Long Term Heat Transfer Simulation Through multilayer building wells with Phase Change Materials

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Abstract

This study evaluates the thermal performance and energy cost implications of integrating Phase Change Materials (PCM) into building walls with brick and concrete core materials, under Baghdad, Iraq's climatic conditions. A numerical simulation was conducted using MATLAB to analyze the heat transfer and temperature distribution across wall configurations, with a focus on PCM thickness ranging from 0.01 m to 0.1 m. The simulation assumed a constant indoor temperature and real outdoor boundary conditions over one year, accounting for hourly variations in heat flux, wall temperatures, and energy costs. Results demonstrated that incorporating PCM significantly reduced heat flux and stabilized the wall's internal temperature, leading to lower energy costs for heating and cooling. For brick walls, the optimal PCM thickness was determined to be 0.07 m, yielding an annual energy cost of 150 USD. For concrete walls, the optimal PCM thickness was found to be 0.05 m, with an energy cost of 120 USD. The concrete wall exhibited superior thermal performance and cost efficiency compared to the brick wall due to its higher thermal conductivity and density, which enhanced heat storage and transfer. These findings highlight the effectiveness of PCM-enhanced walls in improving energy efficiency and thermal comfort, particularly in climates with high-temperature variability. This work provides insights for optimizing wall configurations and selecting PCM thickness to achieve sustainable building designs and cost-effective energy management.

Keywords- Phase Change Materials PCMs, Transient Heat Transfer, Heat Energy Storage, Effective Specific Heat Function, optimization depend on energy savings.

I. INTRODUCTION

Optimizing heat transfer management in buildings is crucial for achieving energy sustainability and cost-effectiveness. To this end, the integration of advanced materials and technologies into building envelopes has garnered significant attention from both researchers and practitioners. Among these innovations, combining phase change materials (PCMs) shows great promise for enhancing energy efficiency and occupant comfort. PCMs are renowned for their high heat capacity, exceptional energy storage potential, and low heat transfer coefficient. When integrated into building envelopes, PCMs can store and release latent heat during phase transitions, stabilizing the inside vibes temperatures and reducing dependence on mechanical ventilation systems, further boosting the building's overall energy performance. Numerical simulations have historically played a pivotal role in understanding heat transfer dynamics within building structures, providing valuable insights for the effective implementation of these materials.

Zhaoli Zhang et al[1] conducted a study on a Dynamic Insulation System (DIS) that integrates airflow with Phase Change Materials (PCM) to create a complicated structure with adjustable thermal resistance. The system was developed to address building overheating. Theoretical modeling was based on the heat transfer between the PCM and the phase change behavior of the PCM and the circulating air. The findings showed the thermal resistance can be altered through forced air turbulence and natural convection, with the latter providing the lower thermal resistance, and then by natural convection and sealed cases. Temperature and phase change distributions indicated that turbulent air enhances the uniformity of temperature and phase transition within the PCM. A higher height-to-length (H/L) ratio and increased PCM cavity height, enhance airflow and improve heat transfer between the air and PCM. A DIS-PCM module with either a low flow rate or a large heat input exhibits rapid heat transfer and faster PCM melting. The developed DIS-PCM module was then integrated with a multi-layered hollow wall to explore its potential for mitigating building overheating. The results demonstrated that the system lowered the average temperature of the inside surface of the wall and increased heat dissipation from the indoor environment, effectively addressing overheating issues, even with small temperature differences between indoor and

http://doi.org/10.58564/IJSER.3.3.2024.226

ambient conditions. Furthermore, the internal thermal comfort can be precisely controlled by adjusting the airflow rate. In summary, the innovative DIS-PCM system tackles overheating by modulating thermal resistance in response to different operating conditions, offering significant advantages for building energy conservation through latent heat thermal storage.

Ayman G. Anter et al[2], investigated a new method to enhancing the efficiency of energy in buildings (EEB) through the addition of Phase Change Materials PCMs into building structures. The present study focused on evaluating the long time thermal performance of a building wall containing various thicknesses and types of PCM during the hot summer days in Aswan, Egypt. The thermal behavior of the wall was analyzed without and with the PCM layer under varying external weather conditions. ANSYS 2020, a simplified 2D thermal model was developed and simulated. The study examined the effects of different PCM thicknesses (1, 2, 3, 4, 6, and 8 cm), different PCM kinds (RT-42, RT-31, RT-27, RT-,35HC, and lauric acid), and placement within the wall (outer, inner, and middle layers) on the internal wall temperature. The findings revealed that incorporating PCM within the wall reduces inside heat transfer and asses the temperature of the interior vibes closer to the comfort level. Among the PCM types tested, RT-35HC demonstrated the best thermal performance. The optimal placement of PCM was found to be 1.5 cm on the inner and outer sides of the wall. Simulation results over three months showed that the average inside wall surface temperature was 27.7°C with PCM and 31.1°C without PCM. Moreover, placing 1.5 cm of RT-35HC-PCM on both sides of the wall resulted in a reduction of 66% in overall energy saved during the summer.

Tao Xie et al [3], presented a study to investigate the heat transfer characteristics of a new composite multilayer thermal insulation material MTIM. This innovative insulation material is composed of alumina aerogel and silica aerogel, doped with stearic acid PCMs and erythritol. The researchers utilized a combination of the Enthalpy Method, the Discrete Ordinate Method, and the Finite Volume Method to account for the combined effects of conduction, radiation, and phase change heat transfer. Using a numerical model, the study analyzed the heat transfer behavior of the MTIM with two different arrangements of the PCM. The findings showed that: (1) placing the phase change materials at the lower part of the MTIM did not improve its thermal insulation performance; (2) however, positioning the PCMs in the middle successfully enhanced its thermal heat reduction properties; (3) there exists an optimal PCM doping content that minimizes the temperature of the MTIM, thereby maximizing its thermal heat reduction performance.

