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Effect of double layer phase change material in building roof for year round thermal management

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Abstract

Efficient and economical technology that can be used to store large amounts of heat or cold in a definite volume is the subject of research for a long time. Latent heat storage in a phase change material (PCM) is very attractive because of its high-energy storage density and its isothermal behavior during the phase change process. Thermal storage plays a major role in building energy conservation, which is greatly assisted by the incorporation of latent heat storage in building products. Increasing the thermal storage capacity of a building can enhance human comfort by decreasing the frequency of internal air temperature swings so that the indoor air temperature is closer to the desired temperature for a longer period of time. However, it is impossible to select a phase change material to suit all the weather condition in a given location. The PCM that reduces the internal air temperature swing during the winter season is not suitable for the summer season as the PCM remains in the liquid state at all the times during these months and hence the system cannot exploit the latent heat effect. This paper attempts to study the thermal performance of an inorganic eutectic PCM based thermal storage system for thermal management in a residential building. The system has been analyzed by theoretical and experimental investigation. A double layer PCM concept is studied in detail to achieve year round thermal management in a passive manner.

Keywords: Latent heat thermal energy storage; Space heating and cooling; Building energy conservation; Thermal management; Phase change material; Encapsulation

1. Introduction

Scientists all over the world are in search of new and renewable energy sources. One of the options is to develop energy storage devices, which are as important as developing new sources of energy. Thermal energy storage systems provide the potential to attain energy savings, which in turn reduce the environment impact related to non-renewable energy use. In fact, these systems provide a valuable solution for correcting the mismatch that is often found between the supply and demand of energy. In the recent years the research on the use of the PCM is increasingly being considered for solar heating system, waste heat recovery, load leveling for power generation, building energy conservation and air-conditioning applications.

There are several promising developments are taking place in the field of application of PCMs for heating and cooling of building. Arkar and Medved [1], Stritih and Novak [2] designed and tested a latent heat storage system used to provide ventilation of a building. The results of their work, according to the authors, were very promising. Phase change dry wall or wallboard is an exciting type of building integrated heat storage material. Several authors investigated the various methods for impregnating gypsum and other PCMs [3–8] in wallboards. Limited analytical studies of PCM wallboard have been conducted, but few general rules pertaining to the thermal dynamics of PCM wallboard are available.

Lee et al. [9] and Hawes et al. [10] presented the thermal performance of PCM's in different types of concrete slab blocks. They studied and presented the effects of concrete slab alkalinity, temperature, immersion time and PCM dilution on PCM absorption during the impregnation process. Wood lightweight concrete is a mixture of cement, wood chips or saw dust, which should not exceed 15% by weight, water and

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Nomenclature

c_{p_l}	specific heat of liquid PCM (kJ/kg K)
c_{p_s}	specific heat of solid PCM (kJ/kg K)
c_1, c_3	specific heat of roof top slab, concrete slab (kJ/kg K)
f	implicit factor
h_i	inside heat transfer coefficient (W/m^2 K)
h_o	outside heat transfer coefficient (W/m^2 K)
k_1, k_2, k_3	thermal conductivity of roof top slab, PCM panel and concrete slab (W/m K)
L_1, L_2, L_3	thickness of roof top slab, PCM panel and concrete slab (m)
q_{rad}	solar radiation flux (W/m^2)
Δt	time step (s)
T	temperature (°C)
T_i	current time step temperature at ith volume cell (°C)
T_i^0	previous time step temperature at ith volume cell (°C)
T_{in}	initial temperature (°C)
T_{room}	room temperature (°C)
T_s	surface temperature (°C)
T_{sky}	sky temperature (°C)
T_∞	ambient temperature (°C)
δx_1, δx_2, δx_3	nodal distances (m)
Δx_1, Δx_2, Δx_3	control volume length of roof top slab, PCM panel and concrete slab (m)

Greek letters

α	absorptivity
λ	latent heat of PCM (kJ/kg)
ρ_1, ρ_2, ρ_3	density of roof top slab, PCM panel and concrete slab (kg/m^3)
σ	Stefan Boltzmann constant
ϵ	emissivity

additives. This mixture can be applied for building interior and outer wall construction. For integration in wood lightweight concrete, two PCM materials Rubitherm GR40, 1–3 mm and GR 50, 0.2–0.6 mm were investigated by Mehling et al. [11]. Zhang et al. [12] presented the development of a thermally enhanced frame wall that reduces peak air-conditioning demand in residential buildings. Ismail and Henriquez [13] proposed a different concept for thermally effective windows using a PCM moving curtain.

University of South Australia (UniSA) [14] developed a roof-integrated solar air heating/storage system, which uses existing corrugated iron roof sheets as a solar collector for heating air. Lin et al. [15] put forward a new kind of under-floor electric heating system with shape-stabilized phase change material (PCM) plates. Hed [16] investigated PCM integrated cooling systems for building types where there is an over production of heat during the daytime such as offices, schools and shopping centers. Free cooling was investigated at the University of Zaragoza/Spain by Zalba et al. [17]. The objective of the work was to design and construct an experimental installation to study PCMs with a melting temperature between 20 and 25 °C.

The approach at the University of Nottingham [18] is a replacement of a full air-conditioning system by the new system, called a nighttime cooling system, which is easy to retrofit. To reduce the air-conditioning load of airtight and insulated apartment building, Kuroki et al. [19] proposed a ventilation system that makes use of both thermal storage and outdoor conditions. The Sustainable Energy Centre (SEC) at University of South Australia [20] started work with PCMs in the mid 1990's with the development of a storage unit that can be used for both space heating and cooling. The night time charging and day time utilization process during both heating and cooling seasons for a storage system comprising of two different PCMs integrated into a reverse cycle refrigerative heat pump system utilizing off peak power. In order to achieve thermal storage capacity approximately equal to the heat gains within the space during the daily cycle, a new concept for the concrete panel was developed by Koschenz and Lehmann [21] to incorporate this system in a lightweight building that can be retrofitted. Velraj et al. [22] presented a detailed study on PCM based Cool Thermal Energy Storage (CTES) integrated with building air-conditioning system in Tidel Park, Chennai, India which is an active system where the storage tank is kept separately away from the building.

Stetiu and Feustel [23] used a thermal building simulation program based on the finite difference approach to numerically evaluate the latent heat storage performance of PCM wallboard in a building environment. Fraunhofer Institute [Germany] [24] simulated the thermal behavior of building components in order to compare the dynamic performance of different types of wall constructions incorporating different amounts of PCMs. Athienitis et al. [25] conducted an extensive experimental and one-dimensional non-linear numerical simulation study in a full scale outdoor test room with PCM gypsum board as inside wall lining.

Bransier [26] was the first to analyze cyclic melting/freezing of a phase material (PCM). He used a one-dimensional conduction mode1 to analyze conductive cyclic phase change of a slab and a concentric PCM module and found that a maximum of two interfaces could coexist during cyclic melting/freezing. Hasan et al. [27] developed a one-dimensional cyclic phase change heat conduction model for a plane slab and carried out a detailed parametric study on the effects of various parameters on the energy charge/discharge. Brousseau and Lacroix [28] carried out a numerical analysis for the cyclic behavior of alternative melting and freezing in a multi-plate latent heat energy storage exchanger. This paper attempts to study the thermal performance of an in-organic eutectic PCM (48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O) kept in the roof for thermal management in residential building. An experimental investigation and the numerical simulation analysis were also performed for various conditions.

