Energy and Economic Analysis of Combined Use of Phase Change Material with Insulation in Residential Buildings

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Abstract

The increase in energy demand in residential structures has obtained substantial attention in recent decades. One of the solutions to reduce the energy demand could be using phase change materials (PCMs) and insulation. Researchers have primarily focused on using PCMs and insulation in building envelopes to enhance energy efficiency, despite the associated costs. In this research, various cases were generated by varying the thickness and location of PCM and insulation among different building components. Technoeconomic analyses were conducted to identify the optimal thickness and placement of PCM and insulation in various building components. The results of the building simulations indicated that PCM thickness of up to 10 mm can be incorporated into the roof of a residential building in Mumbai. The best-performing case resulted in a 17.3 % reduction of the cooling load compared to the base case, with a payback period of 5 years.

Keywords: EnergyPlus, phase change material, simple payback period, thermal insulation

1. Introduction

The demand for primary energy consumption in the building sector is consistently increasing due to a rise in occupants' thermal comfort expectations (Kalbasi & Afrand, 2022). India is the third largest energy-consuming country after the United States and China. It is expected to decrease its energy demand to meet the net zero targets in 2070 (Jaganmohan, 2024). As per India's Cooling Action Plan, the national and space cooling demand are projected to rise 8 times and 11 times by factors of 700% and 1000%, respectively, by 2037-38, compared to the 2017-2018 levels (Cell, 2019). This underlines the need for passive cooling strategies in buildings to conserve energy.

As a passive measure, using thermal insulation is an easy-to-install and cost-effective method to reduce the cooling or heating demand. The researchers have tried to optimize the thickness, location, and type of material to increase the insulation's usefulness. Kaynakli (2023) focused on finding the optimum insulation thickness, while Ozel and Pihtili (2007) determined the optimum insulation location in the wall to maximize the time lag and minimize the decrement factor. Time lag refers to the difference in the time between peak outdoor temperature and peak indoor temperature whereas decrement factor is a parameter to quantify the reduction of temperature variation between external and internal surface.

Similar to thermal insulation, phase change material (PCM) has also gained attention to reduce the energy demand in the buildings due to its advantages such as high energy storage density and the ability to store and release thermal energy with minimal temperature variation. A PCM can be incorporated into the bricks, walls, roofs and windows of the building envelope (Beemkumar et al., 2019; Lamrani et al., 2021; Li et al., 2022; Saxena et al., 2020).

To effectively use the PCM in the buildings, researchers have tried to optimize the location, thickness, and melting temperature of the PCM. Jin et al. (2016) found that the optimal location of the PCM shifts to the outer side of the wall with an increase in the PCM thickness. In another numerical study, after simulating five different PCMs,

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Kalbasi (2022) found the optimal melting temperature of PCM for different climatic conditions.

In previous research, PCM and insulation was separately used in different building components, and their thermal performance was evaluated. Insulation increases the thermal resistance of the building and reduces heat transfer, whereas PCM increases the thermal mass and thermal resistance of the building as it uses both sensible and latent heat. Therefore, the combination of insulation and PCM could increase energy savings and reduce the thermal load of the building.

Only a limited number of studies have investigated the thermal performance of insulation and PCM combinations. The results of the study by Kalbasi and Afrand (2022) show that combining PCM and insulation reduces the annual energy demand by 12.6%. Another study by Arumugam et al. (2022) focused on identifying the optimal position of the PCM and insulation. The results suggested using them on the outer surface, irrespective of the building's location.

To the best of the author's knowledge, no study has examined the combined use of PCM and insulation from an economic perspective. Also, the two known studies combining PCM and insulation have not evaluated the optimum building component, i.e. walls or roof, for integrating PCM and insulation. Therefore, the objective of this study is to find an optimum component to integrate the combination of PCM and insulation to maximize energy savings and minimize the payback period. This was done for residential buildings in Mumbai, which have warm and humid climate conditions.

2. Methodology

2.1 Building model description

Figure 1 shows the building's floor plan, used for current study, with a total carpet area of 1367 ft^2. The building drawings were provided by Team SHUNYA, which was developed for the U.S. Solar Decathlon Build Challenge 2023 (Team SHUNYA, 2023). The building had two bedrooms, a double-height living room, a dining room, a kitchen, two toilets, a utility area, and a battery area.

To restrict the scope of the analysis to building envelope-related thermal load and performance, the building was considered unoccupied, with no lighting, computers, or office equipment. The infiltration through the building envelope was assumed to be 0.35 ac/hr.

