



Numerical and Design Study of Beehive in Building for Thermal Storage During Hours of Absence of Solar Radiation

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ABSTRACT

This study investigates the numerical and design performance of Phase Change Materials (PCMs) embedded in a beehive structure within building envelopes for thermal energy storage during periods without solar radiation. Using Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent, the study examines how the PCM system stabilizes indoor temperatures and improves energy efficiency. The research focuses on three months: January, November, and December, in Baghdad, Iraq, where diurnal solar radiation variations and temperature patterns are prevalent. Results reveal that the PCM-enhanced structure effectively absorbs heat during peak solar radiation hours, with solar radiation peaking at 574 W/m² in January, 596 W/m² in November, and 557 W/m² in December. The heat storage and release ability of the PCM keep up the interior temperature at its maximum of 309.96K and 310.04 K in Jan and Nov and 309.23 K in Dec with slightly less drop in the evening. The heat transfer coefficient was maximum in November 11.37 W/m²-K, while the PCM mass fractions showed significant phase change and the maximum value 0.425 in November. The thermal efficiency of the system was highest in November at 68.23% and also fluctuates slightly in the other remaining months. This study suggests that PCM systems, especially with the beehive structure, additionally improve isothermal stability and energy densities of the buildings in the changing climate, which is cost-effective and a more environmentally-friendly strategy for regulating heating and cooling requirements.

1. Introduction

The utilization of packaged Phase Change Materials (PCMs) in building design for the storage of thermal energy has however received much emphasis over the last two decades given increased emphasis on sustainability and energy efficient strategies in fighting the effects of global warming. This literature review analyses the developments of PCM technology, the employment of beehive structures for heat storage and numerical methodologies for the modelling of PCM behaviour in buildings during intensive night and day with lack of direct sun radiation.

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PCMs are materials whose main function is to absorb and release a substantial amount of thermal energy when undergoing phase change between the solid and liquid state. In this respect, they are best suited for indoor climate control, where they are able to store heat that enters the structure during warm periods, and to release it against backdrops of no solar heat. PCMs have been in use since the 20th century but modern enhancements have enhanced the proper functioning of PCMs in energy efficient structures. Khudhair and Farid, 2004, classified all the type of PCMs and focused on building applications and highlighted the use of latent

heat storage system to minimize energy requirement for heating and cooling load. Zalba et al. (2003) [2] pointing to the potential of using PCMs for regulating indoor temperature in passive solar buildings provided energy consumption trends that depicted impressive variations. The use of PCMs in building cooling was further investigated, with differences in the performances of organic and inorganic materials established by Tian and Zhao (2013) [3]. Organic PCMs have improved chemical stabilities in comparison with inorganic ones where, however, the low thermal conductivity is an important element for using PCMs in building reflections.. Among many applications of PCMs the most popular are used in building structures, including walls, floors and roofs, with focus on minimizing the dependency on active heating and cooling systems. Building on this, Cabeza et al. (2011) [4] further demonstrated the possibility of achieving up to 30% energy saving when the building envelope was incorporated with PCM. New design concept of PCM integration into the beehive structure of the building is relatively young, pointed out by Mr. Tien Dung Nguyen, which is hexagonal, as the hexagon shape can store maximum elements in a small space. This structure enables better surface area volumes ratios enhancing heat transfer process. Computational simulations have now taken an important role in forecasting the behaviour of PCMs in building-integrated systems. The applicability of Computation Fluid Dynamics (CFD) analysis and Finite Element Methods (FEM) permits appropriate mathematical modeling of heat transfer interfaces in PCM incorporated systems. In a comparative analysis of numerical PCM-enhanced walls, Zhou et al. [5] used CFD and FEM to analyze heat transfer characteristics. It was shown that when developing an accurate model, both phase change processes must be accounted and external boundary conditions, like solar radiance. PCM integrated building designs have a huge literature search while the implementation of PCM into building codes consumer and energy efficiency standards are still emergent. Berardi and Naldi (2017) [6] also disclosed some problems with the regulation of extensive use of PCM technologies, mentioning

that, despite a high potential of the materials, the efficiency depends on the quality of their integration, maintenance, and climate conditions.

In their research, Memon et al. (2015) [7] examined the capacity of microencapsulated PCMs in concrete walls and showed that the integration causes in increase in the thermal mass of the building and temperature control during non-solar hours. Wang et al. (2018) [8] discussed on the light of the incorporation of metal foams to increase the thermal conductivity of PCMs. Their work revealed that metal-PCM composites enhanced the heat exchange conduct and are therefore fit for use under conditions where temperatures fluctuate. These composites in PCM are set as a promising area of the future research because of their possibility to significantly improve thermal properties of building applications if compared with the existing ones. Future outlooks for PCM studies examine new materials and solutions to the current difficulties in the design of PCM coupled systems and more accurate numerical models for prognosis of long-term performance. With the focus shifting to sustainability, PCM researchers are investigating bio-based materials from plant oils and animal fats. Sarı et al. (2016) [9] highlighted the performances of the bio-based PCMs integrating it into buildings having comparative characteristics with typical paraffin systems. The most recent work to address this issue focuses on applying computational methods, including machine learning, for selecting appropriate PCM materials and designing PCM incorporated systems using climate characteristics and building parameters. Increasing design efficiency was also pointed out by Agyenim et al. [10] as one of the benefits of using AI-based simulations for long-term performance prediction.

