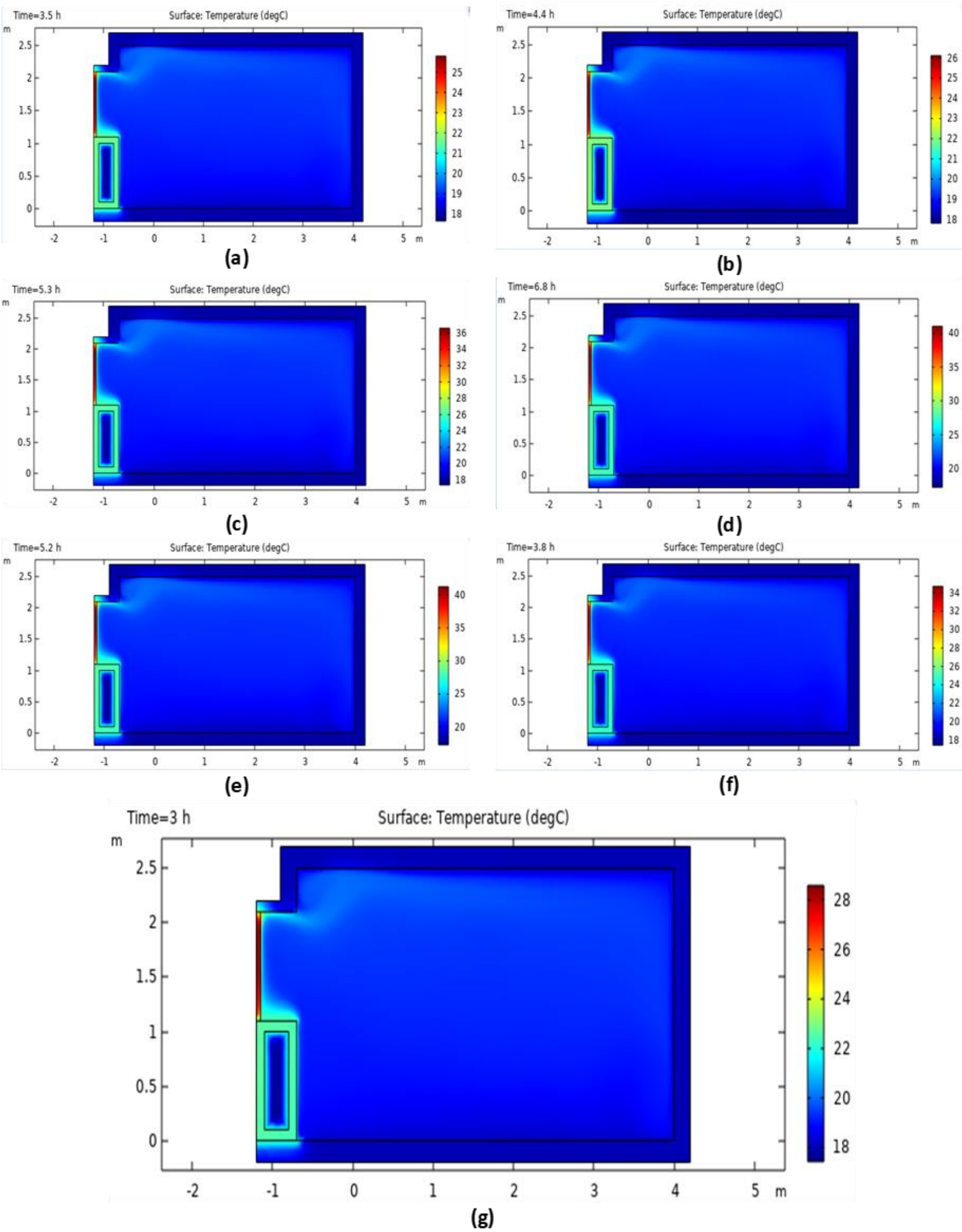

Figure 10. Temperature distribution of the room for the month: (a) January, (b) February, (c) March, (d) April, (e) October, (f) November, (g) December

The analysis of room temperature data indicated that the use of nano-enhanced phase change material (NePCM) resulted in a noticeable increase in temperature, especially during the colder months as shown in Figure 12.

