Numerical analysis of energy savings due to the use of PCM integrated in lightweight building walls

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Abstract. A new type of PCM layer integrated into an exterior building wall is to reduce the amplitude of the indoor temperature and maintaining the better thermal comfort for human beings. A numerical simulation has been carried out with and without integration of PCM in building walls. In this paper, the effect of different configuration of external building walls were studied and analyzed by the integration of PCM building walls. Using finite difference method, one dimensional transient heat transfer model was developed and solved. The indoor temperature was also analyzed for the summer and winter climatic conditions of Chennai city, India (13.1 Latitude and 79.9 Longitude) in the PCM and Non-PCM buildings. The building wall consists of clay brick with filled with PCM. The numerical simulation result shows that, PCM filled with clay brick wall improves the thermal inertia significantly. Location of PCM layer in the building wall is one of the important factors to reduce the heat gain in the building wall before it enters the room.

Keywords: Phase Change materials, Energy efficient buildings, Building energy Conservation, Thermal Performance, DESIGNBUILDER

1. Introduction

The building sector is one of the largest energy consumers around the world with a total of 30–40% of the global energy consumption in which a substantial amount of energy is used to enhance indoor thermal comfort [1]. Also, the energy consumption in this sector has been increased rapidly in recent years due to high living standards, increased population growth, and people spending more time indoors. The energy used by the buildings was mainly generated by the heat gain through building envelopes. Among it, the building wall was consumed the energy around 25%, followed by the roofs for 22%, windows for 23% and others for 30%. The massive construction of the enveloped building wall is to reduce the energy consumption of the buildings. Increasing thermal mass of building walls is to increase the thermal performance, knowing as passive cooling energy saving methods [2]. The building thermal system maintains at the building envelope, in which the thermal balance between energy consumption, energy production and storage of energy within the building. This thermal balance considerably affected by the factor’s external thermal solicitations and the external building envelopes act as a barrier to external
factors[3]. The construction of building envelope plays a major role in determining the cooling energy demands of a building. Naturally available cool thermal energy is utilized to minimize the use of mechanically assisted air conditioning systems in buildings[4]. However, the construction of traditional building material gives thermal mass to a building bricks or blocks of construction make it heavy construction and high volume. The choice of suitable construction method provides an opportunity to enhance the thermal comfort, reducing the energy demands for space conditioning system and diminishes indoor temperature swings by absorbing heat and gradually releasing it when the decrease the ambient temperature, leading to a reduction and a shift the peak load[5]. The energy storage system can be used with high storage density and high thermal capacity. The dynamic building envelope materials could be used to control the heat flow into and out of buildings. The innovative macro encapsulated Phase change materials (PCMs) have been considered as a way to increase the energy efficiency, ability of storing and releasing large amounts of heat within a small volume and thermal inertia of buildings [6]. PCM has been integrated in building envelopes to improve the thermal comfort and reducing the cooling/heating loads [7]. B. James and P. Delaney studies stated that, PCMs incorporated buildings in various climatic weather zones in the USA, can potentially save 10–30% of the annual heating loads [8]. An experimental work was carried out in USA showed the results, 10–26% of the energy savings were attained in summer months by using PCMs in building walls [9]. The plaster incorporating micro encapsulated PCM was coated on interior building walls which is reduced by 2 K indoor temperature and maintained the thermal comfort for longer periods in German [10]. Experimental analysis of PCM integrated building was investigated and results found that, the PCM building walls could make the interior comfort temperature and decreasing the cooling load of air-conditioning system[11, 12]. Also, during off- peak period in the winter season, heat pump could be used to melt the PCM in wallboards above the transition temperature. The stored heat energy could be released in a room at peak hours in which the heating demand might be reduced [13, 14] thermal performance. The conventional residential building results has been compared and evaluated with the PCM residential building.

Macro encapsulated PCM integrated in clay hollow brick in Mediterranean countries was investigated and discussed using temperature, relative humidity, solar radiation and climatic weather condition. The west and south facing walls equipped with thin layer of PCM was analyzed under different climatic weather conditions. The heat flux reductions were 29.7% and 51.3% for the west and south wall respectively. The maximum heat flux time delays were 2.3 hour for west wall and 1 hour for south wall. The maximum daily heat transfer reduction were 3.6% in the west wall and 27.1% in south wall [15]. The energy and economic analysis of the integration of PCM in typical multistory office building located in five different cities of China, was simulated for a whole year. The simulated results showed that the energy savings resulting from PCM integration were more prominent for office buildings located in cold
regions as well as in cold winter and hot summer regions [16]. The economic analysis of PCM integrated office buildings were not sufficient to recover the investment which is located in different cities of China. During summer and winter season, the energy savings was found that the integration of PCM building in Zhengzhou, Changsha and Shenyang has high economic value and the investment appear to be attractive. However, the investment of PCM buildings cannot be recovered in Hong Kong and Kunming and do not offer economic benefit. The potential of PCM in minimize the energy consumption at different climatic condition of Australia and the effectiveness of PCM have been analyzed using EnergyPlus building simulation software. Five different PCM melting temperature ranges were used to identify the optimum melting range of PCM for each city. The potential of PCM building has reduce the energy consumption in Australian cities under warm temperate, cold temperate and mild temperate zones. The PCM building has very minor effect on hot and humid climate zone. The effectiveness of PCM depends on PCM layer thickness, surface area, thermostat range, location of application and local climate in building. The Melting point of PCM was selected outside the temperature range does not provide efficient energy reduction irrespective of the maximum reduction in temperature fluctuations [17].