Being a passive building component, the efficiency of Phase Change Materials is greatly determined by the environment in which they are employed. It is evident that different climates affect thermal storage in its ability to meet the varying conditions such as frequent temperature changes, availability of solar radiation and cooling or heating load. Some prior studies have investigated how PCM systems could be optimized according to the particular climatic

conditions. In areas where temperature differences between day and night are small, PCMs help to smoothen the bumps in indoor temperature requiring no reheat or cooling. Pomianowski et al. (2013) [11] proved that use of PCMs incorporated in the exterior of Danish houses decreased heating energy needs by 17–25% for the entire winter period. In regions of high daytime temperatures and high cooling loads, shifting, PCMs are being used for thermal storage during the day and end-use at night for minimum effect of hot nights. Feldman et al. (2015) [12] examined the effectiveness of PCM integrated roofing systems in tropical climate and pointed out that the cooling load can be reduced substantially whenever cooling is often costly, especially during nighttime when solar electricity is unavailable. While in cooler climate such as heating DOMINANT energy PCA's, where thermal heat energy from solar source or external source is available during the day, PCMs store such heat energy and emits it during the night. Sharma et al. (2009) [13] explored the possibility of using PCM-based wallboards in the homes of Canada and found that maximum energy saving of around 20 percent of heating energy can be achieved if appropriate type of PCM and construction characteristics of the building are taken into consideration. Another main difficulty of developing PCM systems is due to its application of solar energy as well as outdoor temperature. Under conditions which solar resource is unavailable particularly during the night or cloudy day the performance of PCM systems depends on the heat storage and release characteristics of the PCM. Similarly, Zhou et al. (2009) [14] assessed sensitivity of PCM on solar radiation. Their study stressed the need of proper estimation of heat fluxes in PCM systems in conditions when there is no solar energy input, for example, at night or during the cloudy day. The researchers concluded that highly ineffective system designs could either transfer heat with a high rate thus causing thermal discomfort or with a low rate hence not being efficient in controlling temperature. These challenges and opportunities of PCM integration were reviewed by Berardi and Naldi (2018) [15] on the building code. They pointed out that even though energy saving are evident, the absence of

fixed criteria for measuring PCM has hampered its inclusion in formal regulations. They also called for the growth of evaluation mechanisms that will help in PCM adoption in national building standards in terms of testing methods as well as performance indicators.

Abdulritha Khazaal (2024) [16] Phase change materials (PCMs) are recognized for their significant role in thermal energy storage systems due to their ability to efficiently store and release heat. Recent advancements in this field focus on enhancing PCMs with nanoparticles to improve their thermal properties. This study comprehensively investigates the thermal performance of Nano-Enhanced Phase Change Materials (NEPCM) in an enclosure, emphasizing the effects of temperature variation and nanoparticle incorporation. Hussein et al. (2022) the placement of PCMs within building walls was examined to determine their effectiveness in maintaining room temperatures after sunset. The findings show that as the thickness of the concrete layer increases, the capacity of the PCM to store heat also improves. Similarly, the gypsum layer's thickness plays a crucial role in transmitting and storing heat from the concrete. The study identified the optimal configuration as a concrete thickness of 100 mm and a gypsum layer of 15 mm, providing the best thermal performance for heat retention post-sunset. Khazaal et al. (2023) focused on how different nanoparticle concentrations (0.1%, 0.3%, and 0.5% by weight) affect the thermal properties of NEPCMs. The enclosure's low-temperature wall, lined with paraffin wax, is integrated with nanoparticles to assess their impact on phase change behavior. Notably, the study finds an inverse relationship between nanoparticle concentration and the mass fraction of NEPCMs, with the mass fraction decreasing from 0.86 to 0.08 as nanoparticle concentration increases. This suggests that incorporating nanoparticles significantly alters the thermal properties of NEPCMs. Ramadhan and Al-Ali (2024) focused on the catalytic dry reforming of methane by a LaNiMnO_3 perovskite catalyst: A kinetic study. Sol gel derived catalyst was used and the effects of the operating temperatures were evaluated. The catalyst was highly effective, and the

activation energy computed was 30.728 kJ/mol. The study was effective in the synthesis of a new catalyst that exhibited satisfactory catalytic efficiency. Akeiber (2024) focused on a system with four distributed generations; solar photovoltaic, wind, diesel generator and battery storage system. The system is intended to help to regulate energy supplies for outstation facilities and decrease the dependency on diesel power settings. The system is capable of producing of a range of power levels; the solar PV panels produced 30.38 kW while the wind power ave 3213 kW. The system also act as a source of back up power hence cutting on the of diesel and emissions. Ali et al. (2024) looked at the effects of CO₂ emission on global warming and considers the use of solar energy as a mode of averting this. It discusses the viability and value of solar power, the prospects of solar energy and potential for integration with other forms of renewable energy. This issue supports the international approaches.

2. Methodology

FLUENT as part of ANSYS package is recognized as one of the most effective CFD tools employed in fluid dynamics applications including heat transfer processes and other kinds of engineering systems analysis. It offers a reliable basis for users to simulate and design a wide range of potential systems with little as laminar flows and multiple with as vigorously executed turbulence as well as multiphase interactions. The software has employed numerical techniques mostly the finite volume methods in solving governing equations of fluid mechanics and thermodynamics. Fluent achieves the capability of approximating these real life physical processes by discretizing these equations over a computational domain. The software also features transient analysis, heat transfer analysis, phase change analysis and more thus can be applied in aerospace engineering, electromechanical systems, energy conservation, automotive engineering and biomedical material engineering. Moreover, ANSYS Fluent provides options for parameters of meshing, boundary conditions, and solvers that enable using of the main program adapted to

concrete computation conditions. The Post Processing of this software provides additional utility that allows users to closely study and interpret the finding of the simulations performed in relation to the flow of fluids and the efficiency of a particular system.

In the given study, running fluid is taken to be PCM, they have to suppose the flow as transient, three dimensional, Newtonian, compressible and laminar.

