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Energy-saving potential of a passive cooling system for thermal energy management of a residential building in Jaipur City, India

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ABSTRACT

In building sectors, a substantial portion of the energy is consumed for the use of space cooling and heating of the system. Phase Change Material (PCM) based passive cooling method is one of the innovative methods for energy-saving and temperature control of the buildings. In the present study, PCM integrated thermal performance of the building has been simulated through numerical assessments using EnergyPlus software for Jaipur city. This study evaluates the temperature reduction of a PCM building with a phase change temperature of 24 °C was integrated into the building wall. The results show that the PCM building maintains the comfort temperature for the whole year without any mechanical system. This building result helps in achieving zero energy in buildings which can be used by engineers and architects.

1. Introduction

Nowadays, more attention is focused on modern technics in energy-efficient building sectors according to the increase in global climatic change and energy sustainability [1]. Buildings with energy efficiency design and low energy consumption are important topics to reduce the environmental impact and use of fossil fuel resources. The building sectors consume more than 30% of electrical energy in India for the air-conditioning system to increase thermal comfort indoors. [2]. The building envelopes are used to isolate the inside conditions of a building from variable ambient air temperatures to reduce the heating and cooling load demands inside the building.

Increasing the thermal mass in building envelopes will reduce and control the indoor temperature swings by absorbing the solar heat gain and release the heat energy when there is a change in outdoor air temperatures, which leads to the reduction of peak indoor loads [3]. In recent years, many efforts are taken to study the building thermal performance of PCM integrated into building envelope materials. For application purposes, The PCMs are integrated with building envelopes to increase the thermal comfort for occupants in indoor condition. The PCM integrated wallboard is fabricated and analysed experimentally and numerically. The PCM room temperature was reduced to 9.22 K [4]. A method was proposed in which PCM is contained in pouches with sealed and arranged in aluminium laminated sheets. The thermal performance of the PCM pouches incorporated in the south and west-facing building wall was evaluated under full weather conditions. The result shows that the heat flux reductions for the west and south are 51.3% and 29.7% [5]. Pasupathy and Velraj [6] experimentally studied the double layer PCM integrated into building roofs to attain year-round thermal management in the passive cooling method in warm and humid weather climatic conditions in Chennai city. The results revealed that the indoor air temperature swing was reduced for all climatic conditions. The PCM integrated into the exterior building wall was studied experimentally in the full-scale room during winter, midseason and summer season. The wall surface temperature of the room was reduced to a maximum of 0.2 °C and 1–2 h for the time delay. The cooling load was reduced by 24.32% in the PCM integrated room during summer. The heating load was reduced by around 10–30% during the winter season. The PCM building wall showed year-round excellent thermal performance [7]. The energy performance analysis of the PCM integrated into building envelopes was studied numerically using EnergyPlus

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software in Singapore. The 10 mm PCM layer with a melting temperature of 28 °C was integrated into the building wall to reduce the cooling load of 21–32% [8]. The potential of the PCM integrated into the residential building was analysed using EnergyPlus software through numerical simulation in Australian cities in different climatic zones. The PCM effectiveness depends on local climatic conditions, the thickness of the PCM layer, and thermostat range. The annual energy savings of 17 – 20% were achieved in hot and humid cities [9]. The thermal performance of residential buildings enhanced with encapsulated PCM in the building envelope was studied in summer conditions. The peak heat fluxes were reduced by 36.5% when compared to the conventional building wall [10]. PCM has attractive advantages, as the heat of fusion is generally large in compari- son with sensible heat changes, high storage capacity, high density and high specific heat, nontoxicity and non-flammability, and low volume required during the phase change. The selected HS 24 PCM is economically feasible. [11].

