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Experimental investigation and numerical simulation analysis on the thermal performance of a building roof incorporating phase change material (PCM) for thermal management

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Abstract

Thermal storage plays a major role in a wide variety of industrial, commercial and residential application when there is a mismatch between the supply and demand of energy. 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. Several promising developments are taking place in the field of thermal storage using phase change materials (PCM) in buildings. It has been demonstrated that for the development of a latent heat storage system (LHTS) in a building fabric, the choice of the PCM plays an important role in addition to heat transfer mechanism in the PCM. 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. 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. Experiments are also conducted by circulating water through the tubes kept inside the PCM panel to test its suitability for the summer months. In order to achieve the optimum design for the selected location, several simulation runs are made for the average ambient conditions for all the months in a year and for the various other parameters of interest.

Keywords: Latent heat thermal energy storage; Space heating and cooling; Building energy conservation; 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. Latent heat storage is a relatively new area of study although it previously received much attention during the energy crisis of late 1970's and early 1980's where it was extensively researched for use in solar heating systems. When the energy crisis subsided, much less emphasis was put on latent heat storage. Although research into latent heat storage for solar heating systems continues, recently it is increasingly being considered for waste heat recovery, load leveling for power generation, building energy conservation and air conditioning applications.

As demand for air conditioning increased greatly during the last decade, large demands of electric power and limited reserves of fossil fuels have led to a surge in interest with regard to energy efficiency. Electrical energy consumption

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Nomenclature

C_1, C_3	specific heat of roof top slab and concrete slab (kJ/kg K)
c_{pl}	specific heat of liquid PCM (kJ/kg K)
c_{ps}	specific heat of solid PCM (kJ/kg K)
f	implicit factor
Gr_{L}	Grashof number
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 bottom concrete slab (W/m K)
L_1, L_2, L_3	thickness of roof top slab, PCM panel and bottom concrete slab (m)
Nu_{L}	Nusselt number
Pr	Prandle number
q_{rad}	radiation flux (W/m^2)
Re	Reynolds number
T	temperature (°C)
T_∞	ambient temperature (°C)
T_i^0	previous time step temperature at ith volume cell (°C)
T_i	current 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)
α	absorptivity
$\in$	emissivity
h_{sl}	solid–liquid enthalpy change (kJ/kg)
σ	Stefan Boltzmann constant
ρ_1, ρ_2, ρ_3	density of roof top slab, PCM panel and bottom concrete slab (kg/m^3)
Δt	time step (s)
δx_1, δx_2, δx_3	nodal distances (m)
Δx_1, Δx_2, Δx_3	control volume length of roof top slab, PCM panel, bottom concrete slab (m)

varies significantly during the day and night according to the demand by industrial, commercial and residential activities. In hot and cold climate countries, the major part of the load variation is due to air conditioning and domestic space heating, respectively. This variation leads to a differential pricing system for peak and off peak periods of energy use. Better power generation/distribution management and significant economic benefit can be achieved if some of the peak load could be shifted to the off peak load period. This can be achieved by thermal energy storage for heating and cooling in residential and commercial building establishments.

There are several promising developments going on in the field of application of PCMs for heating and cooling of building. Zalba et al. [1] performed a detailed review on thermal energy storage that dealt with phase change materials, heat transfer studies and applications. Farid et al. [2] also presented a review on the analysis of phase change materials, hermetic encapsulation and application of PCMs. Mehling and Hiebler [3] summarized the investigations and developments on using PCMs in buildings. Murat Kenisarin1and Khamid Mahkamov [4] presented a review of investigations and developments carried out during the last 10–15 years in the field of phase change materials, enhancing heat conductivity, available fields of using PCM, and clarifying typical questions.