Wendong Li et al[4], present a study on adding the Phase Change Materials PCMs into the building wall, which has shown potential in the reduction of the heat load and shifting the peak energy demands. While traditional static PCM systems provide some benefits, they suffer from limitations, such as inefficient latent heat utilization and restricted thermal exchange for free outdoor cooling and heating. These shortcomings result from fixed insulation layers that limit the interaction between the PCM and the environment. To overcome these challenges, the study introduces an innovative concept known as Dynamic Shiftable PCM (DSMPCM), which enables the PCM layer to reposition within the wall structure by compressing an air layer, allowing it to adapt to varying weather conditions. The research compares DSMPCM with both static PCM walls and walls without PCM. Results demonstrate the clear superiority of DSMPCM, achieving reductions in monthly heat gain and loss of 135.53% to 535.73% and 2.92% to 58.76%, respectively, during summer and winter. The study also identifies optimal PCM thermal properties, air layer configurations, and wall thicknesses to maximize performance under diverse climate conditions. Moreover, control strategies are optimized to minimize thermal loads on the building envelope, further enhancing energy efficiency. This work highlights the potential of DSMPCM as a transformative solution for sustainable building design. By dynamically adapting to environmental conditions, DSMPCM significantly improves energy efficiency, enhances thermal comfort, and offers a scalable approach for addressing energy challenges in modern construction.

Guixiao Zhang et al[5], investigated an innovative building wall system designed to enhance energy efficiency in building envelopes. This wall was meticulously analyzed using computational fluid dynamics, focusing on its ability to harness passive solar energy during winter. The system is engineered to absorb and store solar energy during the day and release it into the building at night. A distinctive feature of the wall is its Phase Change Material (PCM) layer, which dynamically shifts positions with the insulation layer. During daylight, the PCM is positioned between the outer brick layer and the insulation to capture solar energy, while at night, it swaps positions to maximize heat release indoors. The study compared the thermal performance of this dynamic wall with two alternatives: a wall without PCM and one with a static PCM layer. Results demonstrated that the proposed wall significantly outperformed the others, achieving energy savings of up to 89% compared to conventional heating systems during extremely cold winters. Remarkably, this system required only 0.32 kg of PCM per cubic meter of conditioned space 50% less than conventional designs—highlighting its efficiency and cost-effectiveness. This research underscores the potential of dynamic PCM-integrated walls as a superior solution for energy conservation in cold climates. By combining innovative material placement and reduced PCM usage, the proposed system offers a practical and efficient approach to sustainable building design.

Ekrem Tunçbilek et al[6], investigated the energy-saving potential of integrating Phase Change Materials (PCMs) with conventional thermal insulation in building external walls. Traditionally, the energy-saving effects of PCMs and insulation have been studied in isolation. This research aimed to explore the combined benefits of these materials in enhancing energy efficiency. A numerical model was developed and rigorously validated using analytical solutions and experimental data. The findings revealed that for wall thicknesses of 16 mm or less, placing PCM on the interior side of the wall delivered superior energy savings compared to insulation alone. In the best-case scenario, PCM achieved 38.2% greater energy savings than insulation at a layer thickness of 6 mm. The study introduced a parameter (ψ) to represent the ratio of PCM thickness (LPCM) to the total thickness of PCM and insulation combined (LPCM + LINS). Synergistic analysis showed that a composite system, such as the C5 configuration with $\psi = 0.05$, conserved up to 7.3% more energy than insulation-only designs ($\psi = 0$). Similarly, the C6 configuration with $\psi = 0.15$ provided an additional 6.4% energy savings compared to $\psi = 0$. Composite designs with ψ values ranging from 0 to 0.6 consistently outperformed designs lacking PCM. Importantly, the activation of latent heat in the PCM proved critical to enhancing the system's thermal performance.

This study highlights the potential of combining PCMs with insulation to achieve greater energy efficiency. By leveraging latent heat storage and optimizing PCM placement, the research demonstrates a promising pathway for improving the thermal performance of building envelopes.

Y. Cascone et al. [7] conducted a study on optimizing PCMs in retrofitting office buildings for energy efficiency in Mediterranean climates, which is crucial for achieving the EU's 2020 sustainability goals. PCMs, with careful consideration of properties, quantity, and placement, are recommended for effective and economically feasible use. The paper presents multi-objective optimization analyses for retrofitting with PCM-enhanced opaque building envelope components. Objectives included minimizing primary energy consumption, global costs, building energy needs for heating and cooling, and investment costs. The research variables encompassed PCM properties, window type, insulation materials, and wall configuration. Post-optimization analyses provided insights for designers, revealing that the HVAC system's operation notably influences optimal PCM properties.

R. F. Jam et al. [8] conducted a study for optimization of the PCM's location and thickness in building walls with an energy-economic analysis. The research emphasizes the significance of energy consumption reducing with thermal insulation in buildings. The PCM is investigated as a form of insulation in an educational building at Hakim Sabzevari University, Iran. Through numerical simulations, the study explores the effects of PCM integration during the hot period of the year. Optimal PCM placement within the wall and various thicknesses (2, 3, 4, and 5 cm) are analyzed. Results indicate heat exchange reductions of 9.8%, 13.4%, 17.5%, and 20.4%, respectively, for different PCM thicknesses. Additionally, a thermo-economic analysis calculates energy savings and payback periods. The study identifies a 3 cm PCM thickness as optimal, resulting in a 50-month payback period through Pareto solutions and the TOPSIS method.