In the present paper, a detailed study of the thermal performance of a phase change material system for thermal energy management in building is analyzed and discussed. An experiment consisting of two identical test rooms has been constructed to study the effect of having PCM panel on the roof of the building. One room is constructed without PCM on the roof in order to provide a reference case for comparison with the experimental room that includes the phase change material. A mathematical model has been developed in which finite volume method is used to predict the thermal behavior of the roof incorporating PCMs. The model is validated with the experimental results and the effect of double layer PCM is analyzed using this model for year round thermal management and the thermal performance is compared with single layer PCM.

2. Modeling of PCM integrated building roof system

The mathematical formulation and the numerical solution methodologies for a PCM integrated roof system are presented in this section.

2.1. Statement of the problem

The physical system considered is a stainless steel panel filled with PCM placed between the roof top slab and the bottom concrete slab, which form the roof of the PCM room. In each cycle, during the charging process (sunshine hours), the PCM in the roof changes its phase from solid to liquid. As melting requires a large quantity of heat at its phase change temperature, the temperature of the concrete slab normally will not exceed the PCM phase change temperature. During the discharging process (night hours), the PCM changes its phase from liquid to solid (solidification) by rejecting its heat to the ambient and to the air inside the room. This cycle continues every day.

The composite wall described in Fig. 1 is initially maintained at a uniform temperature 'T_i'. The boundary condition on the outer surface of roof is considered due to the combined effect of radiation and convection. In order to consider the radiation effect, the average monthly solar radiation heat flux available in the Handbook by Tiwari [29] for every 1-h in Chennai city, India is used. For convection, the heat transfer coefficient (h) value on the outer surface is calculated based on the prevailing velocity of the wind using the Nusselt correlation.

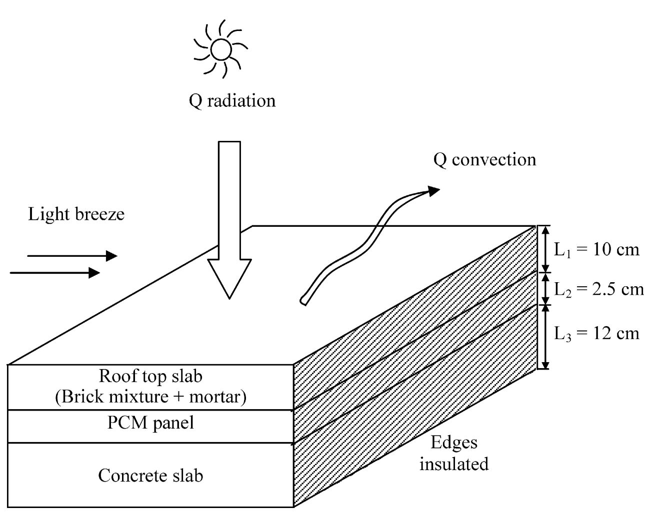


Fig. 1. Sketch of the building roof.

The boundary condition on the inner surface of the concrete slab is considered to be natural convection. As the temperature difference between the room and the wall is very less, most of the earlier researchers have approximated the bottom wall as insulated. However, when the temperature difference becomes appreciable, the effect of heat flow is considerable and hence this convection effect is also taken into account in the present research work.

2.2. Mathematical formulation

For the mathematical formulation of the above-mentioned problem shown in Fig. 1, the following assumptions are made:

(i) The heat conduction in the composite wall is one-dimensional and the end effects are neglected.
(ii) The thermal conductivity of the concrete slab and the roof top slab are considered constant and not varying with respect to temperature.
(iii) The PCM is homogeneous and isotropic.
(iv) The convection effect in the molten PCM is neglected.
(v) The interfacial resistances are negligible.
(vi) The 'c_p' value of the PCM in the panel is considered as follows.

$$T < T_\mathrm{m} - \phi, \quad c_p = c_{p_\mathrm{s}}$$
$$T > T_\mathrm{m} + \phi, \quad c_p = c_{p_\mathrm{l}}$$
$$T_\mathrm{m} - \phi < T < T_\mathrm{m} + \phi, \quad c_p = \frac{l}{2\epsilon}$$

where 'c_p' is the specific heat capacity, λ the latent heat capacity, ϕ the half of the temperature range over which the phase change occurs and T_m is the temperature about which phase change occurs.
(vii) The latent heat value of the PCM is modeled in the above equation as high sensible heat value during the phase change process. Normally all the PCMs change its phase over a range of temperature. In the present model, uniform c_p value is considered during phase change process, though in actual practice, there is variation in c_p value within this small temperature range.

In accordance with the above-mentioned assumption, the governing equation and the boundary condition are developed as below.

Governing equation:

$$k_\mathrm{m}\frac{\partial^2 T_\mathrm{m}}{\partial x^2} = \rho_\mathrm{m} c_{p_\mathrm{m}}\frac{\partial T_\mathrm{m}}{\partial t} \quad [0 < x < L]; m = 1, 2, 3 \tag{1}$$

where $m = 1$ for roof top slab; $m = 2$ for PCM panel; $m = 3$ for bottom concrete slab.

The same equation holds good for all the three material regions by incorporating suitable k, ρ, c_p value. In the exterior boundary ($x = 0$) where the floor is exposed to solar radiation, the boundary condition is,

$$k_1 \frac{\partial T_1}{\partial x}\bigg|_{x=0} = q_{\mathrm{rad}} + h_{\mathrm{o}}(T_\infty - T_{x=0}) \quad (2)$$

The radiation effect is considered only during sunshine hours. In the bottom layer of the concrete slab $x = L$, the boundary condition is

$$+k_3 \frac{\partial T_3}{\partial x}\bigg|_{X=L} = h_{\mathrm{i}}(T_{x=L} - T_{\mathrm{room}}) \quad (3)$$

The instantaneous continuity of heat flux and temperature at the interfaces $x = L_1$ and L_2 are preserved.

Fig. 2 shows the finite volume grid employed for the analysis. Each material of the composite slab is divided into five equal control volumes. The governing equation is discretized using semi-implicit finite volume method and the equations are given below.

