NATURAL COOLING OF BUILDING USING PHASE CHANGE MATERIAL

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ABSTRACT

Due to climatic change, increasing thermal loads in buildings and rising living standards, comfort cooling in buildings is becoming increasingly important and the demand for comfort cooling is expanding very quickly around the world. Cool thermal storage systems have the potential to become one of the primary solutions to the electrical power imbalance between production and demand, but also shift cooling energy use to off-peak periods and avoid peak demand charges. Cool storage system using phase change materials can be used for peak load shifting if they are installed in the building. Phase change material (PCM) are one of the latent heat materials having low temperature range and high energy density of melting – solidification compared to the sensible heat storage. The tests on transient heat transmissions across different roof structures were conducted. It was found that when installing PCM in the withering course (WC-mixture of broken bricks and lime mortar) region nearly uniform roof bottom surface temperature was maintained.

Keywords: building roof, energy storage, heat transmission, latent heat storage (LHS), natural cooling, phase change material (PCM).

INTRODUCTION

As a 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 of interest with efficient energy application. Electrical energy consumption varies significantly during the day and night according to the demand by the industrial, commercial and residential activities. In hot and cold climate countries, the major part of the load variation is due to the air conditioning and space heating respectively. This variation leads to a differential pricing system for peak and off peak periods of energy use. Recent discussions on topics like depletion of fossil fuels and heat waves have brought attention once again to energy efficient cooling systems utilizing renewable energy sources. Climate change has brought additional challenges for cooling systems designers. Significant economic benefit can be achieved by thermal energy storage for heating and cooling in residential and commercial buildings. Buildings that will have large mass will react slowly to changes in heating and cooling demands.

Latent heat storage (LHS) in a phase change material (PCM) is very attractive because of its high storage density with small temperature swing. Thermal energy storage in the walls, ceiling and floor of the buildings may be enhanced by encapsulating or embedding suitable PCMs within these surfaces. They can either capture solar energy directly or thermal energy through natural convection. Increasing the thermal storage capacity of building can increase human comfort by decreasing the frequency of internal air temperature swings so that indoor air temperature is closer to the desired temperature for a longer period of time. Many phase change materials has been studied and tested for different practical uses by many scientists. This paper attempts to analyze the information about application of PCM in the building roofs for residential and commercial establishments.

PCM CLASSIFICATION AND PROPERTIES

In 1983, Abhat [1] gave the general classification of energy storage material in Fig.1 and also by Lane [11, 12], Dinser and Rosen [13]. These papers gave the full detail like classification and characteristics of PCM. Zalba [2] listed the properties of different PCM's (Organic, Inorganic, Fatty acids) like density, specific heat, thermal conductivity and melting temperature. Some of the important properties required for PCM are

- High latent heat of fusion per unit mass, so that a lesser amount of material stores a given amount of energy.
- High specific heat that provides additional sensible heat storage effect and also avoid sub cooling.

- High thermal conductivity so that the temperature gradient required for charging the storage material is small
- High density, so that a smaller container volume holds the material
- A melting point in the desired operating temperature range.
- The phase change material should be non-poisonous, non-flammable and non-explosive and corrosiveness to construction material
- No chemical decomposition, so that the (LHTS) system life is assured.
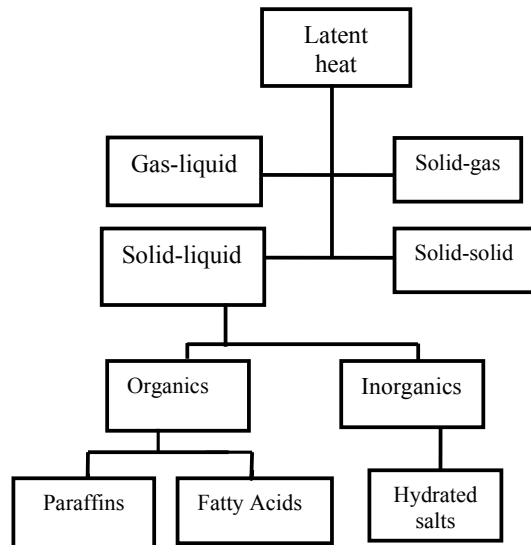- PCM should exhibit little or no super cooling during freezing