Arkar and Medved [5], Stritih and Novak [6] 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 of impregnating gypsum and other PCMs [7–12] 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. [13] and Hawes et al. [14] presented the thermal performance of PCM's in different types of concrete blocks. They studied and presented the effects of concrete 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 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. [15]. Meng Zhang et al. [16] presented the development of a thermally enhanced frame wall that reduces peak air conditioning demand in residential buildings. Ismail et al. [17] proposed a different concept for thermally effective windows using a PCM moving curtain.

UniSA (University of South Australia) [18] developed a roof-integrated solar air heating/storage system, which uses existing corrugated iron roof sheets as a solar collector for heating air. Kunping Lina et al. [19] put forward a new kind of under-floor electric heating system with shape-stabilized phase change material (PCM) plates. Hed [20] 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 [21]. 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 [22] 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. [23] proposed a ventilation system that makes use of both thermal storage and outdoor conditions. The sustainable energy centre (SEC) at University of South Australia [24] 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 ceiling panel was developed by Markus Koschenz and Beat Lehmann [25] to incorporate this system in a light weight building that can be retrofitted. Velraj et al. [26] 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 [27] 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] [28] 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. [29] 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 [30] was the first to analyze cyclic melting/freezing of a phase change material (PCM). He used a one-dimensional conduction model 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. [31] 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 [32] carried out a numerical analysis for the cyclic behavior of alternate melting and freezing in a multi-plate latent heat energy storage exchanger.

In the present paper, a detailed study on the thermal performance of a phase change material based thermal storage for energy conservation in building is analyzed and discussed. An experimental set up consisting of two identical test rooms has been constructed to study the effect of having PCM panel on the roof for thermal management of a residential building. One room is constructed without PCM on the roof to compare the thermal performance of an in-organic eutectic PCM (48% $CaCl_2 + 4.3\%$ $NaCl + 0.4\%$ $KCl + 47.3\%$ H_2O), which has melting temperature in the range of 26–28 °C. A mathematical model has been developed and the finite volume method is employed for the computation of thermal behavior of the roof incorporating PCMs. A comparison with the experimental results is made and several simulation runs are conducted for the average ambient conditions for all the months in a year and for the various other parameters of interest. During the summer months, as the PCM does not change to the solid state during the night hours, experiments are conducted to test the possibility of removing the heat from the PCM slab and the ceiling by circulating water through the PCM panel.

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 in 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 change its phase from solid to liquid. 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 is initially maintained at a uniform temperature "T_i". The boundary condition on the outer surface of roof is considered due to the combine 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 [33] for every one-hour 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 [$Nu_L = 0.664(Re_L)^{0.5}(Pr)^{0.33}$].

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 small, 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 [$Nu_L = 0.54\ (Gr_L \cdot Pr)^{0.25}$].