2.2.1. Exterior node

The equation for the top volume cell is written as below

$$\left(\frac{\rho_1 c_1 \Delta x_1}{\Delta t} + \frac{fk_1}{\delta x_1} + h_{\mathrm{o}} f\right) T_1 - \frac{fk_1}{\delta x_1} T_2 = h_{\mathrm{o}} f T_\infty + (1-f)\left[\frac{k_1(T_2 - T_1)}{\delta x_1} - h_{\mathrm{o}}(T_1 - T_\infty)\right] + \frac{\rho_1 c_1 T_1^0}{\Delta t}\Delta x_1 + \alpha q_{\mathrm{s}} + \sigma[\alpha T_{\mathrm{sky}}^4 - \epsilon T_{\mathrm{s}}^4] \quad (4)$$

2.2.2. Inner node

The equation for any volume cell that is located in between the top and bottom volume cells of a particular material is written as below

$$\frac{-fk_{\mathrm{m}}}{\Delta x_{\mathrm{m}}} T_{i+1} + \left[\frac{\rho_{\mathrm{m}} c_{\mathrm{m}} \Delta x_{\mathrm{m}}}{\Delta t} + \frac{fk_{\mathrm{m}}}{\Delta x_{\mathrm{m}}} + \frac{fk_{\mathrm{m}}}{\Delta x_{\mathrm{m}}}\right] T_i - \frac{fk_{\mathrm{m}}}{\Delta x_{\mathrm{m}}} T_i = (1-f)\left[\frac{k_{\mathrm{m}}(T_{i+1} - T_{-i-1})}{\delta x_{\mathrm{m}}} - k_m \frac{(T_i - T_{i-1})}{\delta x_{\mathrm{m}}}\right] + \frac{\rho_{\mathrm{m}} c_{\mathrm{m}} T_i^0 \Delta x_{\mathrm{m}}}{\Delta t} \quad (5)$$

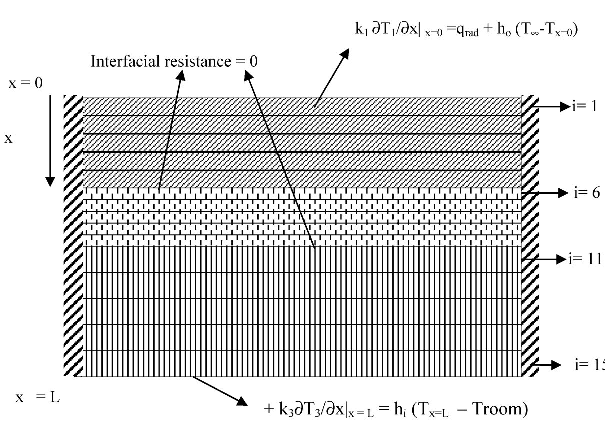


Fig. 2. Finite volume grids for the analysis.

The above-mentioned discretized equations are applicable for volume cells (2), (3), (4), (7), (8), (9) and for (12), (13), (14) for roof top slab, PCM panel and concrete slab, respectively.

$m = 1$, $i = 2, 3, 4$; $m = 2$, $i = 7, 8, 9$; $m = 3$, $i = 12, 13, 14$

2.2.3. Interface node

The equation for the interface volume cell 5 is written as below

$$\frac{-fk_1}{\delta x_1} T_4 + \left[\frac{\rho_1 c_1 \Delta x_1}{\Delta t} + \frac{f}{\delta x_1/2k_1 + \delta x_2/2k_2} + \frac{fk_1}{\delta x_1}\right] T_5 - \left[\frac{f}{\Delta x_1/2k_1 + \Delta x_2/2k_2}\right] T_4 = (1-f)\left[\frac{k_1(T_6 - T_5)}{\delta x_2} - \frac{k_1(T_5 - T_4)}{\delta x_1}\right] + \frac{\rho_1 c_1 T_5^0}{\Delta t}\Delta x_1 \quad (6)$$

where Δx_1 and Δx_2 are the cell thickness of the roof top slab and PCM panel, respectively. Similarly the equation can be written for volume cell (6). The same procedure is extended for control volumes (10) and (11) which involves cell thickness Δx_2 and Δx_3 that corresponds to PCM panel and bottom concrete slab, respectively.

2.2.4. Interior node

The equation for the bottom volume cell 15 is written as below

$$\frac{-fk_3}{\delta x_3} T_{14} + \left[\frac{\rho_3 c_3 \Delta x_3}{\Delta t} + \frac{fk_3}{\delta x_3}\right] T_{15} = f[h_{\mathrm{i}}(-2)] + (1-f)\left[2h_{\mathrm{i}} - k\frac{(T_{15} - T_{14})}{\delta x_3}\right] + \frac{\rho_3 c_3 T_{15}^0}{\Delta t}\Delta x_3 \quad (7)$$

3. Computational procedure

The governing equations along with the boundary conditions are discretized using semi-implicit control volume formulation. The region of analysis is divided into five control volumes for each material. A time step of 2 s is used within the simulation. The system of equations is solved using tridiagonal matrix algorithm (TDMA). The solution methodology is explained in the flow chart as shown in Fig. 3. The initial temperature values are obtained by executing the program, continuously for few days till the routine daily variation attain the same value.

4. Experimental investigation

An experimental set up consisting of two identical test rooms (1.22 m × 1.22 m × 2.44 m) as shown in Fig. 4 has been constructed to study the effect of having PCM panel on the roof of the building. One room is without PCM on the roof and the another one has PCM panel in between the bottom concrete slab

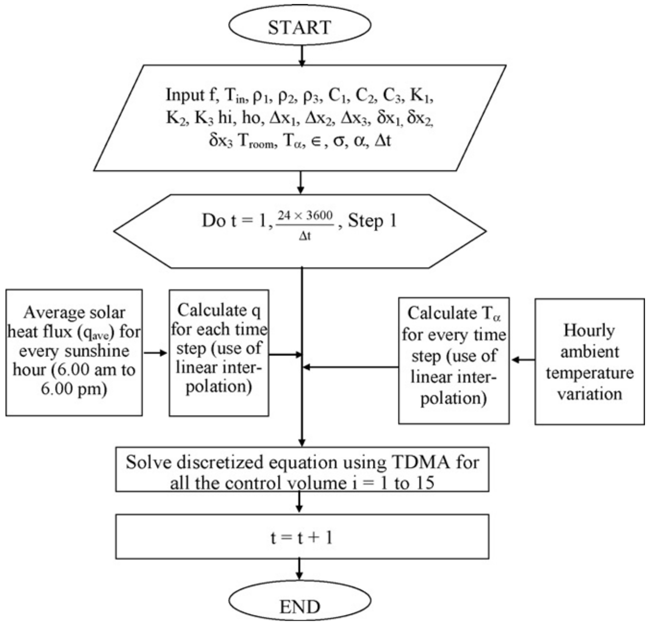


Fig. 3. Flow chart.

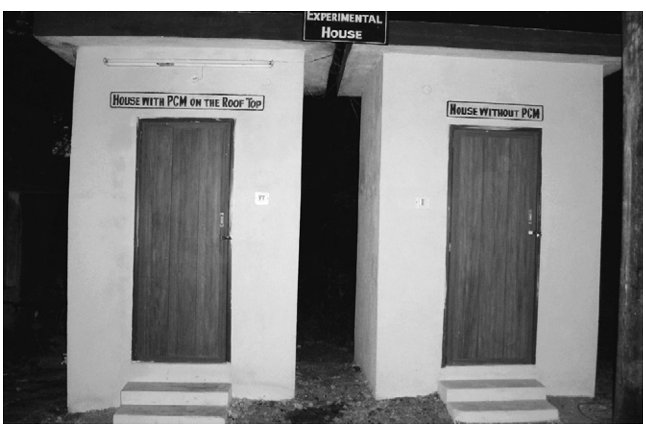


Fig. 4. Experimental test rooms.

and the roof top slab. Thus, it is possible to study the thermal performance of the PCM embedded roof over the conventional one.