2.1 Governing Equations

When running Computational Fluid Dynamics (CFD) analysis with tools such as ANSYS Fluent, the governing equations serve as the basis for analysis of the flow and the thermal condition of the fluids undergoing analysis. These equations are developed from the principles of physics such as, law of conservation of mass, the law of conservation of momentum and the law of conservation of energy.

1. Continuity Equation (Conservation of Mass):

The continuity equation makes certain that balance of the mass is maintained in the system throughout the calculation. It is written as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1)$$

where ρ is the density of the working fluids, and \mathbf{v} is the velocity vector of the fluids, t denotes time.

2. Navier-Stokes Equations (Conservation of Momentum):

They provide a definition of the rate of change of the fluid with respect to time and forces like pressure, viscous stresses as well as body forces like gravity. For an incompressible Newtonian fluid, the Navier-Stokes equation is:

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{F} \quad (2)$$

where p is pressure, μ is dynamic viscosity, and \mathbf{F} stands for external forces which may be used to describe forces in a mass production system.

3. Energy Equation (Conservation of Energy): transport of thermal energy is described by the energy equation while conduction, convection, and viscous dissipation are considered. It is expressed as:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (v(\rho E + p)) = \nabla \cdot (k\nabla T) \quad (3)$$

where E is the total energy, T is the temperature; k is thermal conductivity and Φ is viscous dissipation.

These governing equations are solved numerically using techniques like the finite volume method in ANSYS Fluent, allowing for the simulation of fluid flow, heat transfer, and complex interactions in various engineering applications.

2.2 System Geometry

The shape of the wall was designed in the Solidworks program, which is an engineering program for drawing precise shapes. The dimensions of the wall were 1 meter long and 1 meter wide, the thickness of the outer wall was 10 cm and the inner wall was 10 cm. It contained a honeycomb system for phase-changing materials with a thickness of 5 cm and a hexagonal shape with a waste length of 10 cm. As in Figure 1.

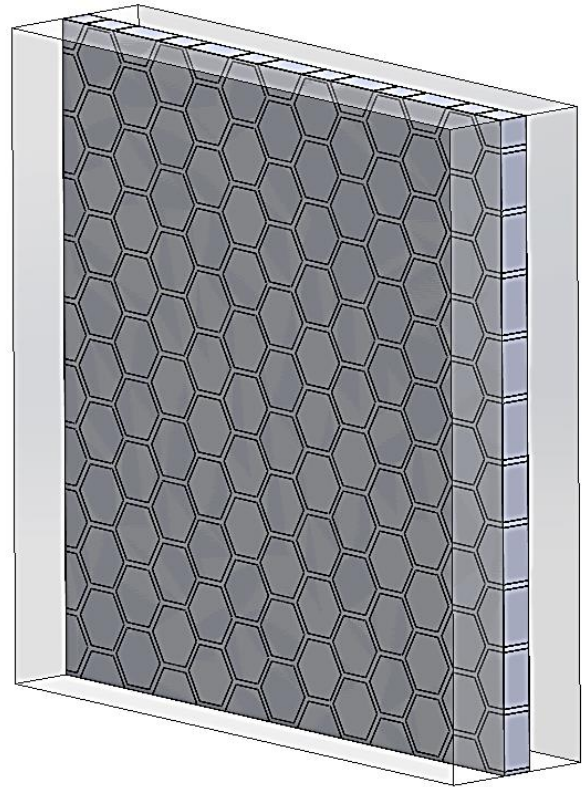


Figure 1. Honeycomb PCM wall

2.3 Mesh Generation

Mostly such kind of unstructured matrices that can do complex calculations have been employed, hence choosing this unstructured tetrahedron framework was correct in the given case.

In just one step, user-ANSYS can produce solid geometry meshes and full off-site model. In the study, there were (1542179) cells were randomly extracted from this tetrahedron element and Element 1 mm is shown in Figure 2.

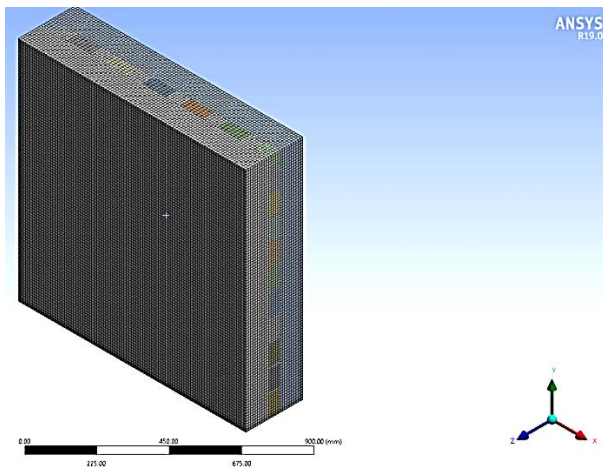


Figure 2. Mesh generated

A dependable mesh is necessary to find a solution to the equation for the simulation process, which is determined by complex algorithms and high dimensional matrix. Then, resolve the situation with the method of a stable mesh and bring it back into the necessary balance. It is necessary to create more than one mesh dependency and more than one mesh for having a wide range of models simulated in the simulator. The element's worth was 1542179 at this time while it was hitting the maximum indoor temperature 40.12 °C as seen in Table 1.

Table 1: Mesh independency

Case	Element	Node	Maximum indoor temperature °C
1	845643	174588	43.22
2	1136570	223067	40.98
3	1358890	264568	40.14
4	1542179	298472	40.12

2.4 Boundary Conditions

The solar radiation of the city of Baghdad in Iraq was obtained during the first, eleventh, and twelfth months of the year 2023, and it was shined on the external wall, and the differences between the results were known through the simulation program, and the PCM material was used during the beehives inside the wall.