M. J. Abden et al. [9] explored the integration of phase change materials (PCMs) with thermal insulation to enhance the energy efficiency of residential buildings. While applying thermal insulation to external walls and ceilings is a conventional practice, this study focused on the combined use of expanded polystyrene insulation and PCM gypsum boards in a typical Australian standalone house. Numerical simulations were performed to evaluate the system's effectiveness in three Australian cities—Darwin, Alice Springs, and Sydney—each representing distinct climates: tropical savanna, hot semi-arid, and humid subtropical, respectively. The findings demonstrated considerable cost savings over a 10-year lifecycle, with reductions of 167.0 AU\$/m² in Darwin, 162.3 AU\$/m² in Alice Springs, and 39.7 AU\$/m² in Sydney. The integration also significantly improved the house's energy performance ratings, achieving enhancements of 3.5, 3.8, and 4.3 stars in the respective cities. Payback periods for the renovations varied based on climate, ranging from as short as 2.2 years to a maximum of 7.5 years. This research underscores the potential of combining PCMs with traditional thermal insulation as a cost-effective strategy to reduce energy consumption and improve thermal comfort in residential buildings, particularly when tailored to specific climatic conditions.

E. Iffa et al. [10] explored innovative thermal energy storage systems for buildings, focusing on their ability to store cooling or heating energy during off-peak periods or when renewable energy is available. These systems were designed to support peak load reduction, alleviate grid stress, and improve indoor thermal comfort. While traditional thermally activated building systems often release stored energy passively due to thermal lag, the integration of active insulation systems was proposed to enhance the control of energy charging and discharging processes. The research introduced a wall system combining active insulation with thermally activated storage components and evaluated its role in providing active cooling energy. Findings revealed that the thermal performance of the system was significantly affected by the core material properties of the storage layer and the spacing of embedded pipes in both the active insulation and storage systems. During energy discharge, the system achieved a heat transfer rate of up to 81.92 W/m². Additionally, the dynamic R-value of the active insulation system varied widely, ranging from less than 1 ft²·°F·h/BTU (0.18 m²·K/W) to as high as 98% of the R-value of foam insulation of comparable thickness. This study emphasizes the potential of integrating active insulation with thermal storage systems to improve energy efficiency and flexibility in building designs, demonstrating its significant contributions to thermal management and sustainable energy use.

Connecting to the previous works, this study delves into the dynamic behavior of heat transfer within building walls with multiple layers, including a base material, which is either brick or concrete, and PCM as adding material. Factors such as material properties and design configurations are considered. We performed a full-year transient simulation, taking into account varying external conditions such as temperature, radiation due to sunshine, and convection assisted by the wind with changing speed. An efficient numerical method is used to perform the calculation. By quantifying the thermal performance under transient conditions, insights can be gained into the effectiveness of PCM integration in regulating indoor temperatures and reducing energy consumption over time. Moreover, the economic feasibility of such integration is evaluated through optimization analyses aimed at determining the most cost-effective thickness and positioning of PCM and insulation layers. By striking a balance between performance enhancement and cost considerations, this research aims to provide actionable recommendations for architects, engineers, and policymakers seeking to implement energy-efficient building solutions. The harsh weather, the energy crises, and the rapidly growing city of Baghdad in Iraq have been chosen for the building study, utilizing data specific to the region and all relevant information taken based on.

II. THE HEAT TRANSFER MODELING

To simulate the heat transfer performance of PCM-enhanced walls using MATLAB, we solve the transient heat transfer equation with phase change. The governing equation can be expressed as:

$$\rho c(T)\frac{\partial T}{\partial t} = \nabla.(k(T)\nabla T) + q \qquad (1)$$

where where:

- ρ represents the density of the material (kg/m^3).
- *k(T)* represents the temperature-dependent thermal conductivity (W/m·C).
- *c(T)* represents the temperature-dependent specific heat (J/kg·C), including the latent heat effect during phase change.
- *T* represents the temperature (°C).
- *q* represents the internal heat generation or sink term (W/m^3).

To represent the phase transition, we use an enthalpy method, where the latent heat is incorporated into an effective specific heat function. This avoids explicitly tracking the phase boundary.

i. Heat Transfer Model in MATLAB

1. Discretization Approach

We use the finite difference method (FDM) for spatial discretization and the explicit or implicit time-stepping scheme for solving the transient heat conduction equation.

- The domain (wall layers) is divided into N discrete nodes.
- Thermal properties (*c(T), k(T)*) are assigned for each material layer (brick, concrete, gypsum, PCM, plaster).
- Temperature evolution is computed iteratively over small-time steps Δt.

2. Algorithm Steps

1. Define the wall geometry and thermal properties of each layer.
2. Discretize the wall into nodes, assigning material properties to each node.
3. Initialize temperature across the domain.
4. Apply boundary conditions (e.g., outdoor temperature, indoor temperature).
5. Solve the heat conduction equation iteratively using a numerical scheme.

Although physical systems typically operate in three spatial dimensions, this analysis simplifies the problem by considering $\Delta y = 1$, $\Delta z = 1$ focusing on a single spatial dimension. In this context, the volume of a cell is computed as $V = \Delta x$, effectively reducing the problem to one-dimensional space. To achieve this, the spatial domain is discretized into an array of cells with centers located at $x_i = i\Delta x, i = 1,...,N_x$, where N_x representing the total number of cells.

Using the central difference formula, the spatial component of the governing equation is discretized, resulting in a one-dimensional form of Eq. (3):

$$\frac{dT_i}{dt} = \frac{1}{c_i \rho_i \Delta x}\left(k_{i,i+1}\frac{T_{i+1} - T_i}{\Delta x} + k_{i,i-1}\frac{T_{i-1} - T_i}{\Delta x} \right) + q \qquad (2)$$

This approach simplifies the problem while maintaining the accuracy needed for further analysis and computation.

ii. Model Assumptions

1. **Assumptions**:
    - Constant thermal conductivity and density for each layer.
    - No convective or radiative heat transfer effects.