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Fig. 1. Floor plan of the building's ground floor and first floor.

For analyzing the thermal performance, a building model was developed with typical wall, roof, and floor structures commonly used in India. The “typical wall” is composed of gypsum plaster (12 mm), brick (210 mm), and gypsum plaster (12 mm). The typical roof and floor for the study are made of cast concrete (200 mm). Clear glass (3 mm) with single glazing is used for windows.

After we analyzed the typical configuration, the combination of PCM and insulation was incorporated on the exterior side of the external wall of the building. The PCM and insulation used for the study were BioPCM®M182/Q25 and mineral wool, respectively.

Table 1. Thermophysical properties of materials (DesignBuilder, 2022).

Material	**k** (W m^{-1} K^{-1})	**ρ** (kg m^{-3})	c_p (J kg^{-1} K^{-1})
Plaster	0.16	600	1000
Brick	0.62	1700	800
Concrete	1.4	2100	840
Glass	0.9	-	-
PCM	0.2	235	1970
Insulation	0.04	48	1381

2.2 Mathematical Modeling

DesignBuilder (2022) and EnergyPlus (2022) were used for drawing and energy simulation of the building, respectively. In DesignBuilder, a new building was drawn and envelope materials were input. Then, the performance of the building was evaluated annually or for a specific period, depending on the requirement. The conduction finite-difference (CondFD) method was used to simulate PCM. In CondFD, the layer of PCM was divided into several nodes. The thermal behavior of

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the PCM was assumed to be an unsteady state without internal heat generation. Eq. (1) was used to numerically solve each node of PCM under the Crank Nicholson scheme.

$$C_p\rho\Delta x\frac{T_i^{j+1}-T_i^j}{\Delta t}=\frac{1}{2}\left(k_w\frac{T_{i+1}^{j+1}-T_i^{j+1}}{\Delta x}+k_E\frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta x}+k_w\frac{T_{i+1}^{j}-T_i^{j}}{\Delta x}+k_E\frac{T_{i-1}^{j}-T_i^{j}}{\Delta x}\right) \quad (1)$$

Here, C_p is the specific heat of PCM, ρ is density, Δx is the PCM thickness, Δt is the time step, k_w is the thermal conductivity of PCM between node i and node $i+1$, k_E is the thermal conductivity of PCM between node i and node $i-1$, T is the node temperature, i is the node being modeled, $i+1$ is the adjacent node towards indoor space, $i-1$ is the adjacent node towards ambient space, j is the current time step, and $j+1$ is the next time step.

The enthalpy-temperature curve was given as input to calculate the enthalpy change during the phase change process. The specific heat of the PCM was updated using the enthalpy-temperature function at each time step.

2.3 Simple payback period (SPP)

In this study, the SPP was determined to find the time required after which a reduction in the required cooling electricity will recover the initial cost of the PCM and the insulation in the walls and the roof. The initial cost of the PCM and the insulation (50 mm) was taken as 165 Indian Rupees per kg and 400 Indian Rupees per m^2 of the insulated area, respectively (Mishra et al., 2012; Saxena et al, 2019). The electricity price was assumed to be 8 Indian Rupees per kWh for calculating the annual savings (Global Petrol Price, 2023).

$$SPP=\frac{C_{PCM}+C_{insulation}}{Annual\ savings} \quad (2)$$

2.4 Procedure

Initially, parametric simulations were conducted by varying the thickness of the PCM and the insulation in the roof to determine the optimal thickness of the PCM and the insulation. A similar approach was applied to find the optimal insulation thickness in the external walls. Subsequently, a set of 50 cases was formulated, using various combinations of PCM in the roof, roof insulation, and wall insulation. The initial model incorporated construction materials representative of a typical wall and typical roof, denoted as the "base case." These cases were simulated to find the optimal configuration concerning cooling load and SPP.

3. Results and Discussion

Fig. 2 shows the annual cooling load and required annual cooling electricity at different thicknesses of PCM in the roof for residential buildings in Mumbai. The graph shows that the incorporation of the 10 mm PCM in the roof reduces the cooling load by 8%. The further increase in the thickness of PCM in the roof did not reduce the cooling load or cooling electricity. Therefore, a typical roof and a roof with 10 mm PCM were considered for further study while creating different combinations with the insulation.