Fig. 5 shows the cross-sectional views of the roof with and with out PCM. The inner walls except ceiling of the rooms are insulated by plywood of thickness 6 mm on all the sides to study the sole effect of PCM panel on the roof. The PCM panel

Table 1
Technical specifications of used PCM

PCM material	48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O
Appearance (color)	Grey
Phase change temperature (°C)	26–28
Density (kg/m^3)	1640
Latent heat of fusion (kJ/kg)	188
Thermal conductivity (W/mk)	
Solid	1.09 [0–27 °C]
Liquid	0.54 [28–60 °C]
Specific heat (J/kg K)	1440 [0–26.5 °C], 125,000 [26.5–28 °C], 1440 [28–60 °C]

is made up of stainless steel of 2 m × 2 m and thickness of 2.5 cm which accommodates inorganic salt hydrate (48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O) as PCM. The properties of the salt hydrate used as PCM in the experiment are given in Table 1.

The PCM salt hydrate mixture is prepared by mixing all the inorganic salts in the appropriate proportion of 48% $CaCl_2$, 4.3% NaCl and 0.4% KCl with the correct quantity of 47.3% of distilled water. The mixture is then agitated properly until the complete dispersion of all the salts in distilled water. The salts KCL and NaCl help in initiating nucleation prevent incongruent melting and sub-cooling. The total mass of the PCM mixture used is 164 kg and the PCM panel is filled with this mixture in its liquid state and sealed properly.

The RTDs (PT 100) are placed in different depths in the PCM panel with perfect sealing. The temperature variation is recorded for every 1 h using the digital indicator. Several experiments are conducted in the PCM room for various conditions. Experiments are also conducted for the room without PCM panel and results are validated with the theoretical analysis.

5. Results and discussion

5.1. Experimental validation

The model presented in the theoretical study is validated using the experimental results obtained during the trials conducted in the month of January and February. During the experimentation, the measured room temperatures vary approximately 27 ± 3 °C. In the theoretical analysis, the room

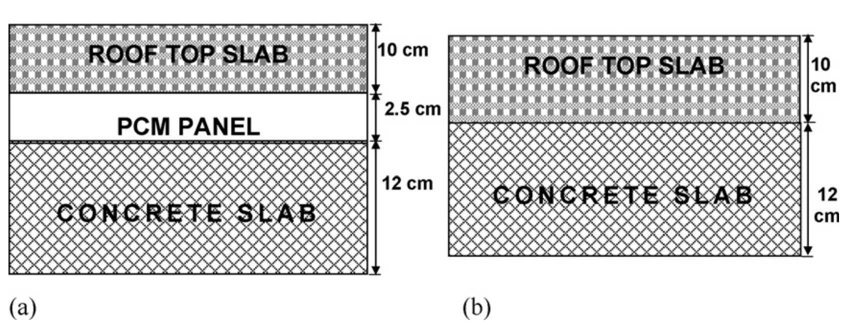


Fig. 5. Cross-sectional view of the roof. (a) With PCM panel and (b) without PCM panel.

temperature is maintained constant with convective boundary condition on the inner surface of the concrete slab during a particular trial. Hence, while comparing the theoretical model with the experiment the room temperature is maintained at a constant temperature of 27 °C as input in the theoretical analysis. The other parameters involved in the analysis are the ambient temperature variation during a day, inside and outside heat transfer coefficients, sky temperature variation, radiation properties of the surface, geometrical parameters and physical properties of the roof material (Roof top slab, PCM and concrete slab). The convective heat transfer coefficient in the outside and inside surface of the roof is calculated using appropriate Nusselt correlation. The measured values/property values obtained from the data book by Tiwari [29] are provided as input in the theoretical analysis. The temperature variations across the roof material for 15 control volumes are obtained from the theoretical analysis. The temperature variations in the bottom surface of concrete slab (ceiling) with PCM and without PCM rooms are shown in Fig. 6 to compare the theoretical model results with the experiment.

It is seen from the graph that the ceiling temperature of the PCM room in the numerical analysis is maintained at a constant value of 27 °C throughout the day. This shows that the environment has little effect on the inner surface of the concrete slab as all the heat energy is absorbed by the PCM kept in the roof. On the other hand, a large fluctuation is observed in the ceiling of the non-PCM room as the outside environment immediately influences ceiling of the non-PCM room. From the experimental results, it is observed that the temperature difference of the ceiling in the PCM and non-PCM rooms is not very appreciable as in the theoretical results. This is due to the fact that ceiling of the roof is highly influenced by the inside room condition which is governed by the ventilation and wall conditions of the room. However, in the experimental trial, a small decrease in ceiling temperature during the day time and small increase in ceiling temperature during the night time is observed in the PCM room which reduces the fluctuation of temperature inside the PCM room. This is due to the large heat storage capacity of the PCM.

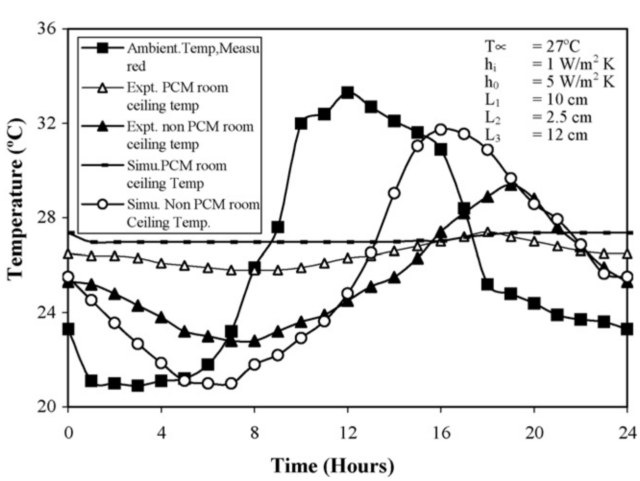


Fig. 6. Experimental and simulated temperature of the ceiling in the PCM and non-PCM room.

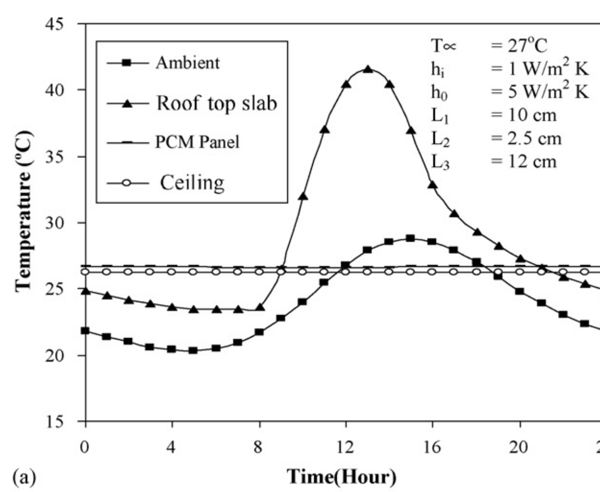
The differences in temperature value between the theoretical and experimental results are due to the following reasons.

- A constant temperature value is assumed in the theoretical analysis, which is not observed during the experiment.
- The actual phase change may not occur during the phase change temperature prescribed in the theoretical analysis.