2.2. Mathematical formulation

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

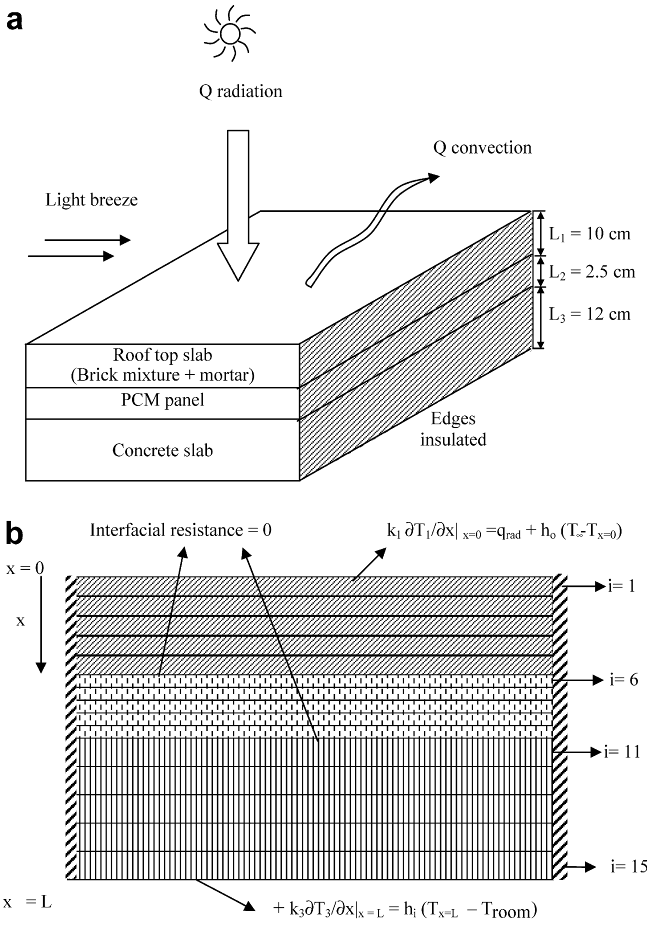

Fig. 1. (a) Building roof, (b) finite volume grid for the analysis.

(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:

$$T < T_m - \Delta T \qquad c_p = c_{ps}$$

$$T > T_m + \Delta T \qquad c_p = c_{pl}$$

$$T_m - \Delta T < T < T_m + \Delta T \quad c_p = h_{sl}/2\Delta T$$

where 'c_p' is the specific heat capacity, h_{sl} is the Enthalpy change of solid–liquid, ΔT is 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:

$$k_m \frac{\partial^2 T_m}{\partial x^2} = \rho_m c_{P_m} \frac{\partial T_m}{\partial t} \quad [0 < x < L];\ m = 1, 2, 3 \tag{1}$$

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,

$$k_1 \partial T_1/\partial x|_{x=0} = q_{\text{rad}} + h_o(T_\infty - T_{x=0}) \tag{2}$$

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

$$+k_3 \frac{\partial T_3}{\partial x}\bigg|_{x=L} = h_i(T_{x=L} - T_{\text{room}}) \tag{3}$$

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

2.2.1. Exterior node

The equation for the top volume cell is written as below

$$\left(\frac{\rho_1 c_1 \Delta x_1}{\Delta t} + \frac{f k_1}{\delta x_1} + h_o f\right) T_1 - \frac{f k_1}{\delta x_1} T_2 = h_o f T_\infty + (1-f)\left[\frac{k_1(T_2 - T_1)}{\delta x_1} - h_o(T_1 - T_\infty)\right] + \frac{\rho_1 c_1 T_1^0}{\Delta t}\Delta x_1 + \alpha q_s + \sigma\left[\alpha T_{\text{sky}}^4 - \in T_s^4\right] \tag{4}$$

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

$$\frac{-f k_m}{\Delta x_m} T_{i+1} + \left[\frac{\rho_m C_m \Delta x_m}{\Delta t} + \frac{f k_m}{\Delta x_m} + \frac{f k_m}{\Delta x_m}\right] T_i - \frac{f k_m}{\Delta x_m} T_i = (1-f)\left[\frac{k_m(T_{i+1} - T_{-i-1})}{\delta x_m} - k_m \frac{(T_i - T_{i-1})}{\delta x_m}\right] + \frac{\rho_m C_m T_i^0 \Delta x_m}{\Delta t} \tag{5}$$

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

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

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

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

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 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) 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 another one has PCM panel in between the bottom concrete slab and the roof top slab. Thus it is possible to study the thermal performance of the PCM embedded ceiling over the conventional one. 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 is made up of stainless steel of 2 m by 2 m and thickness of 2.54 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. This PCM salt hydrate mixture is stored in a closed stainless steel metallic container of capacity 0.1 m^3. It is important to note that the container must always be in a closed-sealed system in order to maintain the PCM product integrity. Excess moisture can change the composition of the product and hence it must be airtight.

Table 1
Technical specifications of the PCM (48% $CaCl_2$ + 4.3% NaCl + 0.4% KCl + 47.3% H_2O)[a]

Description	Value
Appearance (color)	Grey
Phase change temperature (°C)	26–28
Density (kg/m^3)	1640
Latent Heat (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)

[a] Ref. [1].