Table 2: PCM Thermal Properties [16]

Property	Unit	Typical Value
Melting Point	°C	24
Latent Heat of Fusion	kJ/kg	180
Thermal Conductivity	W/m·K	0.2
Specific Heat Capacity	J/kg·K	2000
Density	kg/m ³	880
Thermal Expansion Coefficient	1/K	0.00021

3. Results and discussion

Figure 3 illustrates the solar radiation intensity in Iraq for the months of January, November, and December. In January, the solar radiation starts at 37 W/m² at 8:00 AM, increases steadily to reach a peak of 574 W/m² by noon, and then gradually decreases, reaching zero by 6:00 PM. In November, the pattern is similar but with slightly higher intensity, beginning at 126 W/m² at 8:00 AM and peaking at 596 W/m² around noon, before tapering off to zero by 6:00 PM. In December, the radiation is lower than November but follows the same daily pattern, starting at 52 W/m² at 8:00 AM, peaking at 557 W/m² at noon, and declining to zero by 6:00 PM. These variations in solar radiation reflect the typical diurnal cycle and seasonal differences, with higher radiation levels in November compared to January and December, due to the changing position of the sun and atmospheric conditions.

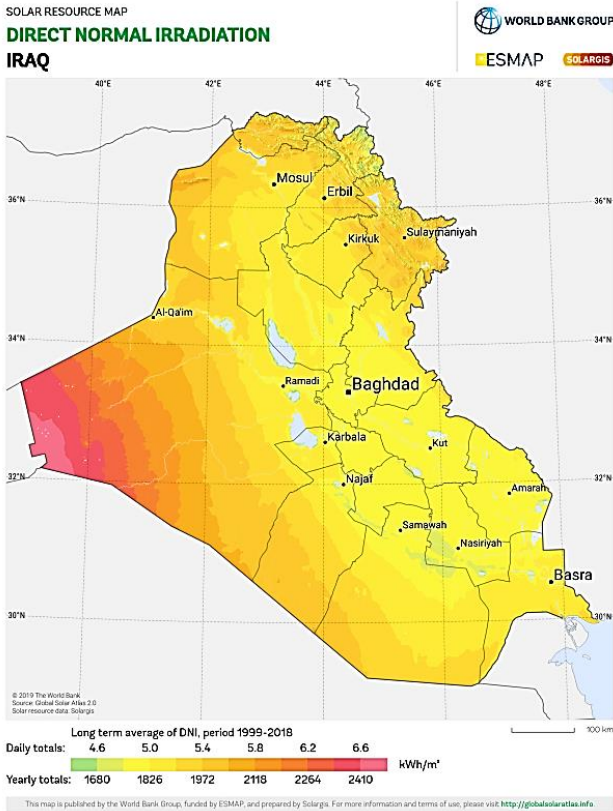


Figure 3. Solar radiation of Iraq [17]

Figure 4 presents the solar radiation of Iraq across different months. The figure shows the variation of solar radiation intensity, starting in the morning and peaking around noon before decreasing by the late afternoon. For January, the solar radiation begins at 37 W/m² at 8:00 AM, gradually increasing to a peak of 574 W/m² by noon and then declining to zero by 7:00 PM. November follows a similar pattern but with slightly higher values, peaking at 596 W/m² at noon. December’s solar radiation is comparable to January, with a peak value of 557 W/m². These fluctuations in solar radiation reflect the typical diurnal pattern, influenced by the month and seasonal changes. The data highlights the potential for solar energy harvesting, especially during peak hours, while also emphasizing the significant reduction in available solar energy during the late afternoon and evening hours.

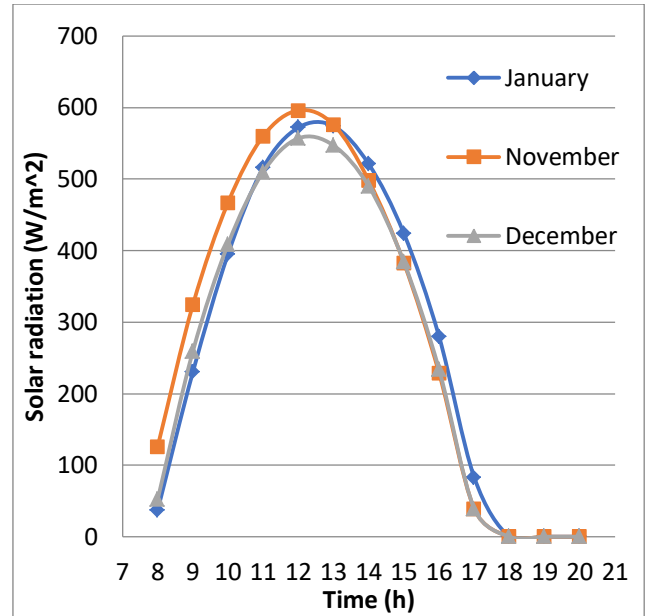


Figure 4. Solar radiation of Iraq in different month [17]

Figure 5 illustrates the outdoor temperature variation over time for the months of January, November, and December. In January, the temperature begins at 295.43 K around 8:00 AM, gradually rising to a peak of 309.69 K around 1:00 PM before dropping back to 292.43 K by 8:00 PM. Similarly, in November, the temperature starts at 296.46 K at 8:00 AM, reaches a maximum of 310.17 K at 1:00 PM, and falls to 290.46 K by the evening. December shows a slightly lower peak temperature, starting at 295.60 K in the morning, reaching 309.18 K by midday, and settling at 289.60 K by the evening. The figure shows a trend of heating up of the temperature in the day and cooling it in the evening – a cycle of the sun heating the surface and the night cooling off. This variation gives insight of thermal loads in buildings especially in regions where there is variation in temperatures, showing heat gain and loss that is solved by the incorporation of phase change materials (PCMs).