Considering the above facts, the trend in the theoretical results is in reasonable agreement with the experimental results. Hence this theoretical analysis is further extended to study the effects during all the seasons in a year and to analyze the effects of other parameters.

5.2. Temperature variation of the roof in the PCM and non-PCM room

The theoretical temperature variation of the roof in the PCM and non-PCM rooms is studied in detail for all the months and the results are presented in Figs. 7 and 8 only for the months of January and July. In the figures, the ambient temperature



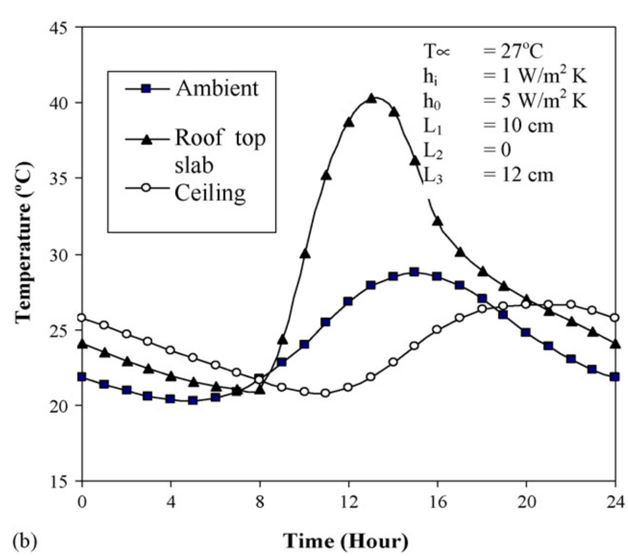


Fig. 7. Temperature variations of the roof in the month of January. (a) PCM room and (b) non-PCM room.

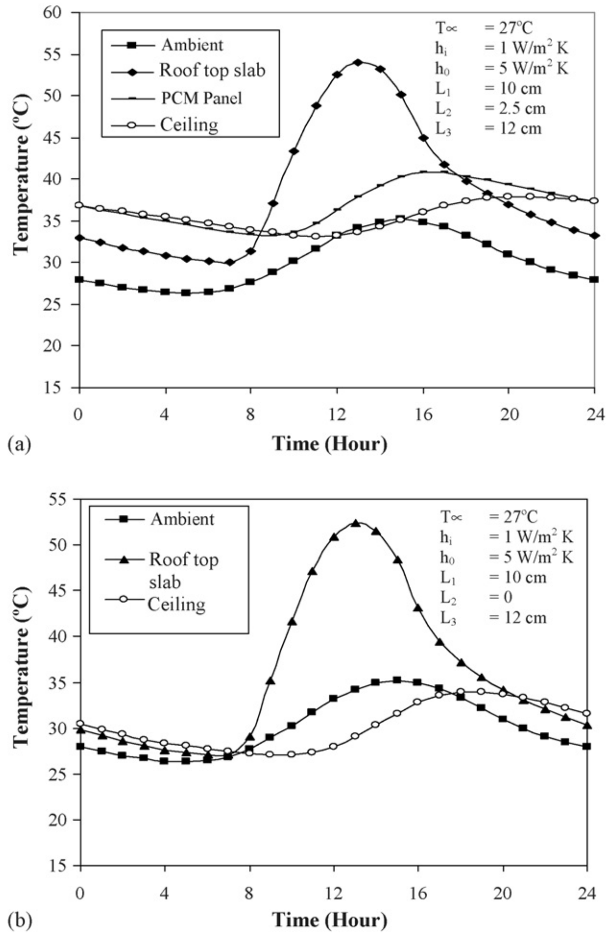


Fig. 8. Temperature variations of the roof in the month of July. (a) PCM room and (b) non-PCM room.

variation during the month, the roof slab temperature, the ceiling temperature and the PCM temperature in the case of PCM room are shown.

Figs. 9 and 10 show, the month wise maximum and minimum temperature variation of the PCM and non-PCM rooms for ceiling and top surfaces of the roof slab, respectively.

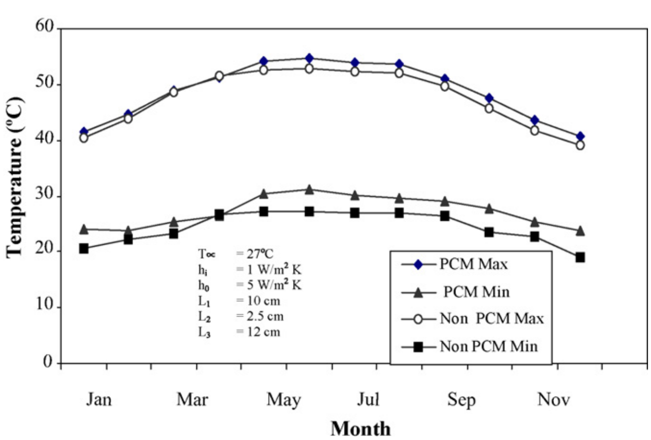


Fig. 9. Monthly maximum and minimum temperature variation of the roof top surface of the PCM and non-PCM room.

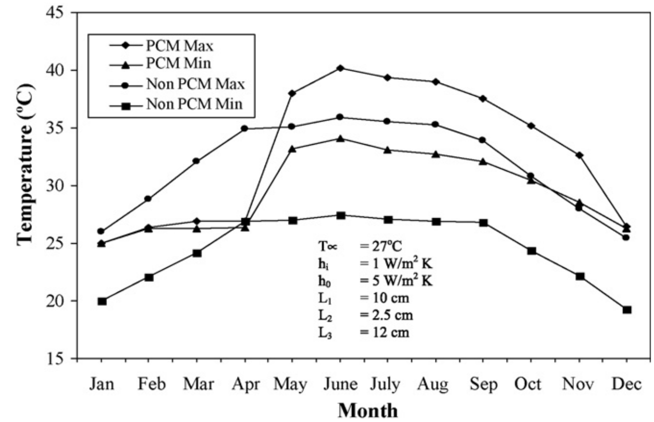


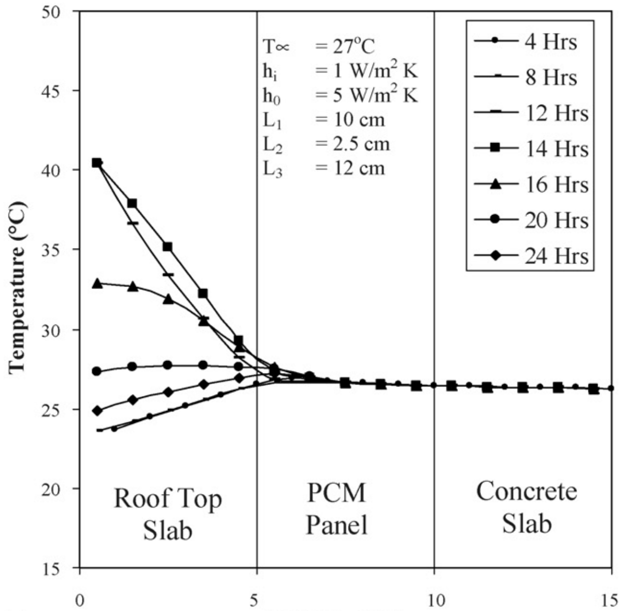
Fig. 10. Monthly maximum and minimum temperature variation of the ceiling of the PCM and non-PCM room.