The PCM slab has water pipes inside it which act as heat exchanger and has the following specification.

- Tube material: stainless steel.
- Length of the tube: 2.25 m.
- Tube diameter: 6.35 mm.
- Number of tubes: 12.

The tubes are connected on both sides to a stainless steel header that has 50 mm diameter and 2.25 m length each and have a length of 2.25 m.

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 and prevent incongruent melting and sub-cooling. The total mass of the PCM mixture used is 164 kg, which, in its liquid state is poured into the panel submerging the heat exchanger pipes, and the whole assembly is sealed properly.

A water tank with a capacity of 200 l is kept at the top corner of the PCM room and the cold water from the tank is allowed to pass through the heat exchanger as and when required. This water is used to cool the PCM when the complete freezing of PCM is not possible in the night hours during the summer. If the PCM does not freeze until early morning of the next day, it may not be ready for next cycle of operation. Under such situation, the cold water is to be circulated through the water tubes until the PCM is solidified. In addition, during peak summer in daytime when the temperature of the PCM starts increasing above its melting temperature, cold water is to be circulated through the tubes to maintain constant temperature (i.e., around

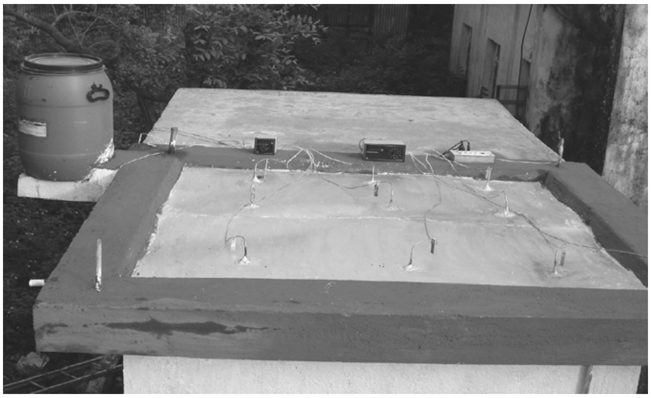

Fig. 2. Arrangement of the temperature sensors before laying roof slab.

PCM melting temperature). The RTD (resistance temperature detector) (Type PT 100) are placed in different depths in the PCM panel with perfect sealing as shown in Fig. 2. The PCM temperature variation is recorded for every 1 h using a digital indicator.

Several experiments are conducted in the PCM room during the months of January and February. 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 order to validate the model, the actual internal room temperature variation should have been accommodated. However this variation is not considered in the theoretical analysis as the objective is to calculate the bottom roof temperature for a given constant room temperature and for various external weather conditions that will be useful to evaluate the effect of PCM panel in reducing the heat load for building. In the theoretical analysis, the room temperature is maintained at a constant temperature of 27 °C with convective boundary condition on the inner surface of the concrete slab during a particular trial. 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 (33) are provided as input in the theoretical analysis. The temperature variations across the roof material for fifteen control volumes are obtained from the theoretical analysis. The temperature variations in the bottom surface of the concrete slab (ceiling) with PCM and without PCM rooms are shown in Fig. 3 to compare the theoretical model results with the experiment.

It is seen from the Fig. 3 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 ceiling 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 the ceiling of the non-PCM room. From the experimental results, a small decrease in ceiling temperature during the day time and small increase in ceiling temperature during the night time is observed which reduces the fluctuation of temperature inside the PCM room. This is due to the large heat storage capacity of the PCM. Further, 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. The differences in temperature value between the theoretical and experimental results are due to the following reasons.

- The ceiling of the roof is influenced by the inside room condition where an actual temperature variation of 27 ± 3 °C exists.
- The effective thermal conductivity of the PCM in the experiment is higher due to the presence of uniformly distributed high conductivity heat exchanger material in the PCM panel.
- The actual phase change may not occur during the phase change temperature prescribed in the theoretical analysis.