Using Energy Plus building simulation software to simulate the PCM building wallboards on summer day in Auckland. The indoor temperature fluctuation was reduced daily up to 4 °C [18]. PCM effect was estimated using Enthalpy method through Energy Plus software. The verification and validation study [19] was conducted recently using Energy Plus software. The thermal performance of PCM buildings was accurately calculated using this same software and met the several building guidelines. Hence, the present study has been investigated and evaluated using “Energy plus”.

From the above literature reviews indicated that, the integration of PCM in building materials is increase the energy storage in buildings in which reduces energy reduction and indoor temperature fluctuation. To the best of the author’s knowledge, no published literature review on PCM integrated in building wall in warm and humid climatic conditions of Chennai city, India and no data is available about potential cooling load reduction by using PCMs in such climate. The aim of the present paper, a detailed study of thermal performance of PCM integrated in building wall was investigated through numerical simulation using Energy Plus software under warm and humid weather conditions of Chennai city (13.1 Latitude and 79.9 Longitude), India. The effects of phase change temperature, location, melting range of PCM, amount of PCM and shape of enthalpy curve on PCM building wall were reduced the heat gain reduction in PCM buildings were studied and reported.

2. Numerical methods and model description

2.1 Numerical method
Simulation of PCM building was carried out using “Energyplus” building simulation software which is developed by U.S Department of Energy. It is a strong tool for simulation of thermal buildings and also has various option and modulus with an enormous data library. Additionally, almost all of its parts have been validated with experimental studies since the first release of the software [20]. The one-dimensional heat conduction finite difference (CondFD) solution is working as heat balance algorithm in EnergyPlus to simulate the thermal performance of PCM in building walls. EnergyPlus with the CondFD algorithm solved by a fully implicit finite difference scheme which is coupled with an enthalpy–temperature function to account for phase change energy was used in this study. The specific heat capacity ($C_p$) of PCMs is updated in each iteration according to the following Equation (1)

$$C_p = \frac{h^j - h^{j-1}}{T^j - T^{j-1}}$$  \hspace{1cm} (1)

Where

$T$ = node temperature (k),

$J$ = actual time step for simulation,

$j-i$ = previous time step,

$I$ = modeled node,

$h$ = user defined function of the specific enthalpy of PCMs as a function of temperature

The iteration scheme assures the correct $C_p$ is used in each time step based on the user defined enthalpy–temperature function [21]. The validation and verification studies for heat transfer calculation and CondFD solution algorithm in EnergyPlus have been performed many researchers [7, 22]. In order to ensure the accuracy of the CondFD model and the simulation, the dissertation space was 3 and the time step was set to one minute for simulation [20]. Moreover, the strong hysteresis PCMs cannot be accurately simulated, so that, negligible hysteresis PCM can be used to attain suitable results [20].

The PCM (HS 29) used for this research has been selected directly from the Design Builder simulation program which is having the melting temperature of 29°C. The phase change energy was considered into account by applying enthalpy-temperature function. The formulation of a node of PCM is given by Equation (1).

2.2 Validation

Many verification and validation has been carried out on ConFD models and PCM of Energy Plus different test in which consist of comparative testing, analytical verification and empirical validation [23].
In addition, EnergyPlus PCM algorithm was validated against experimental data by other researchers [7, 24]. The CondFD solution and PCM algorithms of EnergyPlus were verified and validated against comparative testing, empirical validation and an analytical verification [25]. Furthermore, the EnergyPlus PCM building model was validated against the experimental work [24] which was powerful agreement between numerical simulation results and experimental data.