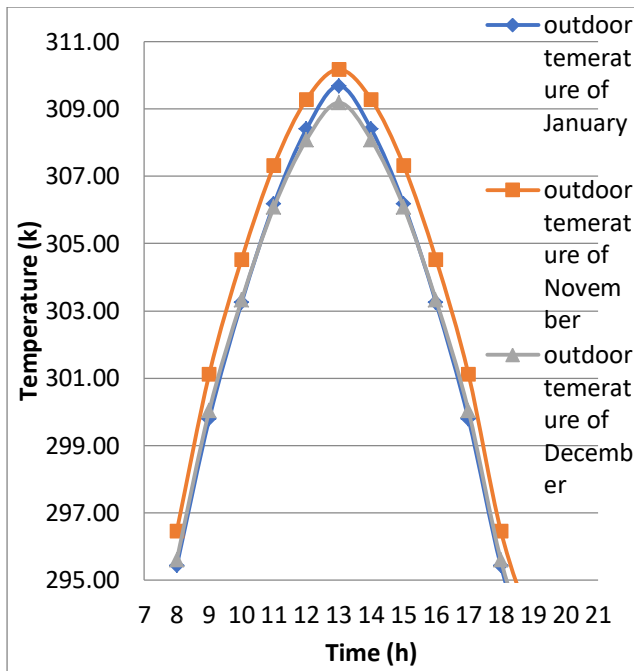


Figure 5. Outdoor temperature with time of different months

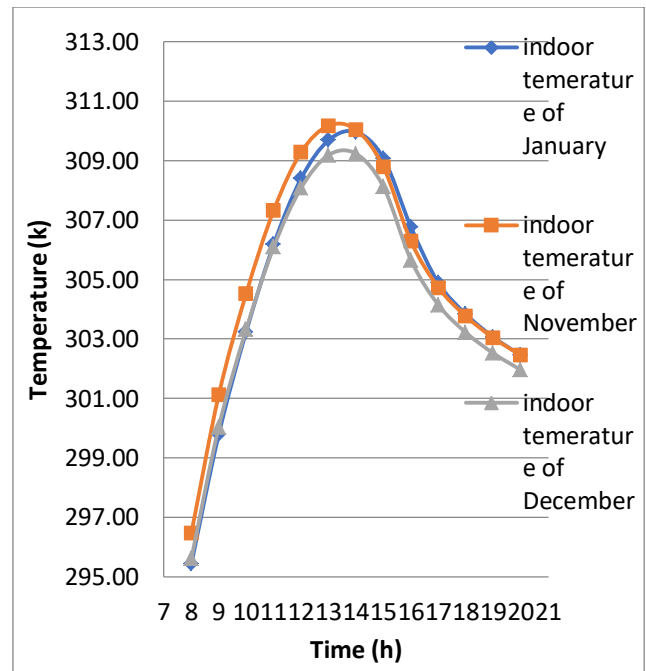


Figure 6. Indoor temperature with time of different months

Figure 6 shows the fluctuation of the indoor temperature by month for the period January, November, and December. In January, the indoor temperature begins at 295.43 K at 8:00 AM, reaches its peak in the middle of the day at 1:00 PM with a value of 309.96 K, gradually lowering to 302.45 K at 8:00 PM. In November, the temperature starts slightly higher at 296.46 K, peaks at 310.04 K around 1:00 PM, starts from 303.19 K at 11:45 | 00 AM and ends at 302.45 K at 11:45 | 00 PM. December follows a similar trend, beginning at 295.60 K, reaching a peak of 309.23 K at 1:00 PM, temperature in the morning drops to 301.96 K after 12:00 PM and drops again by the evening. The figure shows the thermal stability indoors which exhibits less fluctuation than outdoor temperature (5), this proves that the building insulation and thermal storage such as Phase Change Materials (PCMs). The peak temperatures recorded for a number of days exhibits the effect of solar radiation in indoor heating and the relatively slow decay in the evening denotes the heat storage capacity of the PCM.

Figure 7 presents the temperature contours at 10:00 PM of the specific months of January, November, and December. The contour diagram of temperature in Jan reveals high of 309.96 K near the central part of the building and decreases to about 295 K close to the walls implying reasonable temperature differential. November displays similar distribution with warmer center at 310.04 K and cooler strips around the walls which suggest that heat is denser in the middle of the room during this month. December contour looks very similar to month before, with the maximum value of 309.23 K. Temperature distribution maps of the three months show that the PCM is helpful in increasing high temperatures in interior region of the building while keeping minimal heat transfer to the surrounding walls. It demonstrates the need to implement PCMs so as to regulate indoor temperatures especially during peak periods of solar radiation.