The simulated results are not in good agreement with the experimental results due to the above said reasons.

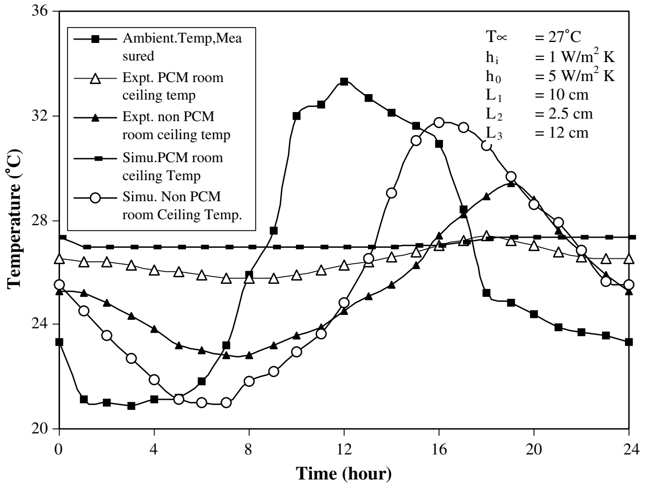

Fig. 3. Experimental and simulated temperature of the ceiling in the PCM and non-PCM room.

However, as similar pattern exists between the theoretical and experimental results, the theoretical analysis is further extended to study the effects during all the season in a year and to analyze the effects of other parameters of interest. This model results holds good when the room is maintained at a constant temperature by an air conditioner and this study will be useful to analyze the variation in the cooling load on the air conditioner due to the heat load through the roof during the entire day.

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. Figs. 4 and 5 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. The roof top temperature attains maximum at noon due to the maximum intensity of solar radiation.

It is observed from 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. 5, 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–April, this has a negative effect in the month of May–November.

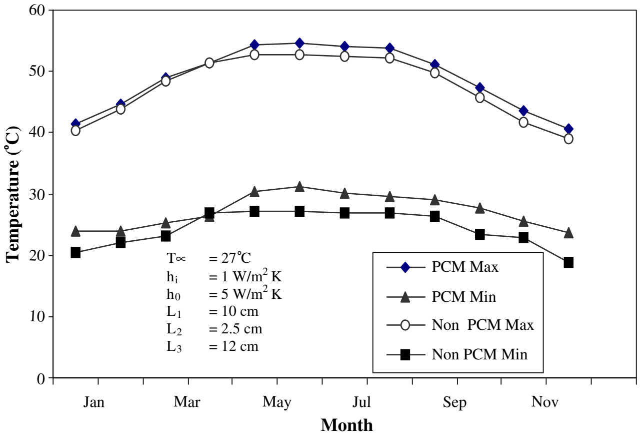

Fig. 4. Monthly maximum and minimum temperature variation of the roof top surface of the PCM and non-PCM room.

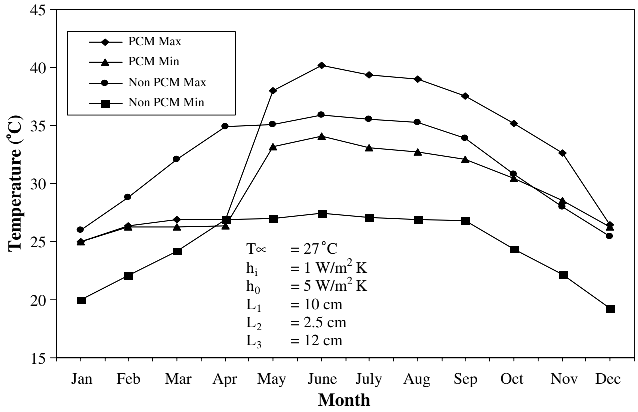

Fig. 5. Monthly maximum and minimum temperature variation of the ceiling of the PCM and non-PCM room.