The integration of PCM in building materials was studied; from the literature, it is evident that the cooling load and the indoor temperature fluctuation was reduced. The present study aims to investigate the real-time residential building integrated with PCM in the building wall. It is simulated and analysed and the results were compared with non-PCM building using EnergyPlus software in Jaipur city (Desert region) in India. The comfort temperature is maintained in the range of 25 ± 3 °C in indoor conditions. The selection of the Jaipur city is located at 75°4″ East longitude and 26°5″ North latitude. The temperature in Jaipur city is comparatively high throughout the year. During the summer season from April to July it has a daily average temperature of 30 °C. The winter season from November to February is pleasant with a daily average temperature of 15 – 18 °C with low humidity. The different months of minimum and maximum average temperature of Jaipur city are shown in Fig. 1.

2. Methodology

2.1. Description of building

A numerical simulation was carried out for a single room residential building as shown in Fig. 2. The living room dimensions of the floor area were 4 m × 4 m × 3 m with one window in the north and west wall with a south-facing door. The size of the window was 1 m in the vertical and 1.2 m in the horizontal direction. The window was located 1.1 m above the floor surface. The window materials, walls, roofs were selected according to Indian standards. The solar transmittance and visible transmittance of the window were 0.45 and 0.7 with thermal conductivity of 0.9 W/m K. The thickness of the window was selected as 3 mm. For the south facing door, a size of 2 m × 0.8 m was selected. The concrete roof thickness was 100 mm. The PCM and non-PCM building wall model is shown in Figs. 3 and 4. The thermophysical properties of the building are given in Table 1. The details of construction of the roof, building walls and ceiling are given in Table 2.

2.2. Simulation details

The PCM and non-PCM buildings were modelled and simulated using EnergyPlus software in different climatic conditions of Jaipur city. The standard weather files were used for the simulation. A year-round simulation was carried out using the conduction finite-difference algorithm (ConFD). This helped to stimulate the PCM building materials in building envelopes. The PCM building is simulated and the change of specific heat due to the phase transition temperature process of PCM is evaluated. The CondFD approach is used to combine with the temperature- enthalpy function, which is used to read the inputs of enthalpies varying the temperature differences and is given by the equation [1].

The enthalpies in each node are updated in every iteration as shown in Fig. 5 to increase the accuracy of the CondFD model. The time step for the simulation was 3 min as recommended by Tabares- Valesco et al. [12].

$$C = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \quad (1)$$

Where T is the temperature of the node, i is the modelled node, j-1 is the previous time step, j is the actual time step and h is the enthalpy of PCM temperature. Specific heat (Cp) is used in each time step, which is based on the temperature- enthalpy function.

2.3. Validation

The CondFD models were used in EnergyPlus software which is used in the PCM building to validate and verify different climatic conditions, evaluated by Tabares-Velasco et al. [12,12]. It consists