This code provides a foundation for simulating heat transfer in PCM-enhanced walls and can be expanded based on specific project requirements. Let me know if you need help refining or interpreting the results!

explanation of the algorithm

1. **Initialization**:
    - Wall layers are discretized into N_x nodes, and thermal properties are assigned. PCM-specific properties (melting range, latent heat) are also included.
    - Boundary conditions set the indoor and outdoor temperatures.
2. **Effective Specific Heat Function**:
    - A function calculates the effective heat capacity of the PCM at each node based on its temperature. This accounts for latent heat during phase transitions.
3. **Time-Stepping Scheme**:
    - An explicit finite difference method is used to update the temperature at each node based on heat conduction from neighbouring nodes.
4. **Boundary Conditions**:
    - Fixed temperatures are applied at the exterior and interior surfaces of the wall.
5. **Visualization**:
    - Temperature profiles are plotted periodically to show how heat propagates through the wall over time.

iii. Effective Specific Heat Function:

The Effective Specific Heat Function plays a vital role in accurately modeling the phase transition behavior of materials, such as Phase Change Materials (PCMs). This function adjusts the specific heat capacity *c(T)* within the temperature range of the phase change to account for the latent heat absorbed or released during melting or solidification processes. This modification ensures that the additional energy dynamics associated with the phase change are appropriately captured in the thermal analysis.

1. **Latent Heat and Phase Change:**

- During a phase change, the material absorbs or releases a significant energy amount, known as latent heat (L), without a noticeable temperature change.
- In PCM, this occurs in the melting/solidification temperature range [$T_{melt,\ min}$, $T_{melt,\ max}$].

2. **Effective Specific Heat:**

- Outside the phase change range, the PCM behaves as a typical solid or liquid, and its specific heat is approximately constant (c_{solid}_c_{liquid}).
- Within the phase change range, the effective specific heat $c_{eff}(T)$ is enhanced by the energy associated with the phase change process:

$$c_{eff}\,(T) = c_{base} + \frac{L}{T_{melt,max} - T_{melt,min}} \qquad (3)$$

where:

  - c_{base}: Base specific heat of the material.
  - L: Latent heat of fusion (J/kg).
  - [$T_{melt,\ min}$, $T_{melt,\ max}$]: Temperature range of phase change (°C).
- If the temperature is below T_{min}: PCM is in the solid state, so the specific heat equals c_{solid}.
- If the temperature is above T_{max}: PCM is in the liquid state, so the specific heat equals c_{liquid} .
- If the temperature is within the phase change range: PCM is undergoing phase change, and the effective specific heat is enhanced by $\frac{L}{T_{melt,max} - T_{melt,min}}$.

III. NUMERICAL METHODS

Using the Explicit Euler method for heat transfer simulations involves discretizing the transient heat conduction equation in both space and time. Here, we detail the method applied to a PCM-enhanced wall simulation.

1.Spatial Discretization (Finite Difference Method)

The wall thickness L_x is divided into N_x discrete nodes, each separated by a distance Δx. The second derivative with respect to x is approximated as:

$$\frac{\partial^2 T}{\partial x^2} \approx \frac{T_{i+1} - 2T_i + T_{i-1}}{\partial x^2} \qquad (4)$$

Where T_i is the temperature at node i.

2. Temporal Discretization (Explicit Euler)

The time derivative is approximated using a forward difference:

$$\frac{\partial T}{\partial t} \approx \frac{T_i^{n+1} + T_i^n}{\partial x^2} \qquad (5)$$

Where:

- T_i^n : Temperature at node i at time step n.
- T_i^{n+1} : Temperature at node i at the next time step ($n+1$).
- Δt: Time step.

By substituting the spatial and temporal discretization into the heat conduction equation, the temperature update at each node becomes:

$$T_i^{n+1} = T_i^n + \frac{\Delta t}{\rho c T_i \Delta x^2}[(k(T_{i+1})(T_{i+1}^n - T_i^n) - k(T_i)(T_i^n - T_{i-1}^n))] + q \qquad (6)$$

a real boundary condition applied on all boundaries: At the indoor surface (i=1): the temperature constant which represents the indoor comfort temperature of the room is equal to 22 °C (fixed boundary condition), while at the outdoor surface ($i=N_x$): the temperature assume equal to 35 °C.

3.Heat Energy Calculation Formula

The total heat energy Q in the system can be calculated as the integral of the heat content over the wall's thickness:

$$Q = \int_0^{L_x} \rho . c_{eff} .T_x \; dx$$

Since the wall is discretized into N_x nodes, we can calculate Q as

$$Q = \sum_{i=1}^{N_x} \rho c_{eff} .T_i \; \Delta x$$

To calculate the energy cost based on the heat energy stored or released by the system, we can use the following approach:

$$C = E \cdot R$$

where:

- E: Total energy consumed or saved (in kilowatt-hours, kWh).
- R: Energy rate (in $/kWh or €/kWh).

  Heat energy (Q) is often calculated in joules (J). To convert it into kilowatt-hours:

$$E = \frac{Q}{3.6 \times 10^6}$$

Where: Q is total heat energy in joules, and 3.6×10^6 is the conversion factor from joules to kWh (1 kWh = 3.6×10^6 J).

Energy Cost Over Time, If you track $Q(t)$, the total energy cost over time is calculated as:

$$C(t) = \sum_t \frac{Q}{3.6 \times 10^6} .R$$

IV. GEOMETRY, MESH GENERATION, AND MATERIALS PROPERTIES

The wall structure consists of multiple layers, each made of different materials to enhance thermal performance and meet practical construction standards. Below are the detailed geometric and material properties for each layer, as one can see in Figure 1.