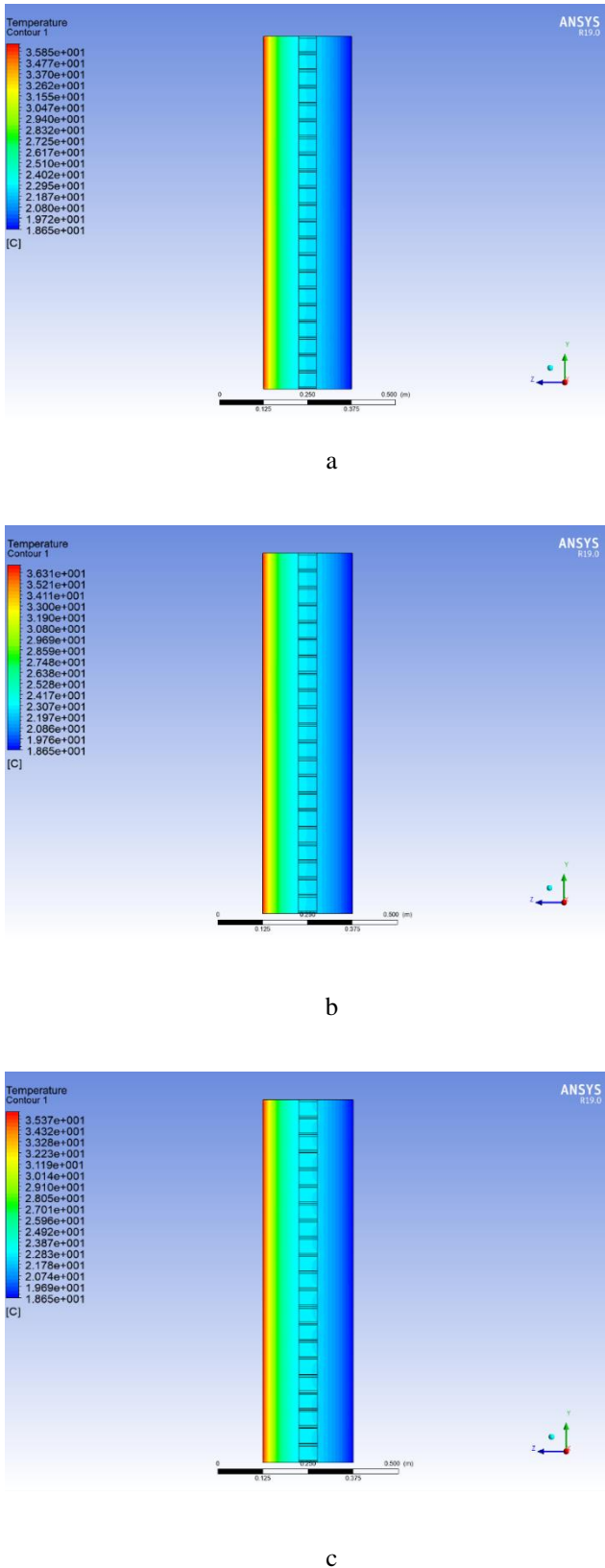


Figure 7. Temperature contour at 1 pm. of different month, (a) January, (b) November, (c) December

Figure 8 shows the time variation of the heat transfer coefficient (HTC) for January, November, and December months. In January, the HTC starts at a very low value of $4.47 \times 10^{-6} \text{ W/m}^2 \cdot \text{K}$ at 8: from 6:00 AM to 8:00 AM the temperature rises to $11.31 \text{ W/m}^2 \cdot \text{K}$ during midday, then gradually descends down to about $10.80 \text{ W/m}^2 \cdot \text{K}$ by evening. November follows a similar pattern, starting at $4.44 \times 10^{-6} \text{ W/m}^2 \cdot \text{K}$ in the morning, peaking slightly higher at $11.37 \text{ W/m}^2 \cdot \text{K}$ around 1: A rise to about $10.71 \text{ W/m}^2 \cdot \text{K}$ in the evening was observed. December's HTC starts at $4.46 \times 10^{-6} \text{ W/m}^2 \cdot \text{K}$ at 8: Predicted value of FRC is highest at 12:00 AM at $0.00 \text{ W/m}^2 \cdot \text{K}$, reaches its peak of $10.99 \text{ W/m}^2 \cdot \text{K}$ at 13:00 PM and declines to the lowest at 22:00 at $10.44 \text{ W/m}^2 \cdot \text{K}$. The HTC values represent the heat transfer from the building material to the surrounding environment in the building and opposed to higher HTC values during peak solar radiation. The small differences between the months are due to some variance in the solar radiation and temperature on the heat transfer coefficients.

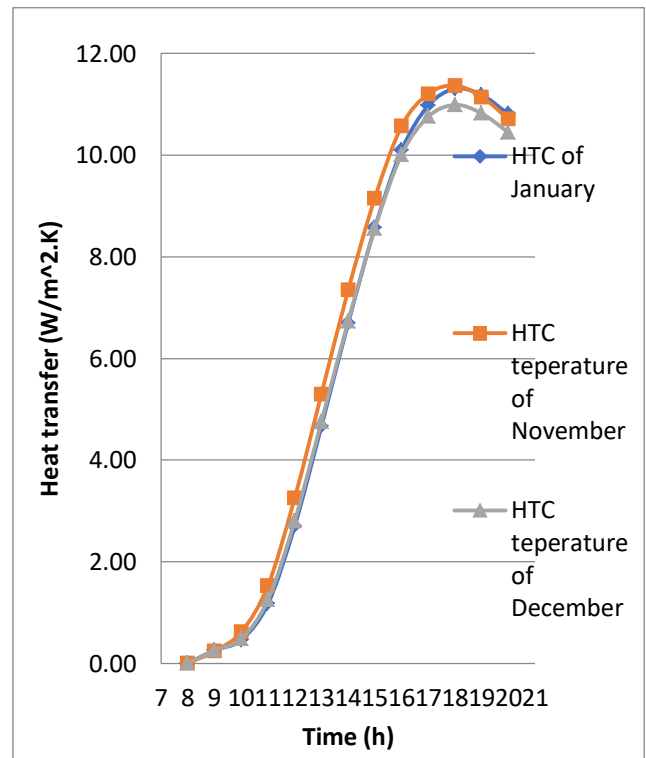


Figure 8. Heat transfer coefficient with time of different months

Figure 9 shows the time dependence of the mass share of the Phase Change Material (PCM) of the building envelop January, 11th November, and December as the amount of melted PCM. In January, the mass fraction starts at zero at 8: It varies from 0.00 AM to 0.405 PM depending on the solar heat gain; afterwards, the PCM solidifies at 8.00 PM to represent 0.001. In November, the mass fraction follows a similar pattern, starting at zero and rising to 0.425 at 1: These figures are for example only: the rate is at 0.049 at 10 of the clock in the morning to lowing down to 0.007 in the evening. December’s pattern is slightly lower, starting at zero and reaching 0.379 by 1:It rises to 0.005 from 12 of |am/pm, then drops down to 0.003 at the end of the day. These trends suggest that PCM is melting during the hours that solar radiation is at its maximum, and therefore able to absorb extra heat while solidification occurs during the evening when temperatures are declining. The small difference between the two is to represent the seasonal changes in solar exposure and temperature.