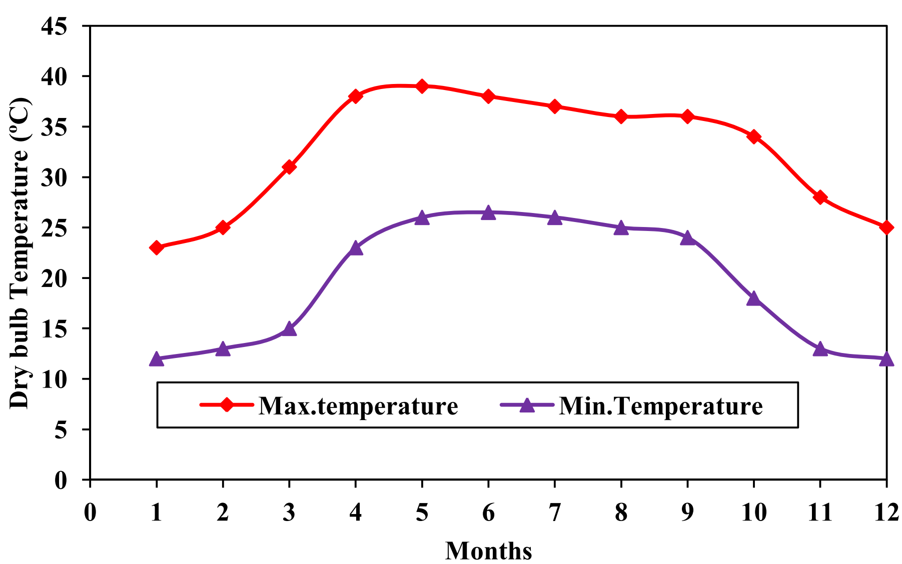

Fig. 1. Minimum and maximum average temperature of Jaipur city in the year 2019.

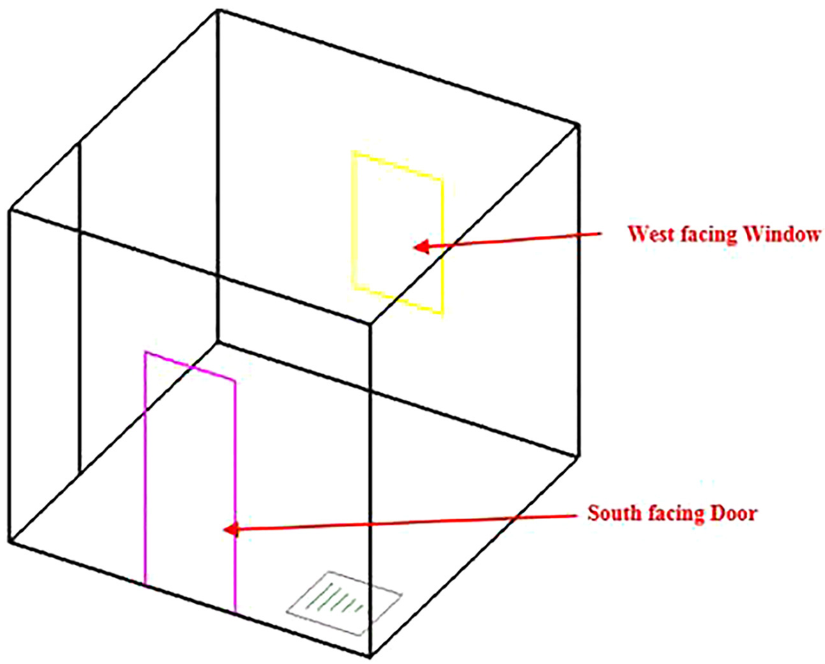

Fig. 2. Building model.

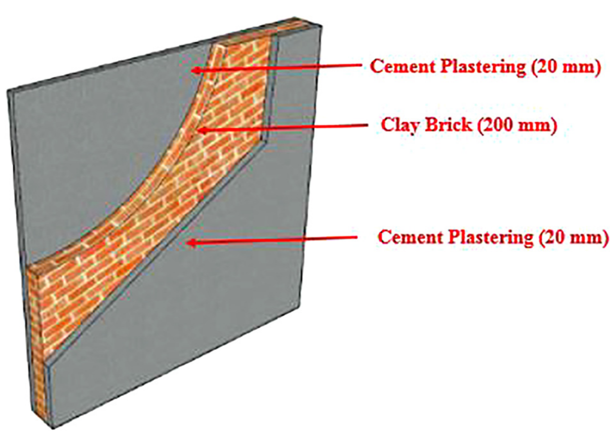

Fig. 3. Schematic of wall.