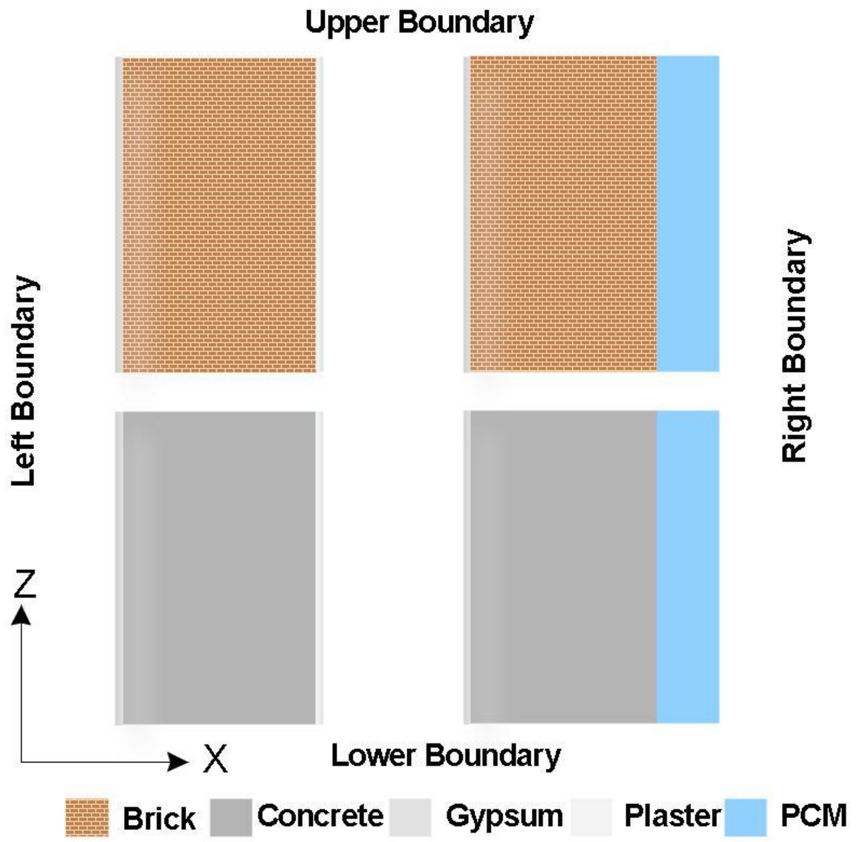

Figure 1. The geometries of the current study cases of study

The simulation scenarios are designed to assess the heat transfer performance of different wall configurations under various conditions. Each scenario focuses on evaluating the impact of varying phase change material (PCM) thicknesses in combination with different base wall materials (brick or concrete). Below is a description of each simulation scenario:

1. **Scenario 1: Gypsum, Brick, Steel, PCM, and Steel Wall Structure**

This scenario involves a multi-layer wall structure composed of the following materials:

- **Gypsum**: A thin layer providing some thermal insulation.
- **Brick**: The main structural layer offering strength and moderate thermal mass.
- **Steel**: A thin layer added for structural support and heat conduction.
- **PCM (Phase Change Material)**: Positioned to absorb and release heat during temperature fluctuations, helping to regulate the indoor temperature.
- **Steel (outer layer)**: Provides external protection and contributes to heat transfer.

The objective of this scenario is to evaluate how different thicknesses of PCM affect the wall's thermal response, particularly its ability to store and release heat over a day-night cycle. The simulation will test multiple PCM thicknesses to identify the optimal thickness for balancing thermal comfort and energy efficiency. The results will help determine how the PCM layer interacts with the other materials, especially the thermal properties of the brick and steel layers.

2. **Key variables for this scenario**:

- PCM thickness: Varying from 0.01 m to 0.1 m (or other appropriate ranges).
- Temperature fluctuations: Simulated for day and night cycles to assess heat absorption and release by the PCM.

3. **Scenario 2: Gypsum, Concrete, Steel, PCM, and Steel Wall Structure**

In this scenario, the wall structure includes the following layers:

- **Gypsum**: As in Scenario 1, it provides thermal insulation.
- **Concrete**: Replaces brick, offering greater thermal mass and slower heat transfer.
- **Steel**: Provides structural integrity and heat conduction.
- **PCM**: Positioned similarly to Scenario 1, but with concrete as the base material.
- **Steel (outer layer)**: Protects the exterior while contributing to heat transfer dynamics.

The focus of this scenario is to investigate how the use of concrete, with its higher thermal mass compared to brick, affects the heat transfer performance of the PCM layer. The simulation will test varying PCM thicknesses and analyze how concrete's characteristics interact with the thermal storage and release capabilities of the PCM. The effect of the concrete layer on the wall's ability to moderate temperature fluctuations over time will be a key area of focus.

4. **Key variables for this scenario:**

- PCM thickness: Varying from 0.01 m to 0.1m (or other suitable values).
- Concrete's thermal mass: The impact of concrete's heat retention properties will be compared with the effect of PCM thickness changes.

The main goal of these simulations is to assess the influence of PCM thickness on the thermal performance of multi-layered wall structures with different base materials (brick vs. concrete). By varying the PCM thickness, the simulation will help identify how to optimize the wall design for energy efficiency and thermal comfort, particularly in buildings with significant daily temperature fluctuations.

For a 1D simulation, we define the mesh along the thickness of the wall. Each node represents a point where material properties and temperature will be calculated, and each element connects two adjacent nodes. We will distribute the nodes along the thickness direction. The nodes are positioned at the boundaries of each element, starting from the wall's outermost side (the PCM layer) and moving inward toward the inner side (the Gypsum layer). Material properties listed in table1 and 2.

Node coordinates: The node positions along the thickness direction are given by $x_i = i \times \Delta x \quad for\ i = 0,1,2,......,N$

Table 1. The Paraffin wax PCM properties [7].

Material	$k\ \left(\mathrm{W \cdot m^{-1} \cdot} C^{-1}\right)$	$\rho\left(\mathrm{kg \cdot m^{-3}}\right)$	$c\ \left(\mathrm{J \cdot kg^{-1} \cdot} C^{-1}\right)$	$Latent\ Heat\left(\mathrm{J \cdot kg^{-1}}\right)$	Melting temperature range °C
PCM_{Solid}	0.2	900	2000	200000	24-28

Table 2. The Structural Materials properties.

