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ABSTRACT

Thermal storage is vital in all applications as it is essential to have storage of energy for the given demand. Latent heat storage facilitate to store more energy and which is essential in all application. Increasing thermal storage capacity of the building roof leads to maintain the temperature of the room for a longer period of time, thus it paves the way for selecting suitable PCM material for thermal storage. This paper concerns about the thermal storage over the roof with the help of inorganic eutectic PCM. Numerous simulation runs are made under various ambient conditions and results are tabulated for better understanding of the PCM material thermal storage capacity.

INTRODUCTION

The consumption of energy varies significantly during the day and night according to the demand in the industrial, commercial and residential sectors, especially, in extensive hot and cold climatic zones. The production of electrical energy through coal/fossil fuel is the main cause for CO_2 emission into the atmosphere, which is widely believed to be contributing to global warming. Additionally, the dependence of the human on this kind of energy attached to the continuous changes of petroleum prices and hence led to promote the research in low cost alternative and environmental friendly energy sources. The building sector is also one of the major energy consumers and its contribution toward global energy consumption is about 40%. The rapid change in the life style and the living standards leads to the growing demand of energy consumption in all the sectors mentioned above. Promoting energy efficiency and conservation in buildings is, therefore, becoming one of the major issues of concern to governments and societies today. Such variation leads to a differential pricing system for peak and off peak periods of energy use. Better power generation management and significant economic benefit can be achieved if some of the peak load could be shifted to the off peak period, which can be achieved by latent heat thermal energy storage of heat or coolness. So, storing of cool thermal energy during off peak period with phase change material is a good solution for shifting peak load for off peak period.

During recent years, research aimed for the development of technologies that can offer reduction in energy consumption, peak electrical demand and energy costs without affecting the level of thermal comfort. Alternative cooling technologies are being developed which can be applied to residential and commercial buildings, in a wide range of weather conditions. These include cooling with ventilation, evaporative cooling, desiccant cooling, slab cooling, cooling through phase change materials, etc. The design of buildings employing low energy cooling technologies, however, presents difficulties, and requires advanced modeling and control techniques to ensure efficient operation. The most common storage media for space cooling are water, ice, and other phase change materials. The phase change materials (PCMs) have been used for various hot/cold energy storage applications in last four decades; however, they have also been used as a storage media for space cooling application. So far, most of the PCMs for cool storage are inorganic salt hydrates, organic paraffin waxes, and mixtures of these 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 e ciency. Electrical energy consumption 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 di erential pricing system for peak and off peak periods of energy use. Better power generation/distribution manage-ment and significant economic benefit can be achieved if some of the peak load could be shifted to the o 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.

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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 wall- board have been conducted, but few general rules pertaining to the thermal dynamics of PCM wallboard are available.

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 e ects 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.

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.

Statement of the problem

The physical system considered is a stainless steel panel filled with PCM (inorganic eutectic 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 time.

The composite wall is initially maintained at a uniform temperature ‘‘Ti’’. The boundary condition on the outer surface of roof is considered due to the combine e ect 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 coe cient (h) value on the outer surface is calculated based on the prevailing velocity of the wind using the Nusseltcorrelation:

$[Nu_L = 0.664(Re_L)^{0.5}(Pr)]^{0.33}$.

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 [NuL = 0.54 (GrL Pr)0.25].

Mathematical formulation

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

1. The heat conduction in the composite wall is one-dimensional and the end e ects are neglected.
2. The thermal conductivity of the concrete slab and the roof top slab are considered constant and not varying with respect to temperature.
3. The PCM is homogeneous and isotropic.
4. The convection e ect in the molten PCM is neglected.
5. The interfacial resistances are negligible.
6. The ‘cp’ value of the PCM in the panel is considered as follows:

$$T < T_M \quad T \quad C_P = C_{PS} T > T_M + \quad T \quad C_P = C_{Pl} T_M \quad T$$
$$< T < T_M + \quad T \quad C_P = \quad {}_{Sl/2 \ T}$$

where ‘c_p’ is the specific heat capacity, h_{sl} is the Enthalpy change of solid–liquid, DT is half of the temperature range over which the phase change occurs and Tm is the temperature about which phase change occurs.

7. 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.

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.