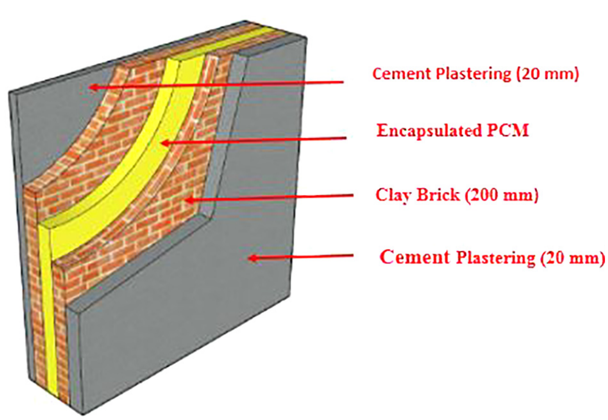

Fig. 4. Schematic of PCM wall.

of empirical validation, analytical verification and testing [13,14]. Also, a single floor single room independent PCM and the non-PCM house were constructed experimentally in warm and humid

Table 1
Thermo-physical properties of (HS 24) PCM.

Phase change temperature	24 °C
Thermal conductivity	0.55(L), 1.05 (S)W/ mK
Thermal Stability	2000 cycles
Flammability	No
Liquid density	1550 kg/m3
Solid density	1621 kg/m3
Base Material	Inorganic
Latent heat	199 kJ/kg

Table 2
Physical properties materials of wall and roof.

Item	Brick	Mortar	Reinforcement
Density (kg/m^3)	1269	1500	2500
Heat storage Co-efficient (W/m^2 K)	7.92	9.44	7.37
Thermal conductivity (W/mK)	0.54	0.76	0.69
Specific heat (J/kg K)	1050	1050	920

climatic conditions of Chennai city, India [15]. The EnergyPlus software was used to model and simulate the PCM and non-PCM building. The simulated results were carried out according to the experimental study. Fig. 6 shows the validation of EnergyPlus software results compared with the experimental studies for the PCM and non-PCM room temperature variation of January in the warm and humid climatic conditions of Chennai city. The macro-encapsulated PCM pouch was integrated into the building wall. The experimental PCM and non-PCM room temperatures were compared with the simulated results. The simulated results followed the same pattern as the experimental results with a deviation of temperature range ± 1 °C for both PCM and non PCM cases.

3. Results and Discussion

The PCM and non-PCM indoor room temperature variations for the months of February, April, May, October and December are presented for the conditions of passive cooling methods in Jaipur city

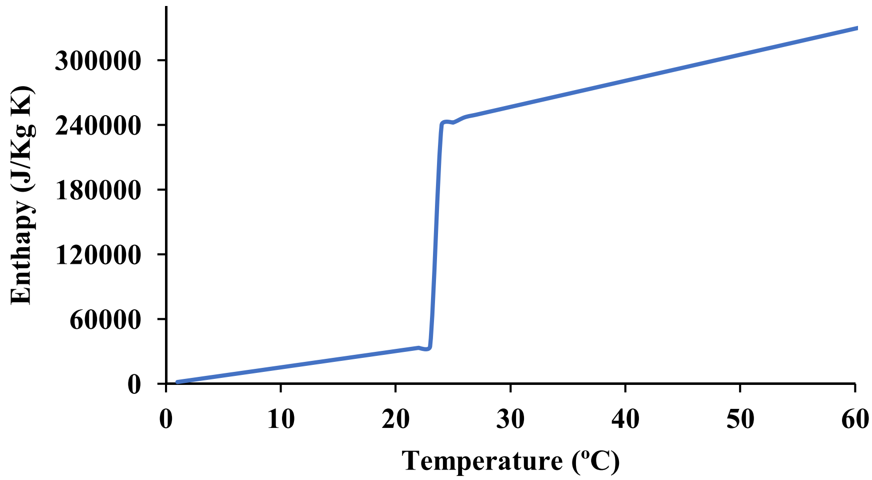

Fig. 5. Enthalpy- temperature graph for HS 24 PCM.