The roof top temperature attains maximum at noon due to the maximum intensity of solar radiation.

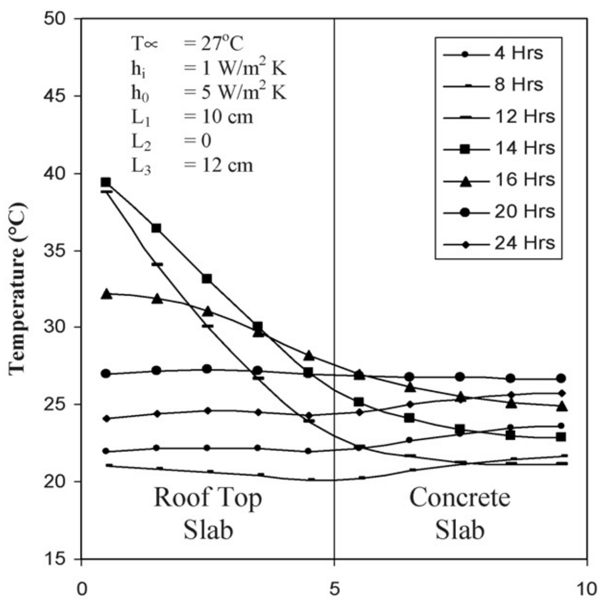
It is observed from all the figures that the roof top surface temperature is slightly higher in the PCM room than the non-PCM room during all the months. This is due to the low thermal conductivity of the liquid PCM, which reduces the heat transmission to the room that in turn increases the roof top surface temperature in the PCM room. The ceiling temperature of the non-PCM room is maximum around 1800 h whereas in the PCM room, it is maximum around 2000 h. This is due to the slow removal of heat from the PCM and the wall to the ambient after the sunshine hours. The introduction of PCM panel in the roof maintains a constant temperature of 27 °C at the ceiling during the entire day in the month of January and this is not observed in the non-PCM room. This is due to the high thermal mass in the PCM and the storage of solar heat gains as latent heat in the PCM while in the non-PCM room the storage of solar gains as sensible heat results in an increase of the ceiling temperature. However, the ceiling temperature in the PCM room attains a maximum temperature of 38 °C during the month of July, which is approximately 4 °C higher than the maximum temperature that attained by the non-PCM room for the corresponding months. In Fig. 9, the same temperature difference is observed during all the months from May to November. Though the introduction of PCM helps in achieving a constant temperature at the ceiling during the month of December to April, this has a negative effect in the month of May to November.

5.3. Temperature distribution across the roof

The temperature distributions across the roof at various time intervals are shown in Figs. 11 and 12 for the PCM and non-PCM rooms for the months of January and July. In the PCM room, during the month of January, the temperature of the PCM panel and the concrete slab are maintained at the same temperature at all the times. The variation in the temperature is observed only across the roof top slab, which is above the PCM panel. In the case of non-PCM room, the temperature variation is observed at the ceiling during all the months. Further in the



(a)

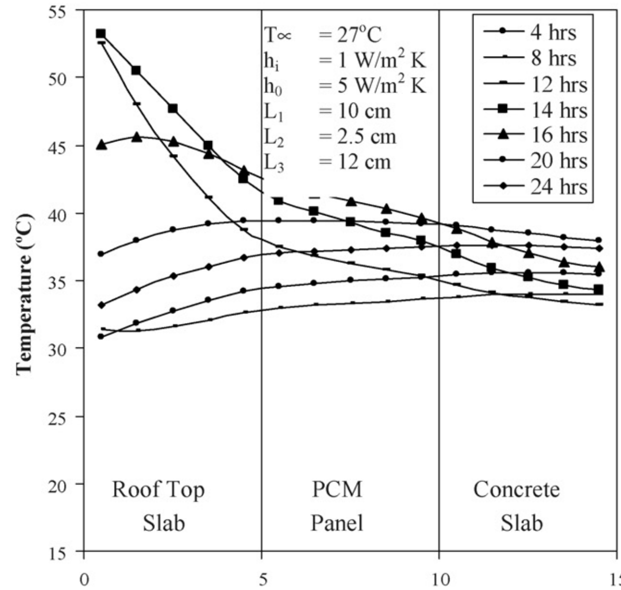


(b)

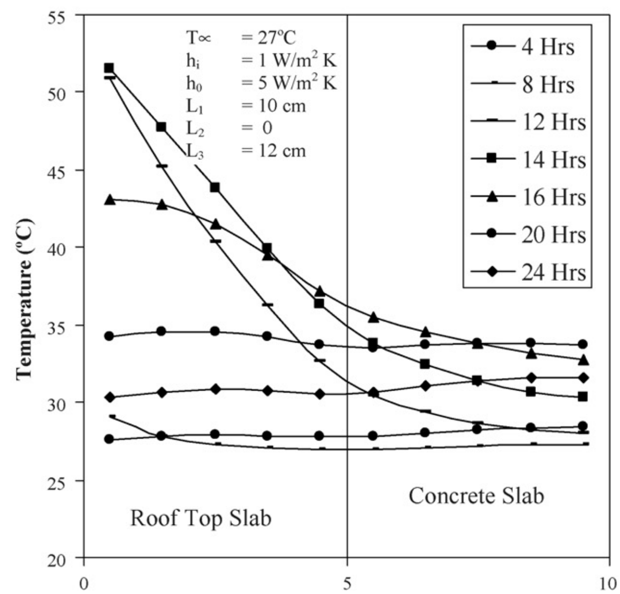
Fig. 11. Temperature distributions across the roof in the month of January. (a) PCM room and (b) non-PCM room.

month of January, the ceiling lies always at a temperature less than 27 °C. However, during the morning hours, the ceiling temperature is maintained at 21 °C, which is less than the comfort temperature. In the case of PCM room, the temperature is always maintained at a constant level of 27 °C, which is the melting temperature of the selected PCM throughout the day during the month of January. Similar trend is observed during the months between December and April.

In the month of July, the temperature variation is observed at the ceiling even in the PCM room. Further the ceiling temperature is maintained always at a temperature higher than the non-PCM room. This is due to the fact that during the



(a)



(b)

Fig. 12. Temperature distributions across the roof in the month of July. (a) PCM room and (b) non-PCM room.

months between May to November, the roof temperature is maintained always higher than the melting temperature of the PCM. Hence the PCM is always in the liquid state and the latent heat storage capacity of the PCM is not utilized during these months. In order to achieve a constant comfort temperature at the bottom of the concrete slab throughout the year, the theoretical study is extended using double layer PCM that is explained in the next section.