Material	$k\ \left(\mathrm{W \cdot m^{-1} \cdot C^{-1}}\right)$	$\rho\left(\mathrm{kg \cdot m^{-3}}\right)$	$c\ \left(\mathrm{J \cdot kg^{-1} \cdot C^{-1}}\right)$
Gypsum	0.17	850	1090
Brick	0.7	1600	840
Plaster	0.721	1762	840
Concrete	1.70	2400	900
Steel	35	7838	423.82

V. RESULTS AND DISCUSSION

The MATLAB simulation results highlight the thermal and economic performance of a wall structure with varying PCM thickness (0.01 m to 0.1 m). Below are the key findings based on heat performance (heat Transfer minimization) and energy cost (USD) analysis:

i. Heat Performance (Heat Transfer Analysis)

1. **Heat Transfer Over Time**:
    - The heat Transfer magnitude decreases with increasing PCM thickness, indicating better thermal resistance with thicker PCM layers.
    - For thinner PCM layers (e.g., 0.01 m), higher heat Transfer is observed during extreme temperature differences (summer and winter), leading to higher heat exchange., see figures (2) and (3)
2. **Optimization**:
    - The PCM thickness of 0.07–0.08 m in the case of brick 0.05–0.06 m in case of concrete and achieves significant heat Transfer reductions, particularly during peak conditions (summer and winter extremes).
    - Beyond 0.08 m PCM m in the case of brick and 0.06 m in case of concrete, the heat Transfer reduction plateaus, suggesting diminishing returns on additional PCM thickness.

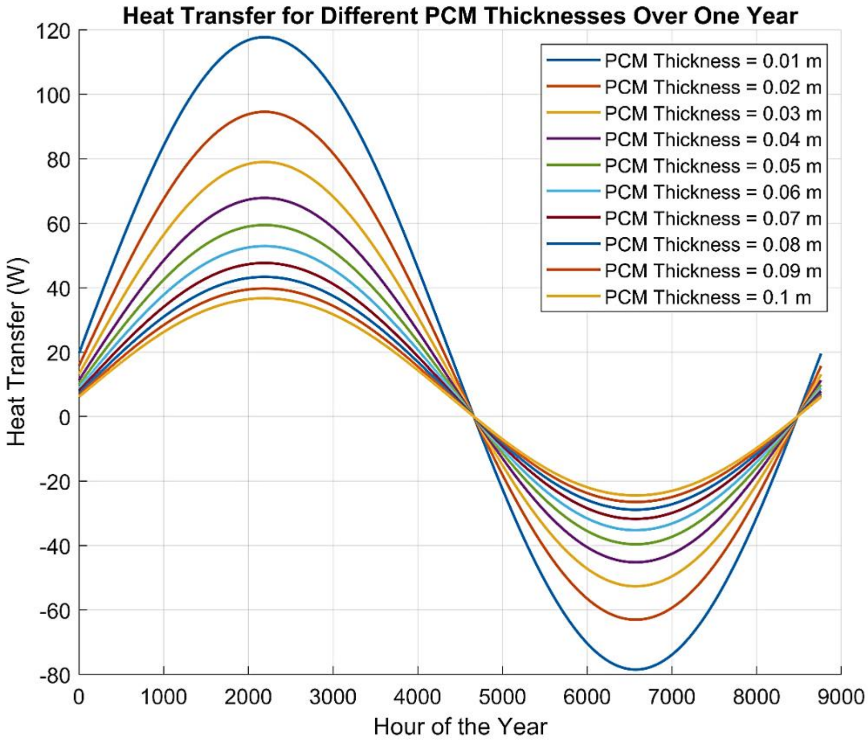

Figure 2. The heat transfer in cases of Brick + PCM

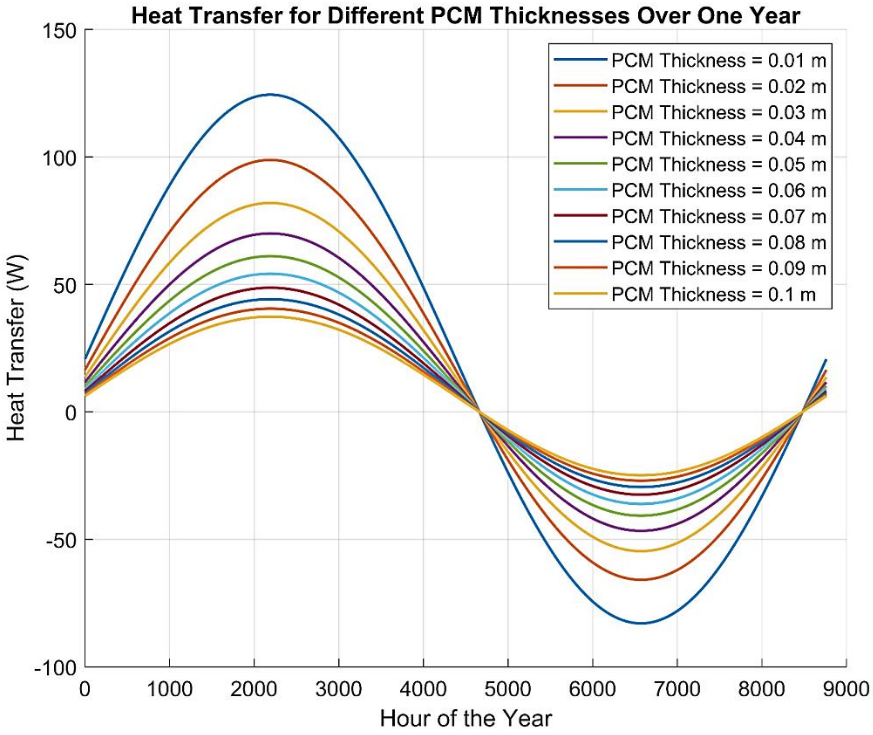

Figure 3. The heat transfer in cases of concrete + PCM

ii.Temperature at the Middle of the Brick Layer

1. **Temperature Profile**:
    - The middle-brick temperature stabilizes with increasing PCM thickness, particularly during the summer season.
    - PCM layers thinner than 0.05 m exhibit higher temperature fluctuations in the brick, leading to less uniform thermal performance. see figures (4) and (5).