5.3. Effect of PCM panel thickness on the concrete slab

In the experimental work carried out in the present research, the roof has a PCM panel thickness of 2.5 cm. In order to study, the effect of PCM panel thickness over the concrete slab on heat transfer, in addition to the figure available for 2.5 cm thickness, two more graphs are drawn as shown in Fig. 6 for a PCM thickness of 1 cm and 3 cm, respectively considering the ambient condition for the month of January. It is observed from the figure that when the PCM panel thickness is 1 cm, the temperature of the PCM and the ceiling start increasing after the noon hours and it reaches a maximum temperature of 35 °C and the ceiling reaches a temperature of 34 °C, whereas the case with PCM thickness 3 cm, the temperature is maintained constant at the phase change temperature throughout the day. However, it is seen from the earlier graphs that the operating temperature is totally above the phase change temperature during the months from May to November. It is construed from all the earlier graphs that a material thickness of 2.5 cm is sufficient to keep the ceiling temperature at a constant level during the months of December–April. However the thickness cannot be increased further to suit for the summer months, as the PCM is not able to attain the original state after the nighttime cooling. Hence, in order to keep the temperature at a constant level slightly above this temperature level during the summer months, water passing through the tubes embedded in the PCM panel is studied and the results are presented in the next section.

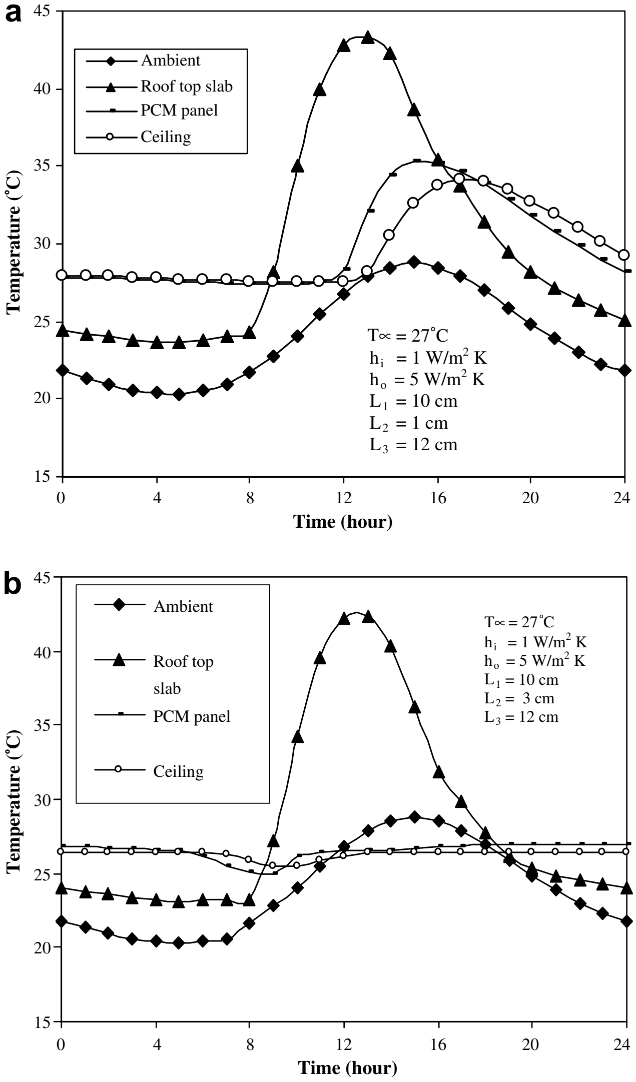

Fig. 6. Effect of PCM thickness in the roof slab (a) 1 cm (b) 3 cm.