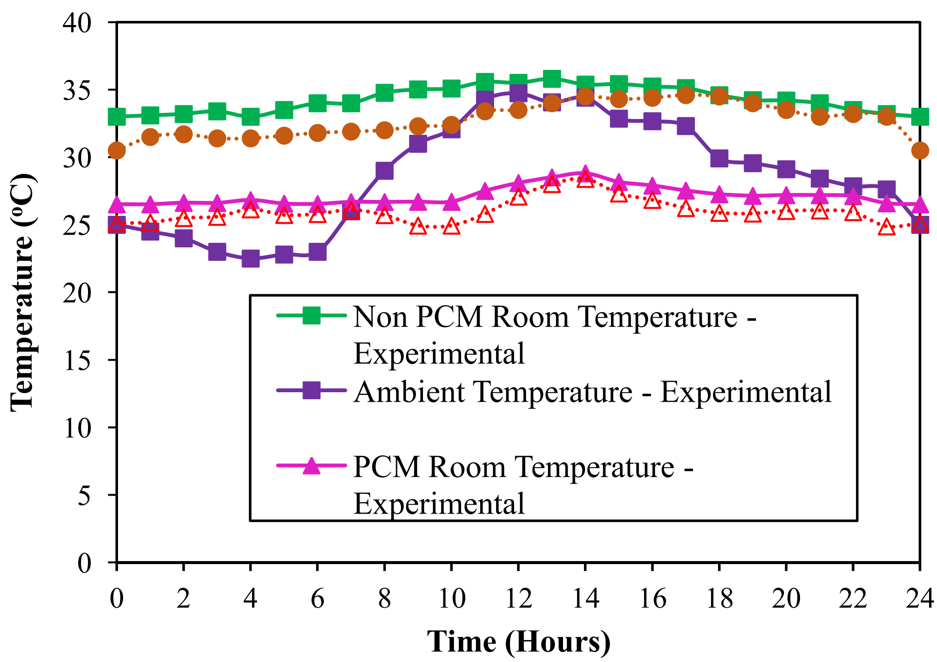

Fig. 6. The room temperature variation for the first of January.

as shown in Figs. 7 to 11. The variations of temperature presented are only for extreme summer and extreme winter seasons. PCM and Non-PCM room temperature variation is for the fifth day of January. Fig. 7 shows the variation of ambient temperature from 10 to 27 °C. The comfort temperature during the day and night time of about 26 °C was maintained in both rooms (PCM and non-PCM room). The room temperature difference is ± 1 °C. The same temperature pattern is followed for the entire month of February.

Fig. 8 shows the variation of PCM and non-PCM room temperature for the first day in the month of April.The outside air temperature varies from 25 to 37 °C. The PCM room temperature was maintained at 27 °C whereas the non-PCM room temperature varied from 27 to 34 °C. The temperature drop for the April month is 6 °C. The same temperature pattern is followed for the entire month. It should be mentioned here, that in both the rooms there is a great difference in temperature. The PCM plays its role in the melting and solidification of the whole PCM which will change the phase cycles and regulate the PCM room temperature.

The diurnal temperature for the month of May is 12 °C. The higher values of minimum temperature are shown in Fig. 9, in the PCM room.. It is noticed from Fig. 9 that the wall integrated with PCM releases more cool energy which will regulate the PCM room temperature. This characteristic is beneficial for the application of a PCM integrated building, as the wall can absorb cool energy which is available during the night time. The absorbed energy is released during the day time when there is no mechanical device inside. The PCM effectiveness was evaluated by comparing the indoor room temperature difference between rooms with and without PCM.