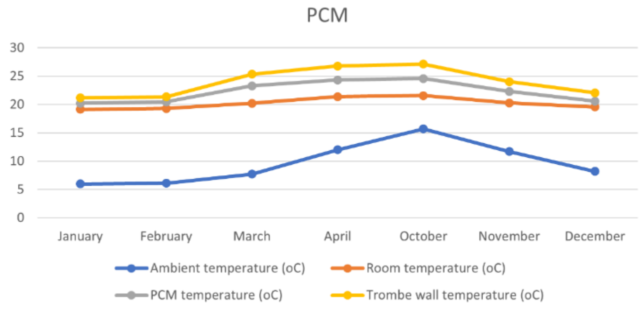

Figure 11. Second simulation temperature data

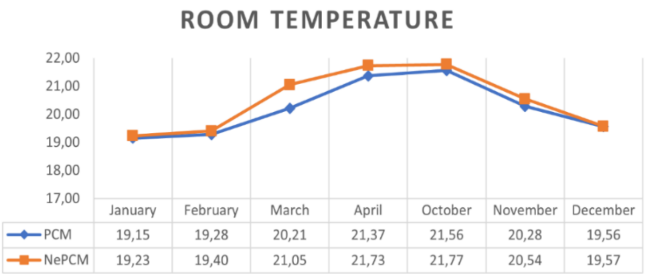

Figure 12. Room temperature comparison between PCM materials

While the differences between the NePCM and non-NePCM scenarios were minimal in January, February, and December, March showed the most significant variation. This pattern can be attributed to two main factors:

Increased solar radiation: In March, there was a relatively higher level of solar radiation, even though the sunshine duration was shorter compared to April. This additional solar energy contributed to greater thermal gain in the Trombe wall, thereby amplifying the temperature difference associated with NePCM.

Latent heat storage capacity: The latent heat storage capacity of NePCM likely played a vital role during this month. When solar radiation was high, the PCM absorbed and stored thermal energy, which was then gradually released during cooler periods of the day or on subsequent days when solar input was less available. This ability to act as a latent heat buffer allowed for a more sustained increase in temperature compared to scenarios that did not utilize NePCM.

The performance of two different phase change materials (PCMs) was examined: n-octadecane (PCM, represented by the blue line) and a composite of n-octadecane with expanded graphite (NePCM, represented by the orange line). The temperature profiles for both materials showed a high degree of similarity; however, the NePCM consistently recorded slightly higher temperatures as shown in Figure 13. The Trombe wall was exposed to solar radiation, allowing for an assessment of the effects of both PCM and NePCM. The analysis indicated that the average temperature of the Trombe wall was slightly higher when NePCM was employed as seen in Figure 14. The temperature difference observed between the Trombe wall conditions with PCM and NePCM closely mirrored the temperature variation between the two materials themselves. This suggests that the enhanced thermal conductivity of the NePCM, attributed to its nano-engineered structure, significantly influenced both its own temperature and that of the Trombe wall. This indicates that the nano-enhancement primarily affects the material's energy storage capacity rather than its temperature-dependent phase transitions. Further analysis revealed a notable difference in the amount of stored energy between the two PCMs. During the colder months, the NePCM demonstrated an average of 16% more stored energy compared to the standard PCM. This enhancement can be attributed to the improved thermal conductivity and heat transfer capabilities provided by the nano-engineered structure of the NePCM, which facilitates more efficient absorption and retention of thermal energy within the material. Using the stored energy, it is possible to adjust the room temperature by approximately 0.2°C in December; although this change may seem minor and not significantly impact nighttime comfort, it is sufficient to maintain a pleasant sleeping environment.