5.4. *Effect of water supply through the tubes embedded in the PCM panel*

In the present experimental investigation, water is allowed to pass through the tubes in the PCM panel to extract the heat at a faster rate. This experiment was conducted during the month of January and the results are shown in Fig. 7 for the PCM room with and without water circulation. The water is passed through the tubes for duration of 30 min around 1600 h. A marginal decrease in ceiling temperature is observed. However, this effect must be appreciable during summer. In the theoretical investigation during month of July around 1600 h, the temperature of the PCM is suddenly decreased by 1 °C, which represents the removal of latent heat from the PCM (around 27 °C). Thereby, the bottom surface temperature of the concrete slab is maintained at a constant level of 27 °C as shown in Fig. 8. The quantity of water required to extract the latent heat from a unit surface area is calculated as 830 kg/m^2. Such a large quantity of cold water per unit area is not easily available during the summer period. Hence a passive system with one more layer of PCM with different phase change temperature above the bottom PCM panel is being studied for the purpose of narrowing indoor air temperature swing to suit all the weather conditions.

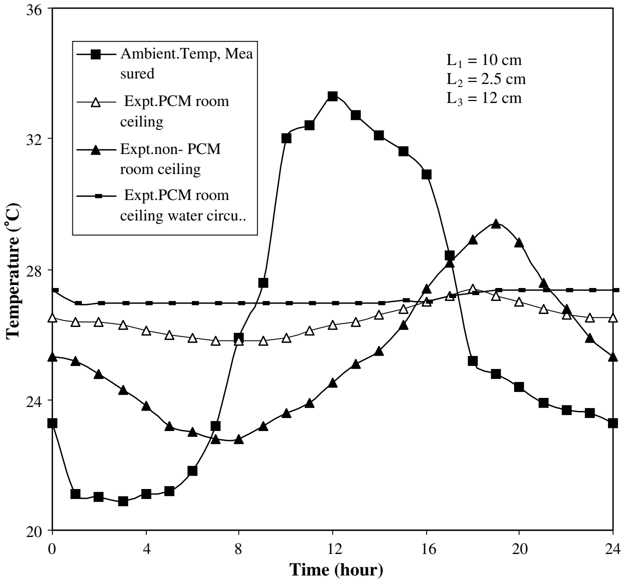

Fig. 7. Experimental investigation of the PCM room in the month of January with water circulation.

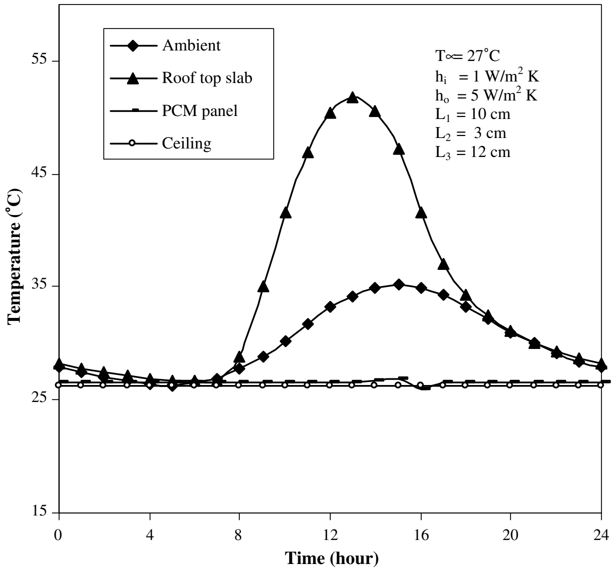

Fig. 8. Theoretical investigation of the PCM room for the month of July with water circulation.

6. Conclusions

Several promising developments are taking place in the field of thermal storage using PCMs in buildings. A literature review 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. 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. A mathematical model has been developed and finite volume method is used to predict thermal behavior of roof incorporating PCMs. In order to achieve the optimum design for the selected location, several simulation runs are made for various parameters of interest. The effect of variation in the ambient condition for all the months, variation in heat transfer coefficient on the outer surface of the roof and the PCM panel thickness are studied in detail. In addition the effect of water circulation through the PCM panel is also attempted for the thermal management during summer months. It is observed from the study that the quantity of water required is very large which is not easily available during the summer months.

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