Figure 10 shows the mass fraction contours of the Phase Change Material (PCM) at 1:00 PM for the months of January, November, and December. In January, the PCM exhibits a maximum mass fraction of 0.405 near the center of the system, indicating substantial melting in the core, while the areas near the walls show lower values around 0.1, representing less melting due to cooler conditions. November shows a higher mass fraction peak of 0.425 in the center, reflecting more extensive melting due to higher solar radiation, while the peripheral regions still retain a lower mass fraction. In December, the mass fraction is slightly lower, with a peak of 0.379, indicating less melting compared to November but following a similar distribution pattern. The contours for all three months highlight that the PCM melting is most pronounced at the system's core, where heat absorption is highest, while the outer regions remain cooler and less affected. This behavior underscores the PCM's role in capturing and distributing thermal energy efficiently during peak solar radiation hours.

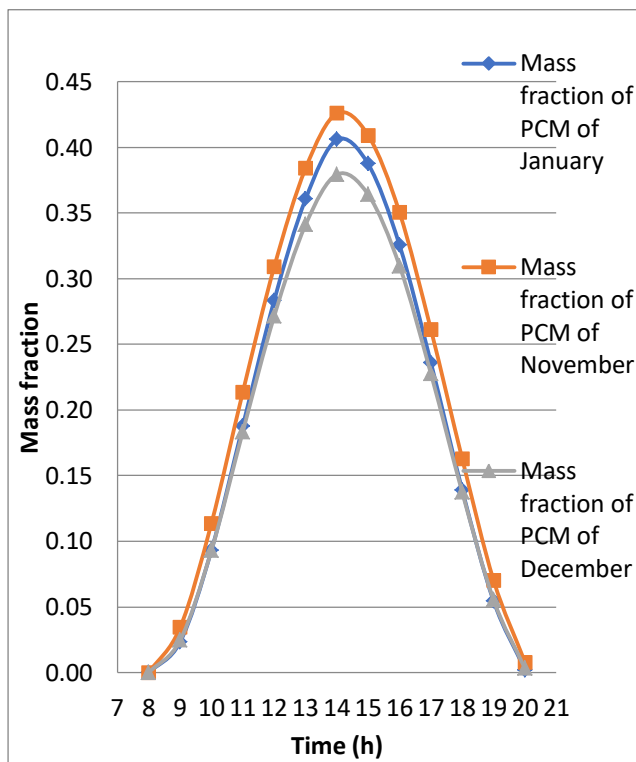
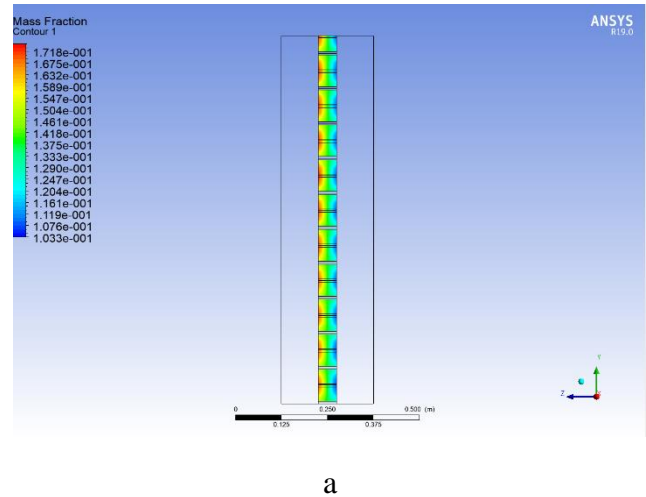


Figure 9. Mass fraction with time of different months



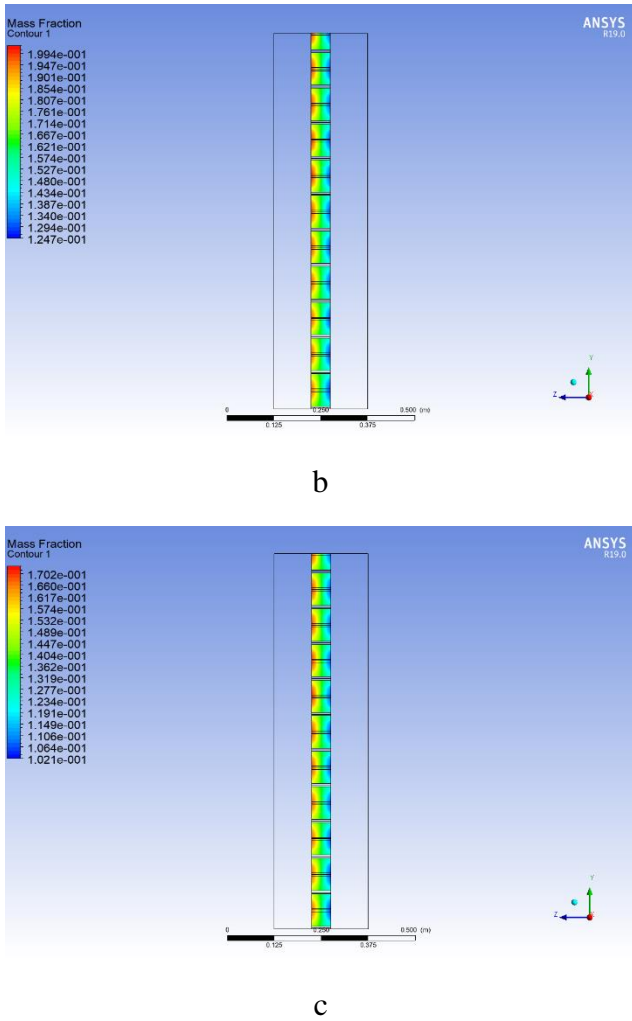


Figure 10. Mass fraction contour at 1pm. of different month, (a) January, (b) November, (c) December