Figure 1: Classification of PCM

DEVELOPMENT OF PCM FOR COOLING OF BUILDINGS

There are three different ways to use PCMs for heating and cooling of buildings exist:
    -PCMs in building walls;
    -PCMs in building components other than walls i.e in ceilings and floors;
    -PCMs in separate heat or cold stores.
In building applications, only PCMs that have a phase transition close to human comfort temperature (20–28ºC) can be used. Some Commercial PCMs have been also developed for building application.
Hawes and Feldman [3] have considered the means of PCM incorporation into the building by direct incorporation, immersion and encapsulation. Peippo et al. [4] considered a PCM impregnated plasterboard as a storage component in a lightweight passive $120m^2$ solar house with good insulation and a large area of south facing glazing in Madison, Wisconsin .The house could save up to 3GJ in a year or 15% of the annual energy cost. Stetiu and Feustel [10] used a thermal building simulation program based on the finite difference approach to numerically evaluate the LHS performance of PCM wallboard in a building environment. Feustel and Stetiu also investigated using double PCM-wallboard to further increase the storage capacity of a building so that the room temperatures could be kept closer to the upper comfort limits without using mechanical cooling. Neeper [5] has examined the thermal dynamics of a gypsum wallboard impregnated by fatty acids and paraffin waxes as PCMs that are subjected to the diurnal variation of room temperature but are not directly illuminated by the sun. Athienitis et al. [6] conducted an extensive experimental and one dimensional nonlinear numerical simulation study in a full scale outdoor test room with PCM gypsum board as inside wall lining. Lee et al. [7] have studied and presented the results of macro-scale tests that compare the thermal storage performance of ordinary concrete blocks with those that have been impregnated with two types of PCMs, BS and commercial paraffin. Hawes et al. [8] presented the thermal performance of PCM's (BS, dodecanol, paraffin, and tetradecanol) in different types of concrete blocks. Hadjieva et al. [9] have applied the same impregnation technique for concrete but with sodium thiosulphate penta hydrate (Na2S2O3.5H2O) as a PCM. A major development in this area is to develop a PCM which will maintain good heat storage during the day and heat loss to the environment during night time.

PROBLEM FORMULATION

ROOF TYPES AND STUDY AREA

Three roof structures are taken for studies are as follows:
Roof -1(RCC) : simple RCC roof (150mm thick);
Roof -2(WC)   : RCC roof (150mm thick) covered with withering course WC (75 mm thick);
Roof -3 (PCM): RCC roof (150mm thick) covered with WC (75mm thick) having PCM in the WC region.

ASSUMPTIONS MADE

To study the system the following assumptions are made:
i) The temperature variation is two dimensional (across width and depth directions only);
ii) The ambient temperature T_{amb} and solar heat flux q_s are the functions of time over the day;
iii) The material properties are constant;
iv) Inside and outside heat transfer coefficients are constant;
v) Radiation heat exchange within the room is neglected;
Due to similar symmetry of all these structures, width of all roofs was taken equally (150mm) for the investigation. Boundary conditions were same for all types of roof.

BOUNDARY CONDITIONS

For right and Left $\quad \dfrac{\partial T}{\partial X} = 0$

Bottom surface   Convection, hi =10w/m^{2}k, T =25ºC
Top surface   Convection, ho = 10w/m^{2}k, T =hourly values
                  Solar radiation flux, q = hourly values

Due to symmetry of roof structures, a small portion of roof cross section is considered. So the end effect of the roof is not considered.