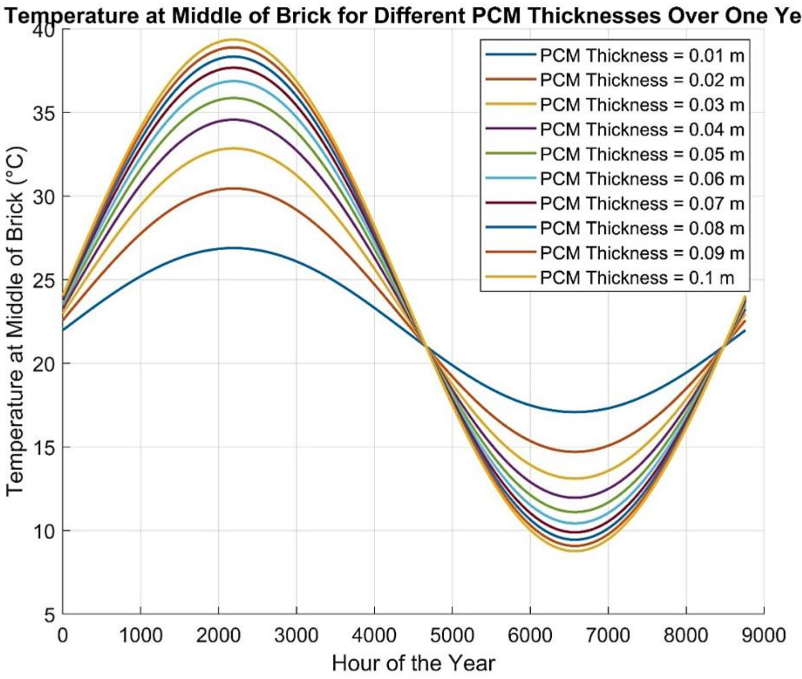

Figure 4. The temperature at the middle of brick layer in cases of Brick

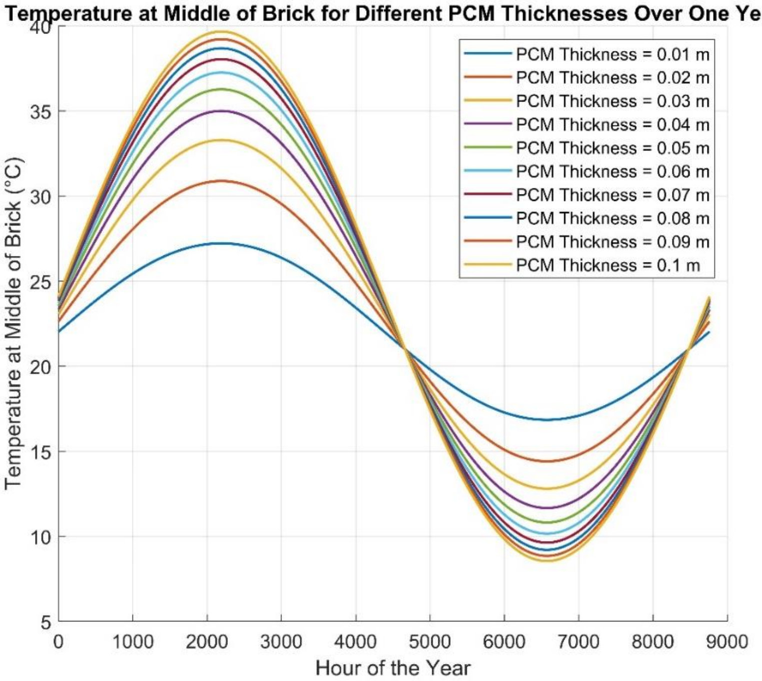

Figure 5. The temperature at the middle of and concrete + PCM

iii.Energy Cost Analysis

1. **Annual Energy Cost (USD)**:
   - The total annual energy cost for heating or cooling decreases as PCM thickness increases, up to a threshold.
   - For PCM thickness > 0.08 m in the case of brick-based and PCM thickness > 0.08 m in the case of concrete-based, the additional energy savings are marginal compared to the cost of extra PCM. see figures (6).