2.3. Building model

A single-zone building with single floor prototype building was selected with floor area of 16 m² (4 m width x 4 m breadth x 3.5 m height) as shown in figure 1. The window was located in eastern and northern side of the building with size of (0.9 m x 1.2 m) size. The 3 mm thickened window glass having solar transmittance of 0.45 whereas the transmittance of visible light and the coefficient of the thermal conductivity of the glass were 0.7 and 0.9 W/m K, respectively. The property of the window glass has given in Table 5. The distance between floor and each window’s bottom was 1 m. The ratio of window to wall area in the northern and southern side was 26% within the range of civil building thermal design code recommended. Based on the solar radiation magnitude, the PCM was arranged in all side of the walls. The sides of the walls covered by PCM and the Schematic diagram of PCM and Non-PCM wall as shown in figure 2 and 3. The details of selected PCM thermophysical properties and details building materials properties with building envelopes details are given in the Table 1 to 4. The PCM was added on the interior surface of exterior building walls. The building model is considered for office use. The effects of PCM cooling energy performance, thermal comfort was investigated with modelling and analysis of PCM and Non-PCM building with same orientation, same materials and same dimensions. The climatic weather data files for building simulations were mostly attained from the EnergyPlus Weather (EPW) database in which weather data provided in EnergyPlus format from 20 sources.

Table 1. Properties of phase change materials (PCMs)

| Property                        | Value |
|---------------------------------|-------|
| Melting point (°C)              | 29    |
| Conductivity (W/mK)             | 0.172 |
| Density (kg/m3)                 | 976   |
| Specific heat (J/kg K)          | 1390  |
| Latent heat (J/kg)              | 194   |
Table 2. Details of building envelope

| Envelope      | Construction (Inside to Outside)                                      |
|---------------|-----------------------------------------------------------------------|
| Floor         | 120 mm reinforced concrete                                            |
| wall          | 20 mm mortar, 200 mm brick, 20 mm mortar                              |
| Wall with PCM | 15 mm mortar, 200 mm brick, 25 mm PCM, 15 mm mortar                  |
| Roof          | 15 mm mortar, 100 mm reinforced concrete, 15 mm mortar               |
Figure 3. Schematic of PCM wall

Table 3. Physical properties of door

| Materials        | Thickness of the door (m) | Thermal Conductivity ‘K’ (W/mK) | Density (kg/m³) | Specific heat (J/kg K) |
|------------------|---------------------------|--------------------------------|-----------------|------------------------|
| Plywood door     | 0.0381                    | 0.12                           | 510             | 1380                   |

Table 4. Physical properties of building envelope

| Building Materials | Density (kg/m³) | Specific Heat (J/kg K) | Thermal conductivity (W/mK) | Thermal Resistance (m²K/W) |
|--------------------|-----------------|------------------------|----------------------------|---------------------------|
| Cement             | 1600            | 1050                   | 0.84                        | 0.15                      |
| Mortar             | 1800            | 1.05                   | 0.93                        | 0.01                      |
| Reinforced concrete| 2500            | 0.92                   | 1.74                        | 0.02                      |
| Thermal insulating materials | 1000 | 0.92 | 0.085 | 0.07 |
Table 5. Window construction

| Optical data type                               | Spectral average |
|------------------------------------------------|------------------|
| Thickness (m)                                  | 0.0035           |
| Front Side Solar Reflectance at Normal Incidence| 0.078            |
| Visible Transmittance at Normal Incidence      | 0.9              |
| Back Side Solar Reflectance at Normal Incidence| 0.078            |
| Solar Transmittance at Normal Incidence        | 0.8              |
| Front Side Visible Reflectance at Normal Incidence| 0.081          |
| Front Side Infrared Hemispherical Emissivity   | 0.85             |
| Infrared Transmittance at Normal Incidence    | 0.0              |
| Back Side Infrared Hemispherical Emissivity Thermal | 0.85       |
| Thermal conductivity [W/m K]                   | 0.9              |

3. Results and discussion

The simulated PCM and Non-PCM room temperatures for the months of January, February, May and June as shown in figure 4 to 7. The simulated results show that, the PCM room temperature profile provides maintained within a thermal human comfort for winter season. During summer season, the PCM room temperature always less than that of Non-PCM room temperature as shown in figure 5 to 8. The PCM layer added in the building wall was reduced the interior PCM room temperate and increasing the energy saving possibilities. The great temperature difference between day and night time will help PCM play its role in solid–liquid phase change cycles transformation and improve the energy saving possibilities. From figure 5, shows that, the higher values of minimum temperature suggest that the PCM walls are discharging more heat than the controller model during cooling process. During day time, the PCM wall can absorbed heat and release it at night time when there is no heat source inside the room. The PCM effectiveness was evaluated by comparing the interior and exterior wall temperature with and without addition of PCM in buildings. During the sunshine period, the PCM can prevent the heat gain enter into interior area whereas at night time the PCM can decrease the interior heat flow losses. In the month of January and February the variation of PCM and Non-PCM room temperature as shown in figure 5 and 6. In the month of January and February the temperature of PCM room Varies from 25 to 29°C. The Non-PCM room temperature varies from 29 to 33°C. The temperature drop for the PCM and Non-PCM room for the January and February month was 6°C. This is true for the entire month of January and February. This month during the early morning hours, the ambient air temperature was very less than that of melting of PCM temperature range for the period of 6 hours in which the temperature of range of 23°C to 26°C. The diurnal temperature variation in Chennai is about 7 °C.
Figure 4. Variation PCM/Non-PCM room temperature for the month of January