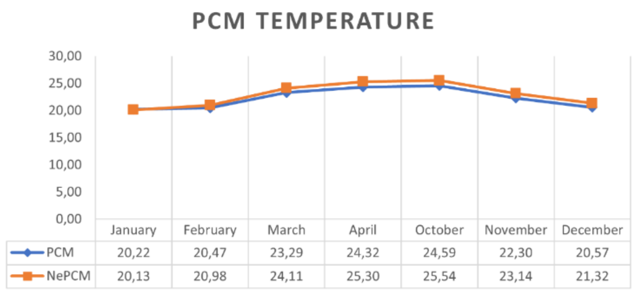

Figure 13. Temperature comparison between PCM materials

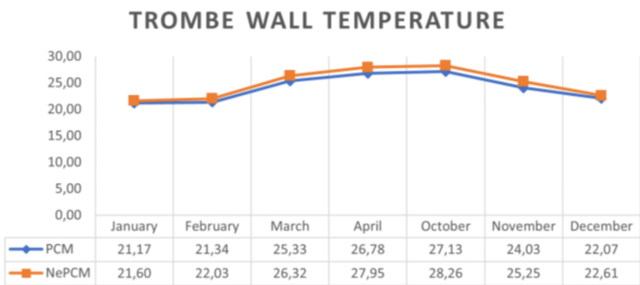

Figure 14. TW temperature comparison between PCM materials

4. Conclusion

This study is confined to a theoretical analysis and numerical simulation focused on the thermal performance of single-sided Trombe walls utilizing two types of phase change materials (PCMs): standard n-octadecane and a nano-enhanced composite of n-octadecane with expandable graphite (NePCM). Through a series of simulations conducted over the coldest months of the year, key findings were obtained that highlight the advantages of incorporating NePCM into passive solar heating systems. The results demonstrated that the use of NePCM led to a noticeable increase in room temperature, particularly during colder months. The contribution of NePCM compare to PCM was observed the most in March. This enhancement was attributed to two primary factors: the higher solar radiation received in March, despite a shorter sunshine duration compared to April, and the superior latent heat storage capacity of NePCM. The ability of NePCM to absorb and gradually release thermal energy significantly contributed to maintaining comfortable indoor temperatures, even during periods of limited solar input. For instance, in December, the room temperature rises from 18°C to 19.5°C while consuming approximately 71.6 kJ of energy, equivalent to a cost of 0.02 kWh. This research offers valuable insights into sustainable building design practices, equipping architects and engineers with crucial information for optimizing passive solar heating systems. Ultimately, the study promotes environmentally friendly and energy-efficient building designs, supporting global efforts to address climate change and reduce greenhouse gas emissions. Furthermore, the analysis revealed that the average temperature of the Trombe wall was slightly elevated when NePCM was utilized, reflecting its enhanced thermal conductivity. This characteristic not only improved the energy storage capacity of the material but also positively influenced the overall thermal performance of the Trombe wall system. The findings indicate that integrating nano-enhanced materials like NePCM can substantially improve the efficiency of passive solar heating systems. By optimizing energy absorption and retention, NePCM serves as a valuable component in designing more effective and sustainable building systems. In conclusion, this research underscores the potential of utilizing nano-enhanced phase change materials in Trombe walls to enhance energy efficiency and occupant comfort. Future studies should explore the long-term performance and economic viability of these materials in real-world applications, as well as their environmental impact, to fully understand their role in advancing sustainable building practices. The significance of this study lies in its contribution to advancing sustainable building design practices. By conducting numerical investigations of Trombe walls using finite element method simulations, this research aims to provide architects and engineers with practical insights for optimizing passive solar heating systems. The findings may influence architectural and engineering decisions by offering a clearer understanding of Trombe wall behavior and their potential role in reducing building energy consumption. Ultimately, this study seeks to promote environmentally friendly and energy-efficient design strategies aligned with global efforts to combat climate change and reduce greenhouse gas emissions.

Ethical issue

The authors are aware of and complies with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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