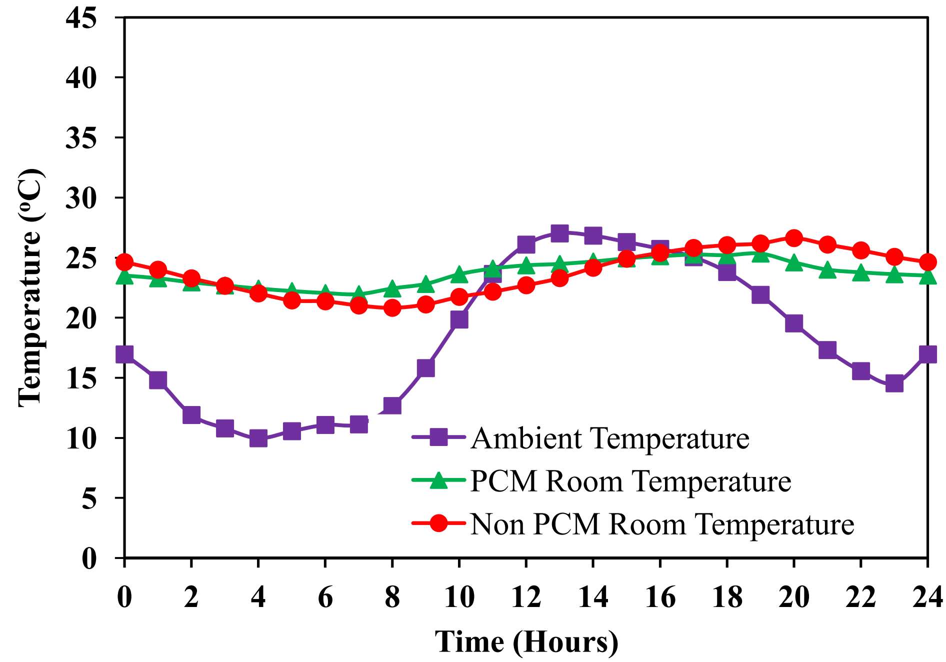

Fig. 7. The room temperature variation for the fifth day of February.

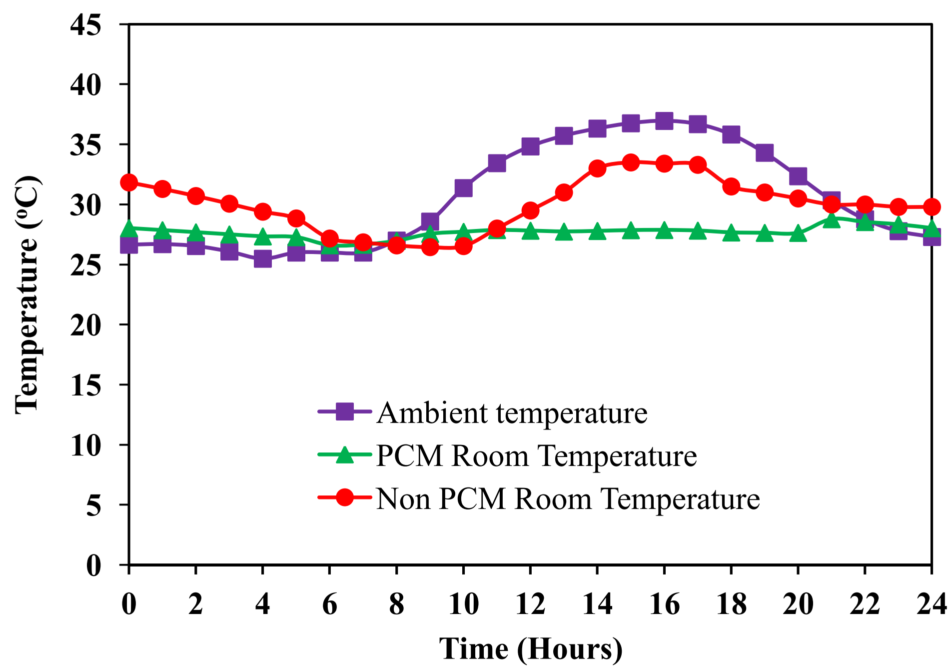

Fig. 8. The room temperature variation for the fifth day of April.

During the day time, the PCM can also diminish the solar heat gain into the building area which will reduce the room temperature fluctuation. The PCM room temperature was maintained at 27 °C whereas the non-PCM room temperature varies from 27 to 36 °C. The temperature drop for the month of May is 8 °C.