Figure 11 gives the thermal efficiency of the Phase Change Material (PCM) system with time for the months the months of January, November and December. In January, the thermal efficiency starts at a low value of 2.68×10^{-5} at 8:00AM Its average increases from 57.14% at 12:00.00 AM to 67.85% at 1:00 PM and slightly drops to 64.86% at 8:00 PM. In November, the efficiency begins similarly at 2.67×10^{-5} , peaks slightly higher at 68.23% around 1:00 PM It starts at 76.54 percent just and slightly drops to 64.27 percent in the evening. December follows a similar trend, starting at 2.67×10^{-5} , reaching a peak of 65.94% by 1:00 PM then drops to 62.68 % in the afternoon. These patterns indicate that the PCM system is highly efficient during midday, when solar radiation is strongest, and its efficiency gradually declines as the temperature drops in the evening. The small differences

between months reflect seasonal variations in solar radiation, with November showing the highest peak efficiency due to stronger solar input compared to the other months.

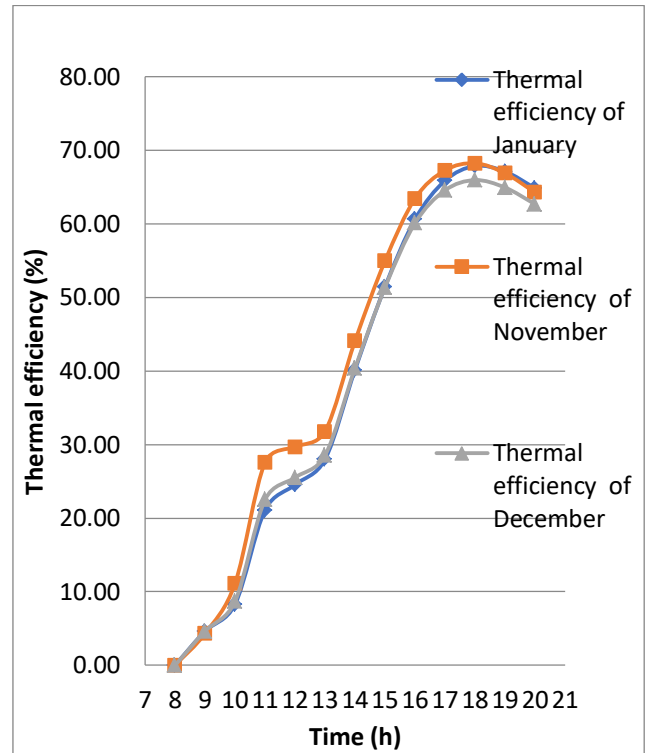


Figure 11. Thermal efficiency with time of different months

4. Conclusions

The work demonstrated the thermal regulation potential of PCM-enhanced building envelopes. The results indicated that the PCM system, integrated in a beehive structure, efficiently managed heat transfer during periods of solar absence, with notable performance across the months of January, November, and December.

1. Solar Radiation and Temperature Patterns: In January, solar radiation started at 37 W/m^2 at 8:00 AM, peaked at 574 W/m^2 around noon, and dropped to zero by 6:00 PM. The outdoor temperature began at 295.43 K at 8:00 AM, peaked at 309.69 K at 1:00 PM, and dropped back to 292.43 K by the evening. In November, radiation was slightly higher, starting at 126 W/m^2 , peaking at 596 W/m^2 , with the

outdoor temperature peaking at 310.17 K at 1:00 PM. December followed a similar pattern, with radiation peaking at 557 W/m², and the outdoor temperature peaking at 309.18 K.

2. Indoor Temperature Regulation: The PCM system helped stabilize indoor temperatures, keeping peak indoor temperatures around 309.96 K in January, 310.04 K in November, and 309.23 K in December, effectively minimizing fluctuations compared to outdoor temperatures. The slower evening temperature decline emphasized the system's capacity for heat retention.

3. Heat Transfer Coefficient (HTC): The HTC in January rose from 4.47×10^{-6} W/m²·K at 8:00 AM to 11.31 W/m²·K by 1:00 PM. Similarly, in November, the HTC peaked slightly higher at 11.37 W/m²·K, reflecting better heat transfer efficiency due to higher solar radiation. December followed a similar trend, with a peak HTC of 10.99 W/m²·K.

4. PCM Melting (Mass Fraction): The PCM mass fraction in January increased to 0.405 by 1:00 PM, indicating substantial melting during peak solar hours, and reduced to 0.001 by evening. In November, the mass fraction was slightly higher, reaching 0.425, while December saw a peak of 0.379.

5. Thermal Efficiency: The thermal efficiency in January peaked at 67.85% at 1:00 PM and declined to 64.86% by the evening. November showed the highest peak efficiency of 68.23%, while December reached 65.94%.

The study conclusively showed that PCM integration, particularly in a beehive structure, plays a vital role in maintaining indoor thermal stability by absorbing excess heat during the day and releasing it at night. This system achieved high thermal efficiency, particularly in November, with a peak of 68.23%. The slight differences in efficiency between the months reflected seasonal variations in solar radiation, but overall, the PCM system consistently contributed to energy conservation and temperature regulation.

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