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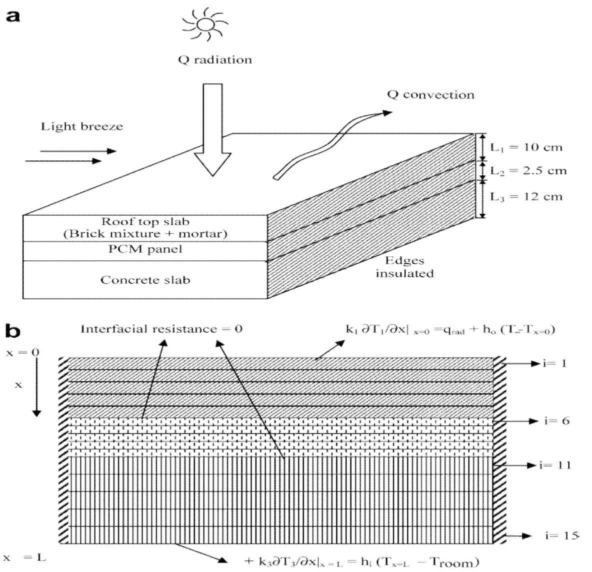

Figure 1 Pcm integrated roof Top

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

Nomenclature

C1, C3 = 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)
k1, k2, k3 = thermal conductivity of roof top slab, PCM panel and bottom concrete slab (W/m K)
L1, L2, L3 = 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^0_i =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
ξ = emissivity
h_{sl} = solid–liquid enthalpy change (kJ/kg)
σ = Stefan Boltzmann constant
ρ1, ρ 2, ρ 3 = density of roof top slab, PCM panel and bottom concrete slab (kg/m^3)
Δ_t = time step (s)
δ_1, δ_2, δ_3 = nodal distances (m)
Δ_1, Δ_2, Δ_3 = control volume length of roof top slab, PCM panel, bottom concrete slab (m)

Mathematical Model

Governing Equation

$K_m \frac{\partial^2 T_M}{\partial x^2} = \rho_m c_{pm} \frac{\partial T_m}{\partial T}$ $[o < x < L]$; $m = 1,2,3$(Equation 1)
M= 1 for roof top slab
M = 2 for pcm panel
M= 3 for ceiling
The same equation holds good for all the three material regions by incorporating suitable k, q, c_p

When the floor is exposed to solar radiation:

$\left[K_1 \frac{\partial^2 T_1}{\partial x}\right]_{x=0} = q_{rad} + {}_0(T_\infty \quad T_{x=0})$ (Equation 2)

In the bottom layer the boundary condition at x= L is

$\left[K_3 \frac{\partial^2 T_3}{\partial x}\right]_{x=L} = {}_i(T_{x=L} \quad T_{room})$ (Equation 3)

Exterior node

Equation for top volume cell is written as:
$\left(\frac{\rho_1 c_1 \; x_1}{t} + \frac{f k_1}{\delta x_1} + {}_0 f\right) T_1 \quad \frac{f k_1}{\delta x_1 T_2} = {}_0 f T_\infty + (1 \quad f)$
$\left(\frac{k_1(T_2 - T_1)}{\delta x_1} \quad {}_0(T_1 \quad T_\infty)\right) + \frac{\rho_1 c_1 T_i^0}{t} \; x_1 + \propto q_s + \sigma[\, T_{sky}^4 \text{-} \,\epsilon\, T_4^s]$
……… (Equation 4)

Inner node

Equation for any node present between top and bottom volume cell is:

$\frac{-f k_m}{x_m} T_{i+1} + \left[\frac{\rho_m c_m \; x_m}{t} + \frac{f k_m}{x_m} + \frac{f k_m}{x_m}\right] T_i$

$\frac{f k_m}{x_m} T_i = 1 \quad f \left[\frac{k_m(T_{i+1} \quad T_{-i-1})}{\delta x_m} \quad \left(k_m \frac{T_i \quad T_{i-1}}{\delta x_m}\right)\right]$
$+ \frac{\rho_m c_m T_i^0 \; x_m}{t}$ (Equation 5)

The above-mentioned discretized equations are applica-ble 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.