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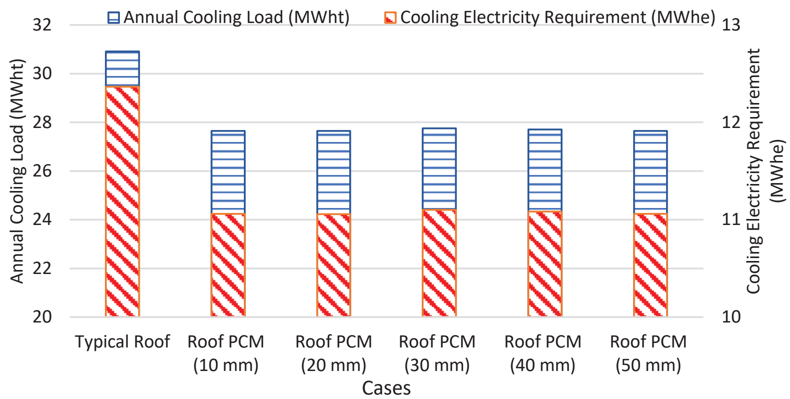

Fig. 2. Comparison of annual cooling load and annual cooling electricity requirement at different PCM thicknesses incorporated in the roof.

Similarly, a parametric study was performed with different thicknesses of insulation in the roof of the building. The cooling load of the building dropped from 2.6% to 4.7%, with an increase in insulation thickness from 10 mm to 100 mm. The reduction in the cooling load did not increase linearly with the increase in the insulation thickness and became almost constant after 50 mm of insulation. Therefore, 10 mm, 20 mm, 50 mm, and 100 mm of insulation thickness were taken into consideration when making a combination with roof PCM and wall insulation.

A parametric study involving the variation of PCM thickness within walls had not been conducted in current study. The PCM in the wall was omitted as it would lead to high capital costs. Then, the thermal performance of the building with insulation in the wall was evaluated. Fig. 3 shows the annual cooling load and annual cooling electricity with a variation of insulation in the walls. The cooling load reduced by 6 %, 9.6 %, 11.8 %, 13.3 %, 14.5 %, 15.3 %, 16 %, 16.7 %, 17.3 %, and 17.4 % with 10 mm, 20 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 80 mm, 90 mm, and 100 mm wall insulation, respectively. The increase in the reduction of the cooling load of the building is less than the uncertainty of the software used. Thus, 10 mm, 20 mm, 50 mm, and 100 mm of wall insulation were considered for making a combination with PCM and insulation in the roof.

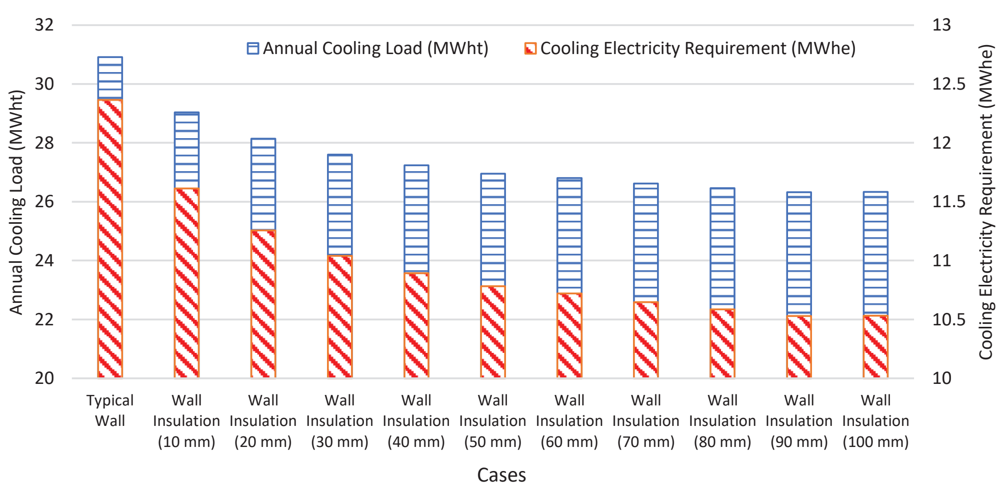

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Fig. 3. Comparison of annual cooling load and annual cooling electricity required at different insulation thicknesses incorporated in the wall.

Based on the selected thickness from the parametric studies of the insulation in walls and roof and PCM in the roof, 50 different cases were created to perform the technoeconomic analysis. Table 2 presents all the cases developed and evaluated using different thicknesses of the insulation and PCM in the walls and the roof. The SPP and cooling load for all the cases were calculated and plotted in Fig. 4.

Table 2. The various cases with a combination of different thicknesses of PCM and insulation in the roof and the walls.