5.4. Effect of double layer PCM placed at the roof

The effect of double layer PCM is studied by incorporating one more additional PCM panel having PCM at a melting temperature of 32 °C kept between the existing 2.5 cm PCM

Table 2
Properties of top layer PCM

PCM material	Climsel C 32
Phase change temperature (°C)	32
Density (kg/m^3)	1485
Latent heat of fusion (kJ/kg)	264
Thermal conductivity of solid (W/m K)	0.7
Thermal conductivity of liquid (W/m K)	0.5
Specific heat (J/kg K)	3600 [0–31 °C], 132,000 [31–33 °C], 3600 [33–60 °C]

panel and the roof top slab. The properties of the PCM selected for this study is shown in Table 2. A simulation run is carried out by varying the PCM panel thickness from 2.5 cm with an increment of 0.5 cm. It is ensured in all the simulation trials that a constant initial temperature of the roof materials including PCM prevails continuously for two consecutive days by executing the program for few days for the given ambient and other input conditions. The results are shown in Figs. 13–15. It is seen from the figures that for the case with 2.5, 3, 3.5 cm the ceiling attains a higher temperature above the comfort zone, as the complete solidification has not taken place during the repeated cycling. In the case with 4 cm thickness, the bottom surface of the top PCM panel maintains a temperature of 32 °C and the ceiling is maintained at a temperature of 27 °C due to the presence of the bottom PCM which has melting temperature of 27 °C. This will provide a comfortable temperature for the room.

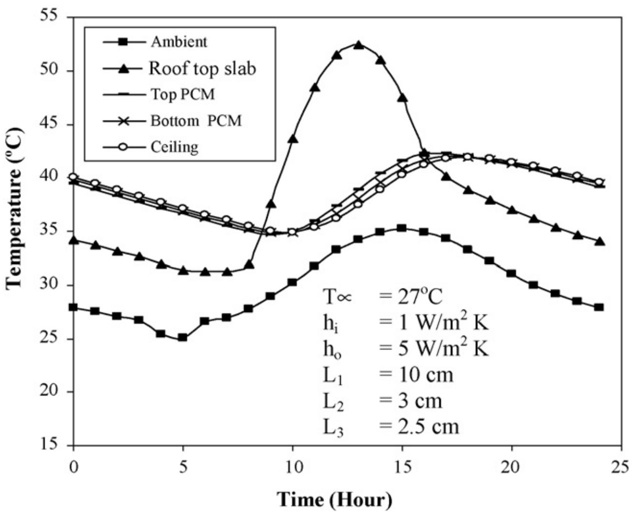


Fig. 13. Effect of double layer PCM in the roof with top layer thickness 3 cm.

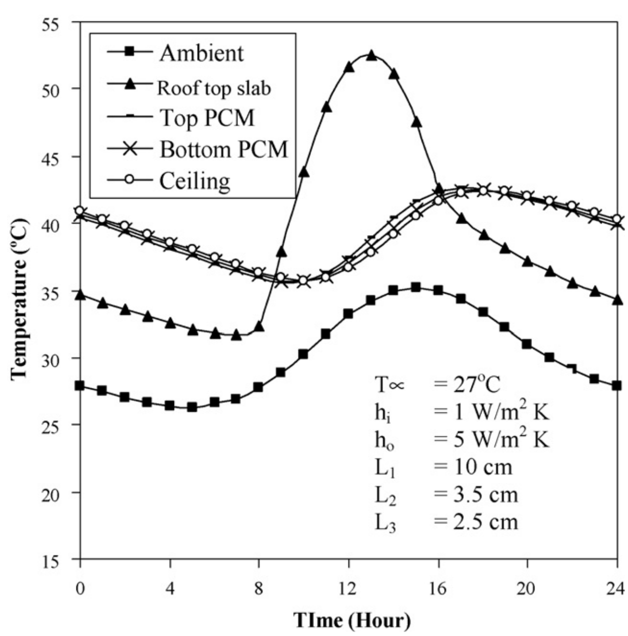


Fig. 14. Effect of double layer PCM in the roof with top layer thickness 3.5 cm.

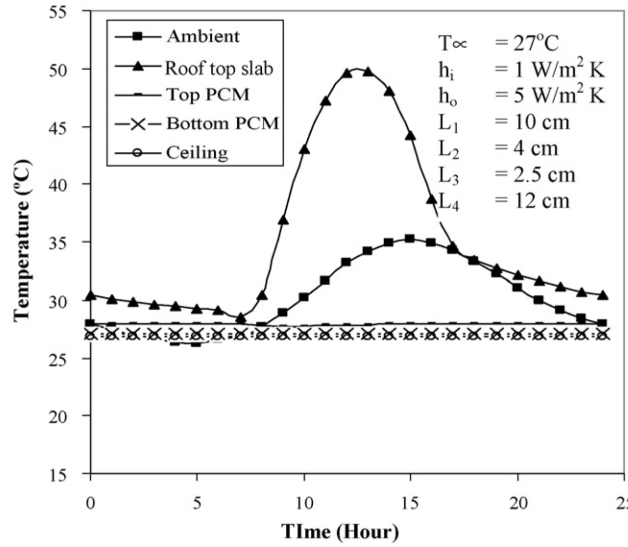


Fig. 15. Effect of double layer PCM in the roof with top layer thickness 4 cm.

Another simulation run is also made for the above said optimum thickness without considering the existing bottom PCM panel and the results are shown in Fig. 16. It is observed from the figure that the ceiling has reached a very high temperature above the PCM melting temperature (i.e. 32 °C)

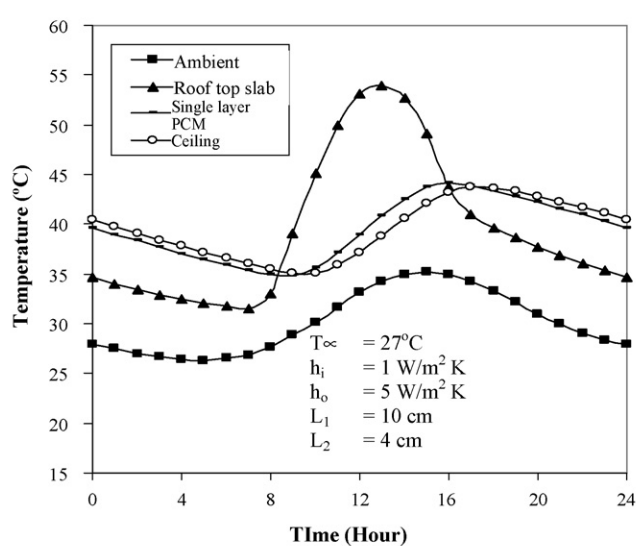


Fig. 16. Effect of single layer PCM (Climsel C32) [4 cm].

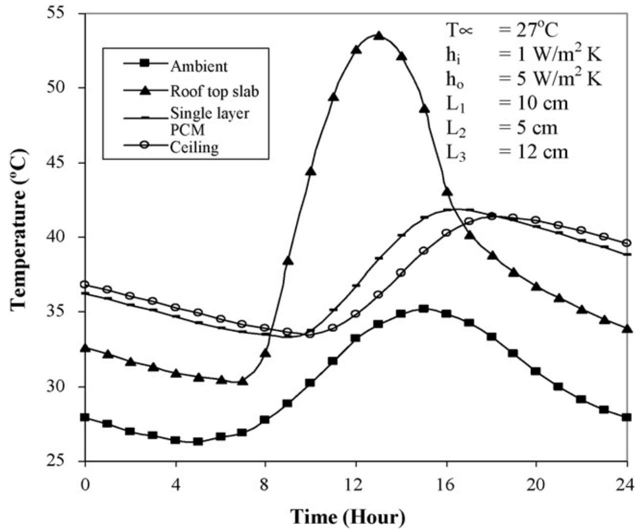


Fig. 17. Effect of single layer PCM (Climsel C32) [5 cm].

when the single layer PCM panel thickness is 4 cm. Hence the simulation run is extended for the single layer PCM panel thickness of 5 cm and 6 cm and the results are shown in Figs. 17 and 18.