Figure 5. Variation PCM/Non-PCM room temperature for the month of February
During the sunshine period, the PCM can prevent the heat gain enter into interior area whereas at night time the PCM can decrease the interior heat flow losses. Figure 4 and 5 shows the variation of PCM and Non-PCM room temperature for the month of January and February. The PCM room temperature varies from 25 to 29°C for the period of 24 hours for the month of January and February months. The Non-PCM room temperature varies from 29 to 33°C. The temperature drop for the PCM and Non-PCM room for the January and February month was 6°C. This is true for the entire month of January and February. This month during the early morning hours, the ambient air temperature was very less than that of melting of PCM temperature range for the period of 6 hours in which the temperature of range of 23°C to 26°C. The diurnal temperature variation in Chennai is about 7 °C.

![Figure 6. Variation PCM/Non-PCM room temperature for the month of April](image-url)
Figure 7. Variation PCM/Non-PCM room temperature for the month of July

The solar radiation heats up the exterior vertical wall surfaces of the building envelope in which larger temperature variation on the building envelope. This permit the PCMs can go through the full melting–freezing cycles leading to the temperature reduction of PCM building. The same temperature pattern is followed for the month of April and July as shown in figure 6 and 7. The ambient air temperature was increases during the night time in April and July months than in January and February. The freezing amount of PCM is less due to highest ambient temperature where it happens during night-time and during day time more melting happens. So that there will be a small rise in PCM temperature and the temperature drop 2-3°C compared to Non-PCM room temperature.

The April and July month with the temperature drop of 2-3°C, the same temperature pattern is followed by due to high ambient air temperature at day and night hours make it difficult in freezing of PCM and PCM change its phase in Small quantity. This temperature drop may be lower thermal conductivity of PCM material. The PCM integrated passive cooling building is good for January to March to due to lower ambient temperature. During summer season, this system underperforms due to higher ambient temperature.

The month wise minimum and maximum PCM and Non-PCM temperature variations as shown in figure 8. The maximum solar radiation reached to the Non-PCM room during noon time, so that it has
reached maximum temperature. Again, the figure 8 shows that the Non-PCM room temperature is always greater than the PCM room temperature throughout the year. The PCM room, a constant temperature was maintained in the building walls at 26°C ± 3°C in January to March months, but Non-PCM wall was maintained at higher temperature. This is due to lower thermal conductivity of PCM and higher thermal mass in PCM room as the latent heat thermal energy storage system. The Non-PCM room stored as sensible heat energy storage and heat flow into the room in which increase the room temperature.

![Figure 8. Monthly minimum and maximum experimental temperature variations of the PCM and non-PCM rooms](image)

4. Conclusion

Several promising methods are taking place in the field of latent heat thermal energy storage system using PCMs integrated buildings. A detailed numerical simulation in PCM incorporation building architecture for space cooling was carried out using EnergyPlus software. It is the evident from the earlier studies that the thermal enhancement in a building due to the addition of PCMs depends on type of PCM, climatic condition, orientation of buildings, melting temperature, design. These parameters are optimized to determine the possibilities of successfully implementation PCM building materials. Therefore, the simulation analysis for the PCM building is definitely is a remarkable and quantifiable guidance for
designing and of PCMs in building application. The selection of PCM for one climatic weather conditions will not be suitable for other climatic conditions.

The numerical simulation analysis was carried out with two identical buildings, both with same dimension, orientation and construction materials were used. One building integrated with PCM in building wall and another building was considered as non PCM building. The integrated PCM building wall was reduced the room temperature by 6°C in the month of January and March and a minimum temperature reduction is 3°C in May month. The selected PCM was performed well during the winter months and during summer months (April–July) a lesser temperature drop is observed. Hence, the PCM based passive cooling system is providing the reduction of indoor temperature and avoids high electrical consumption and reduces the greenhouse effect.

Nomenclature:

- \( C \) : Specific heat capacity (J/kg °C)
- \( T \) : Nodal temperature, (°C)
- \( \rho \) : Density of material
- \( Q \) : heat flux (W/m²)
- \( t_m \) : Phase change temperature (°C)
- \( k \) : Thermal conductivity (W/m °C)
- \( t \) : Thickness of the PCM layer (m)
- \( L \) : Liquid fraction temperature (°C)
- \( LH \) : Latent heat (J/kg)

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