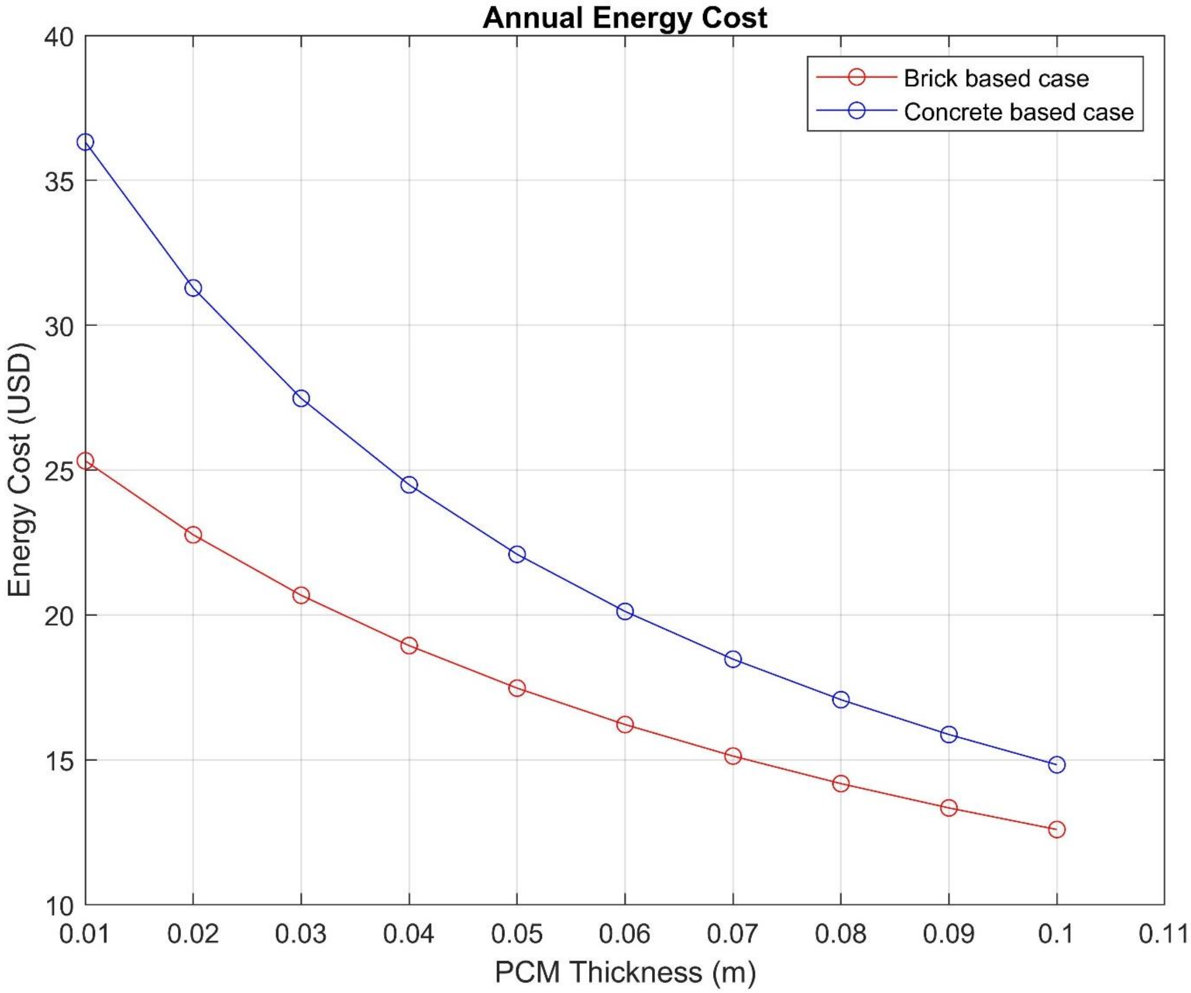

Figure 6. The energy cost over the range of PCM thickness

In Figure 7, we present the Effective Specific Heat function as a function of temperature, plotted over the simulation duration at a specific point within the PCM layer. These plots depict the melting process and the heat storage phenomenon, showing the characteristic heat hump associated with phase transition in the material.

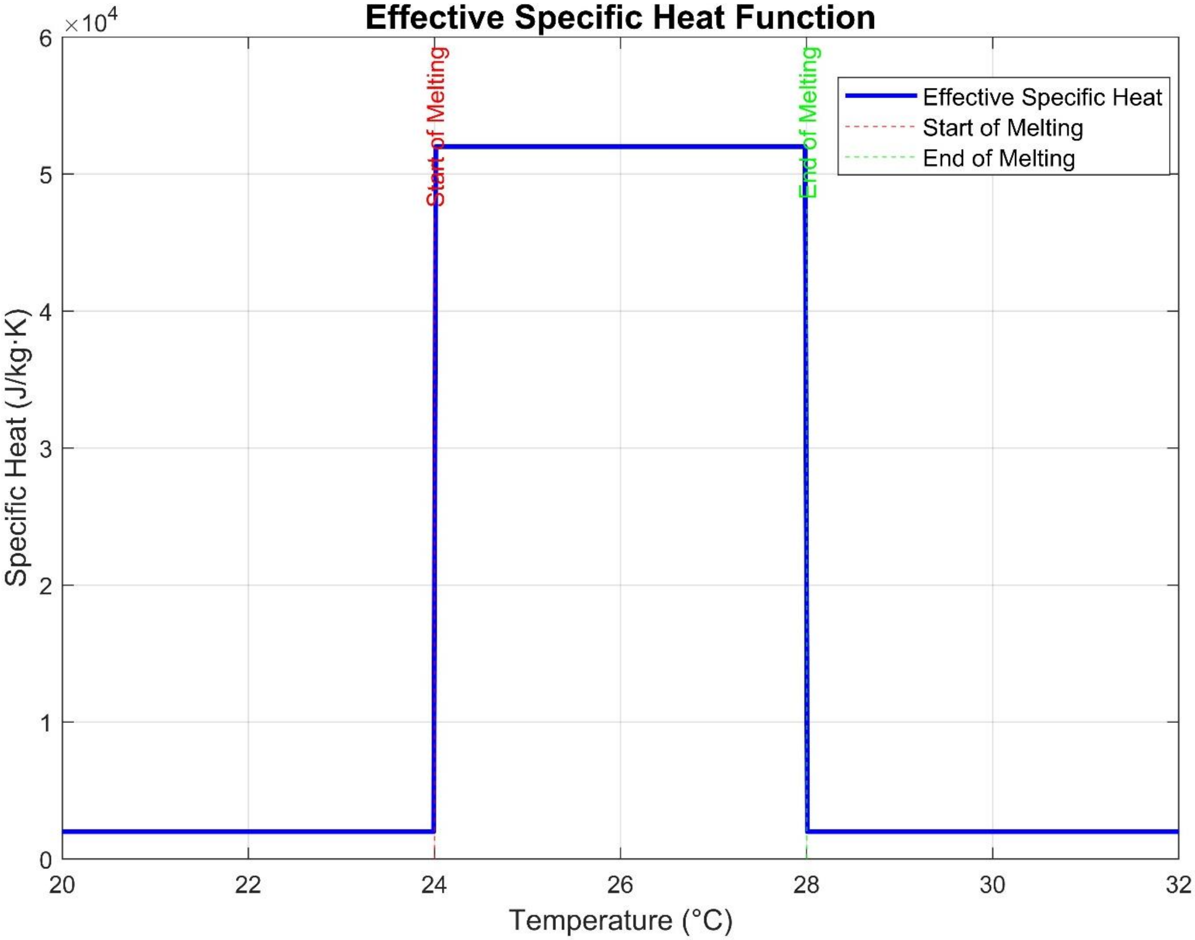

Figure 7. The effective specific heat function

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