The temperature variations in the passive cooling condition in the months of October and December are shown in Figs. 10 and 11. The PCM room temperature is maintained at 26 °C throughout the day. The temperature variation for the non-PCM room is from 26 to 31 °C. The temperature drop for the month of October is 5 °C. The ambient temperature is very low for December which varies from 12 to 22 °C. The PCM room temperature was maintained at 25 °C throughout the day, whereas the non-PCM room maintained a room temperature of 19 to 23 °C. During the night time, heating is required for comfort in the non-PCM room but it is not required for the PCM room.

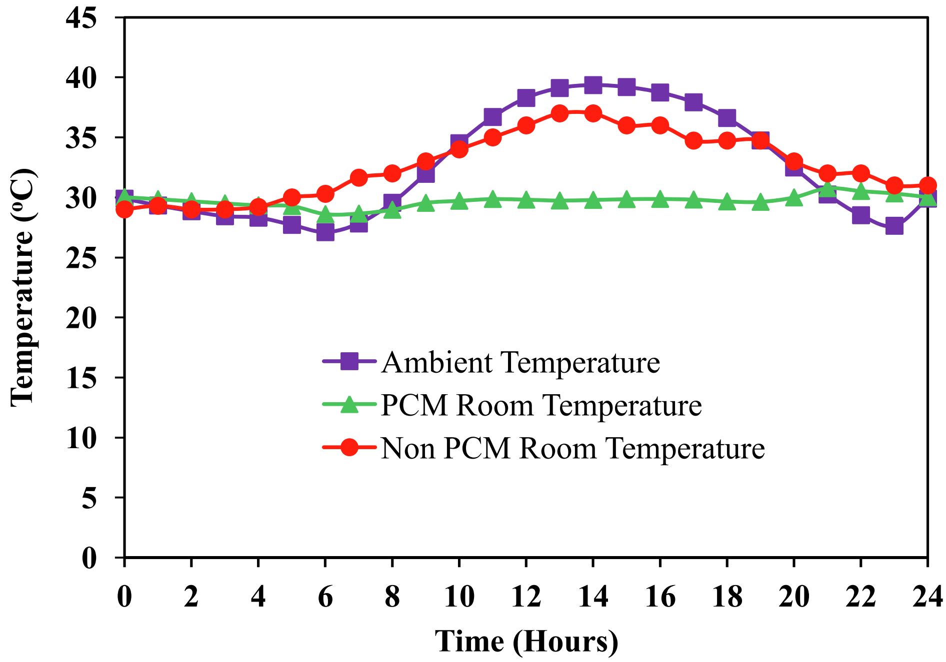

Fig. 9. The room temperature variation for the fifth day of May.