	Roof without PCM					Roof with PCM (10 mm)				
Roof insulation / Wall insulation	0 mm	10 mm	20 mm	50 mm	100 mm	0 mm	10 mm	20 mm	50 mm	100 mm
0 mm	Base case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
10 mm	Case 10	Case 11	Case 12	Case 13	Case 14	Case 15	Case 16	Case 17	Case 18	Case 19
20 mm	Case 20	Case 21	Case 22	Case 23	Case 24	Case 25	Case 26	Case 27	Case 28	Case 29
50 mm	Case 30	Case 31	Case 32	Case 33	Case 34	Case 35	Case 36	Case 37	Case 38	Case 39
100 mm	Case 40	Case 41	Case 42	Case 43	Case 44	Case 45	Case 46	Case 47	Case 48	Case 49

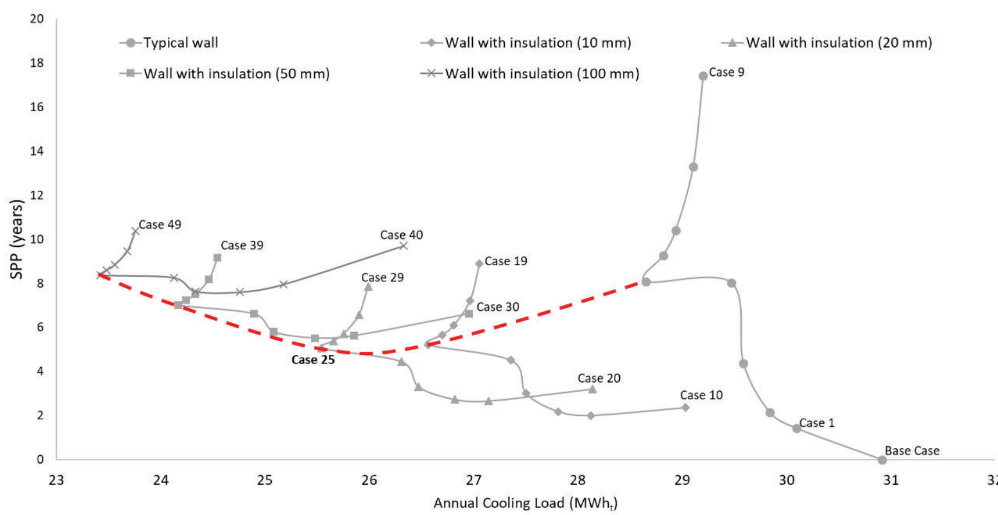

Fig. 4. Optimum case based on the cooling load and payback period (Dashed line connects least cooling load cases of wall with different insulation thickness)

Figure 4 shows that the base case had the highest cooling load, i.e., 31 MWh. The red dashed line connects the cases with minimum cooling load for different thicknesses of wall insulation. Our optimized case would be a case with minimum SPP on the dashed line. Case 25, a roof with 10-mm PCM and walls with 20 mm insulation, was the optimal case, as going to any other point from Case 25 will result in an increase in the cooling load or the SPP. The cooling load for Case 25 was

25.5 MWh, which is 17.3 % less than the base case with a payback period of 5 years.

4. Conclusion

In this study, the cooling load of the residential building was reduced by adding a combination of PCM and insulation. Different cases were developed based on the suitable thickness of PCM and insulation in the roof and walls. The main findings are summarized as follows:

1) For the roof, the optimum PCM thickness is 10 mm, as a further increase in PCM thickness does not reduce the cooling load. The increase in thickness above 10 mm makes it difficult to undergo a complete cycle of melting and freezing.
2) At the same thickness, it was discovered that the thermal performance of insulation in walls performs better than insulation in roofs with an increase in SPP. This is because the wall insulation reduces the overall heat gain of the building as its total surface area is more than the roof.
3) A combination of 20 mm wall insulation with 10 mm of PCM in the roof performs best regarding cooling load and SPP. The cooling energy performance index drops by 17.6 % compared to the base case.

The above conclusion was achieved for Mumbai's warm and humid climate conditions but needs to be examined for other climate conditions. In this study, the optimum case was found by calculating the SPP of the initial investment. However, SPP does not account for cash flows after the payback is achieved and treats all cash flows as equivalent. Because of these limitations of SPP, the lifetime energy savings are not considered and may lead to a different optimum case. Therefore, a detailed economic analysis needs to be performed in future work, including the discount rate, inflation rate, and life of the material.

Conflict of 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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