Interface node

(-fk1/ δx1)T4 + [(ρ1c1Δx1 /Δt) + (f/ (δx1/2k1)+ (δx2/2k2)) + (fk1/ δx1)T5 -[(f/ (Δx1/2ki)+ (Δx2/2k2))] T4 = (1-f) [(k1(T6-T5)/ δx2) - (k1(T5-T4)/ δx1)] + (ρ1c1Δx1To5 /Δt) ……….(Equation 6)

Where Dx1 and Dx2 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 Dx2 and Dx3 that corresponds to PCM panel and bottom concrete slab, respectively.

Interior node

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

(-fk3/ δx3)T4 + [(ρ3c3Δx3 /Δt) + (fk3/ δx3)] T15 = f[hi(-2)] + (1-f) [2hi - k ((T15-T14)/ δx3)] + (ρ3c3Δx3To15 /Δt) ………………………..(equation 7)

RESULTS AND DISCUSSION

PCM VS NON PCM

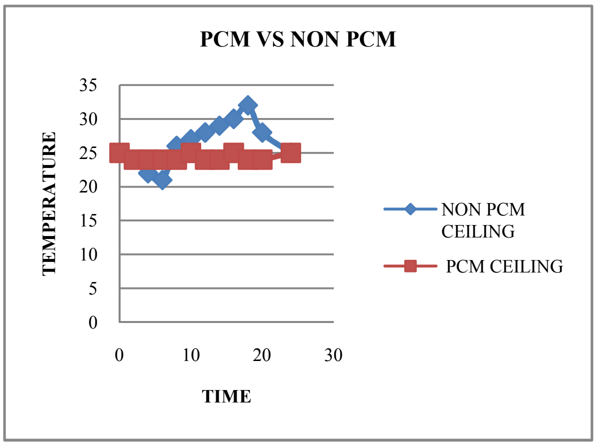

Figure 2 pcm vs non pcm results

PCM With 1 CM length

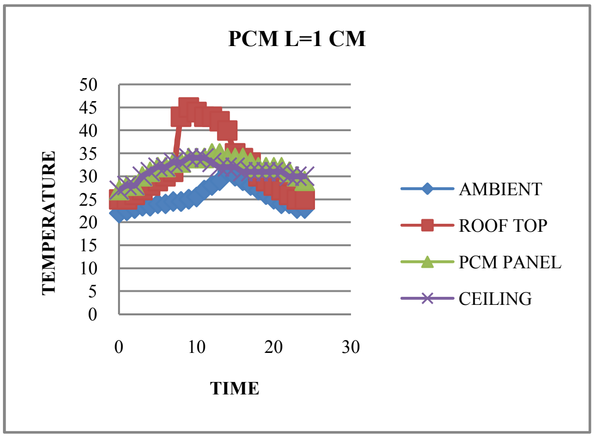

Figure 3 Graphical Results of Pcm with 1cm LENGTH

PCM With 3CM Length

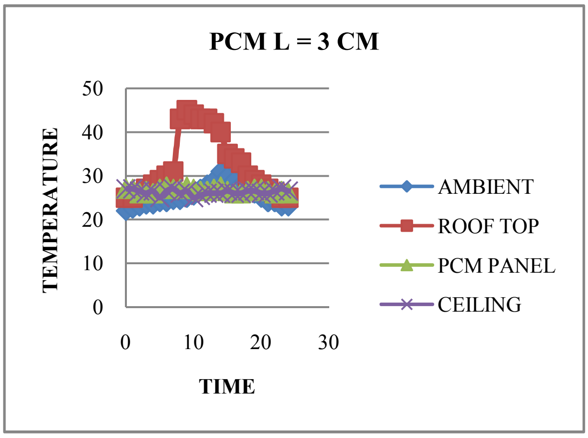

Figure 4 Graphical Results of Pcm with 3cm LENGTH

DISCUSSION

It is quite evident from the results of the Figure 2 that the roof top without pcm will allow more heat to the ceiling and the roof top with pcm will maintain the ceiling temperature as steady as possible.

When the results in Figure 3 and figure 4 are compared we can find that it is very difficult to maintain the ceiling temperature with the length of 1 cm but pcm length with 3 cm thickness provides better results hence pcm material thickness should be above the length of 2.5 cm to provide better results.

CONCLUSION

From the analysis of roof top insulation it is quite evident that the roof top with pcm material provides good insulation and the same can be validated through experiments if required.As there will be variation in climatic conditions always. The results provided here are only for the given boundary condition the same can be applied anywhere with required modification.

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