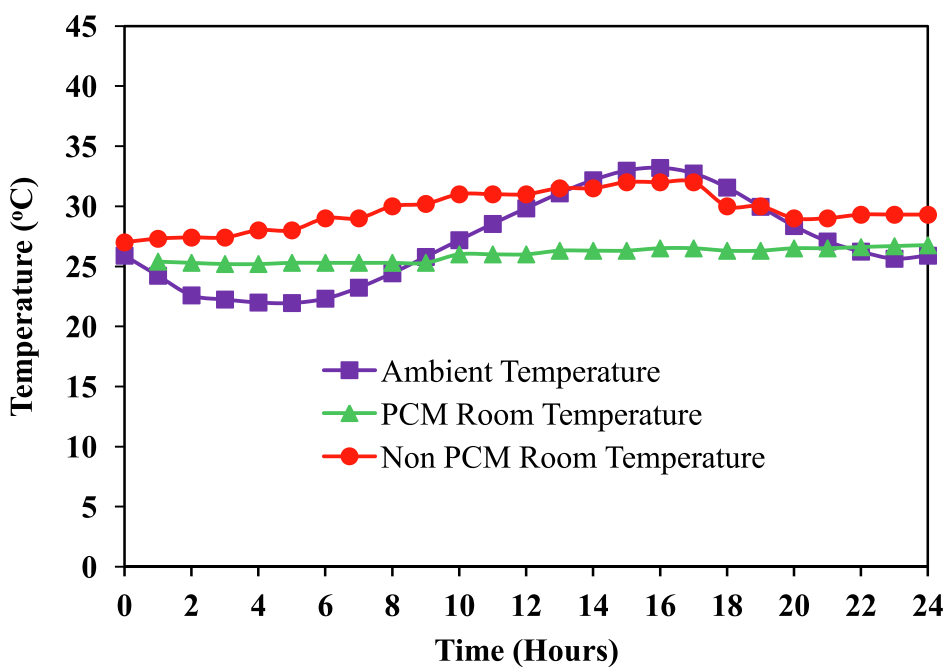

Fig. 10. The room temperature variation for the fifth day of October.

4. Conclusion

The passive cooling latent heat thermal energy system integrated into building envelopes in Jaipur city was evaluated numerically through EnergyPlus software. The PCM and non-PCM room temperatures were simulated at different climatic conditions throughout the year. The simulation results show that the PCM integrated into the building maintained the thermal human comfort temperature throughout the year. During the winter season, the non-PCM required heating during the night time, whereas it was not required for the PCM room because the ambient temperature was very low from December to February. During the summer season, the PCM is active and contributes to maintain the comfort condition in the building.

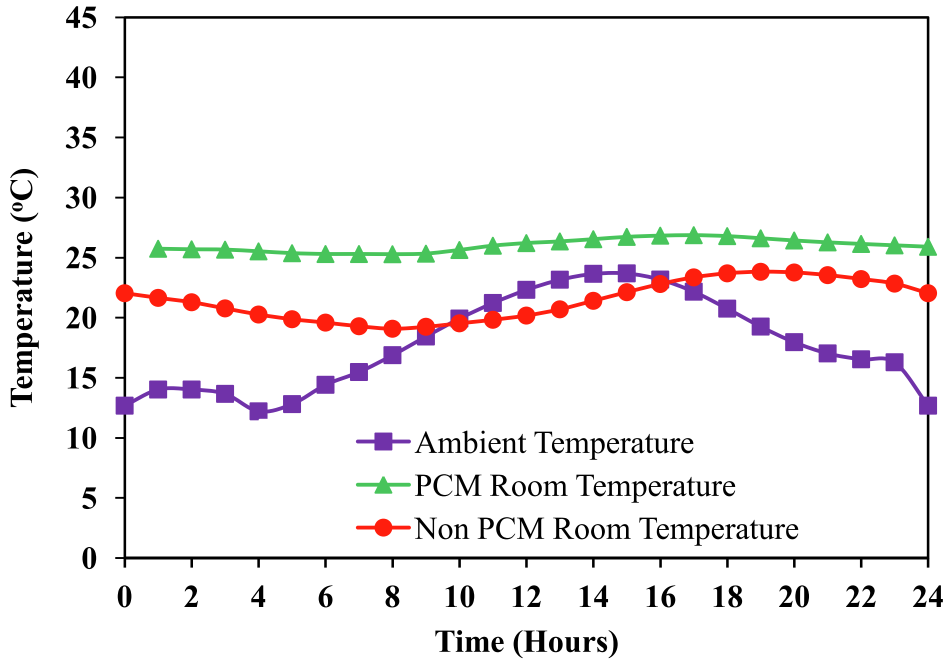

Fig. 11. The room temperature variation for the fifth day of December.

CRediT authorship contribution statement

S. Kumar: . **R. Sheeja:** . **Abraham J.S. Jospher:** . **G. Sai Krishnan:** Writing - review & editing. **Chandrasekar:** . **Antony AroulRaj:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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