It is seen from the figures that the ceiling of the PCM room attains the PCM melting temperature (i.e. 32 °C) only when the PCM thickness of 6 cm is provided. However, to maintain a comfortable temperature of 27 °C at the ceiling, a two layer with two different PCM melting temperature is suggested and recommended from the present observation. The melting temperature of the PCM in the top panel should be selected in such a way that the PCM should solidify in the repeated cycling during the night hours to utilize the benefit of latent heat storage capacity of the selected PCM material. It is observed from the trial that the phase change temperature of the top PCM panel should be selected at least 6–7 °C higher than the average temperature of the ambient that prevails in the early morning hours (3–6 a.m.) during the peak summer month in order to achieve complete solidification of the PCM during all the months in a year for repeated cycling.

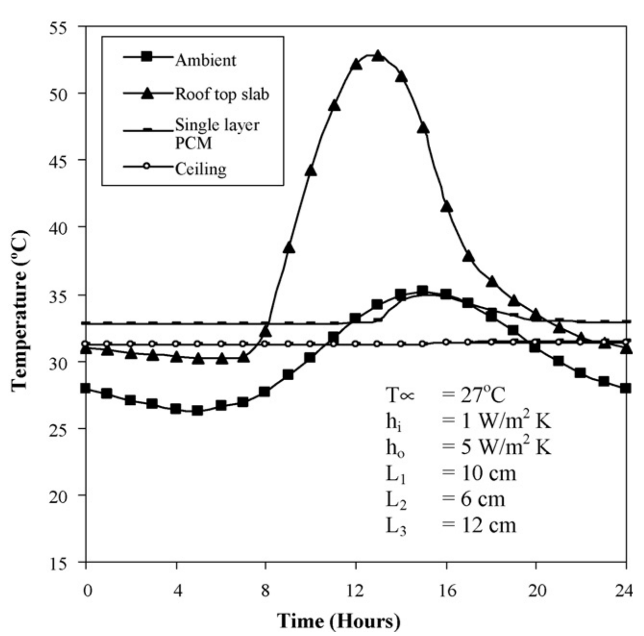


Fig. 18. Effect of single layer PCM (Climsel C32) [6 cm].

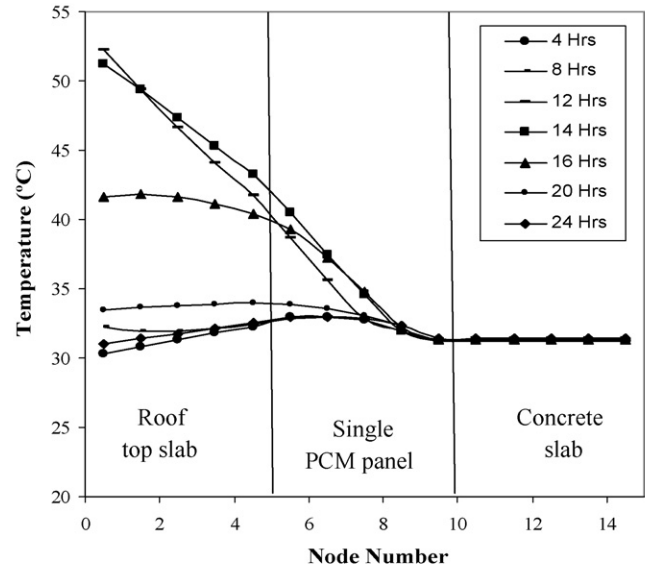


Fig. 19. Temperature distribution across the roof in month of July (single layer PCM).

The temperature distribution across the roof at various time intervals during a day is shown in Figs. 19 and 20 for the PCM room using single layer and double layer, respectively, for the average weather conditions that prevails in a typical summer month of July. It is seen from both the figures that a constant temperature exists throughout the roof at 8 a.m. and a constant temperature at all the times in the bottom concrete slab. However, the temperature of both room ceilings varies as per the melting temperature of selected bottom panel PCM. Hence it is construed that with a double layer PCM it is possible to

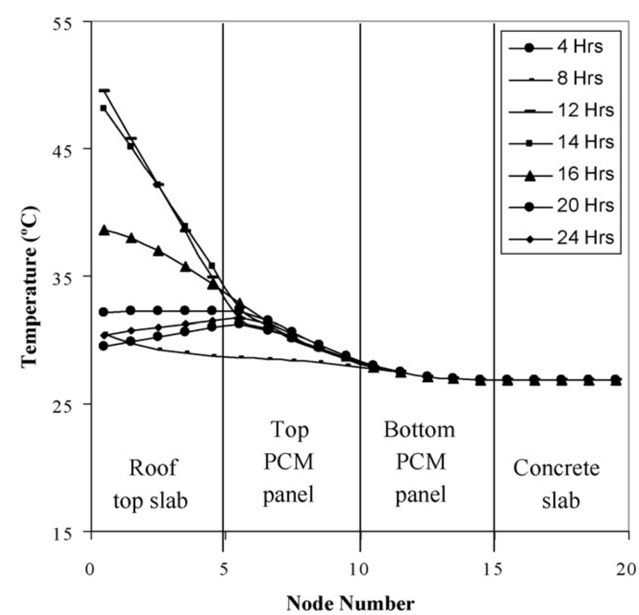


Fig. 20. Temperature distribution across the roof in the month of July (Double layer PCM).

maintain a constant comfortable temperature during all the time in a day and for various weather conditions.

6. Conclusion

Several promising developments are taking place in the field of thermal storage using PCMs in buildings. A detailed study on PCM incorporation in building material, PCMs integration with building architecture for space heating, space cooling and in combination of heating and cooling has been carried out. It is quite evident from the preceding studies that the thermal improvements in a building due to the inclusion of PCMs depend on the melting temperature of the PCM, the type of PCM, the climate, design and orientation of the construction of the building. The optimization of these parameters is fundamental to demonstrate the possibilities of success of the PCMs in building materials. Therefore, the information like operational range and limitations evolved in a project with PCM as heat transport medium and elaborate calculation for analysis supported by a simulation program would definitely be a remarkable and reckonable guidance for deciding and designing PCMs in building application. Being site specific, a detailed study is required for the selection of material and to implement the PCM based thermal storage in buildings at a particular location. The selection of PCM based on phase transition temperature for one climatic region will not be appropriate for another.

In the present research a detailed investigation has been carried out to analyze the thermal performance of the roof of a building incorporating PCM suitable for Chennai city, India and for year round thermal management. A model has been developed and it is validated using the experimental results. Several simulation runs are made using this model for the average ambient condition that prevails at Chennai city, India for all the months in a year and for the various other parameters of interest. It is concluded that for the purpose of narrowing indoor air temperature swing and to suit for all seasons, a double layer PCM incorporated in the roof is suggested and recommended.

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