MATERIALS AND METHODS

The temperature distribution inside the roof was analyzed by using the Finite element analysis software ANSYS 10.The parameters required for the analyses are given below

Table 1: Material property data

Material	Density (Kg/m^3)	Thermal Conductivity (W/mK)	Specific Heat ($J/Kg\ K$)
Concrete	2300	1.279	1130
Withering course	1300	0.25	800
PCM (Octadecane)	780*	0.17*	1750(solid), 2100(liquid)
	Latent heat		2,44,000

*indicates for both solid and liquid state

Solar insulation and weather data of Coimbatore city, Tamilnadu, India during June was used. $T_{sol\text{-}air}$ was found out by using the formula

$$T_{sol}= T_{amb} + (\alpha q_s /h_0) \tag{1}$$

The graph between the Time vs T_{amb} and Time vs. $T_{sol\text{-}air}$ was plotted as shown in the Fig.2
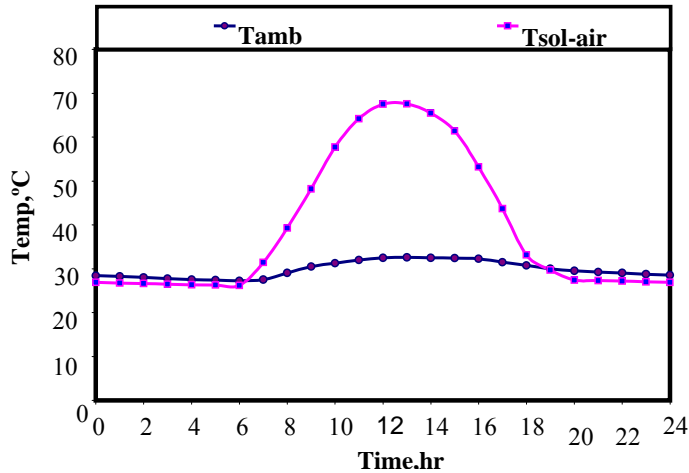
Figure 2: Solar Radiation Data for Coimbatore during June 2006

Numerical simulation work was carried out by considering the roof structures as given below.

TYPES OF ROOF TAKEN FOR STUDY

Roof structures were modeled and solved and simulated by using thermal module of Ansys finite element analysis software. Three types of roof are considered for the case study as shown in the Fig.3.
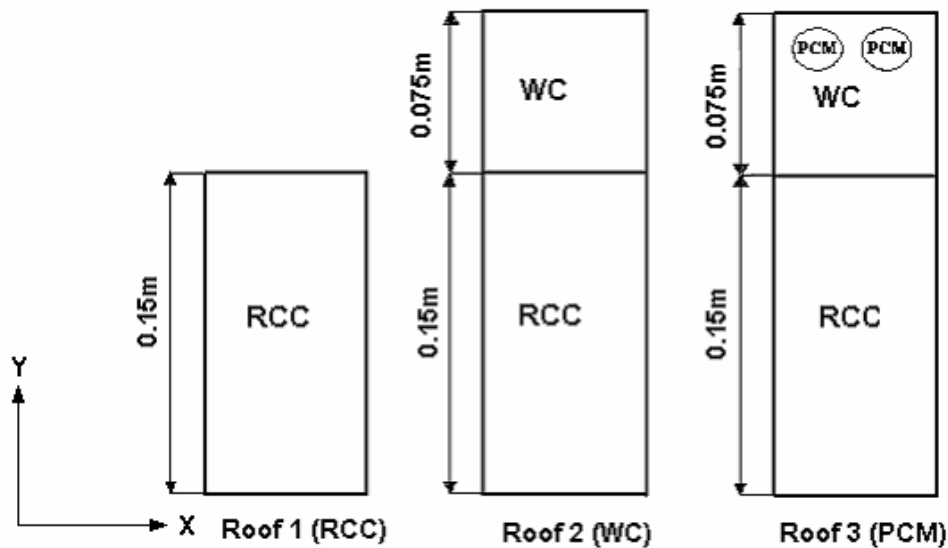

Figure 3: Roof Structures

Grid refinement was carried out and the numbers of elements used were 5000. The roof was maintained at uniform temperature of 25ºC to start the solution for the transient thermal analysis. The effect of this initial condition on the end results are avoided by repeating the solution for several days till the temperature distributions at the end of two consecutive days are equal. About 5daysx 24hours was found to be sufficient for attaining the solution. The 5th day results are presented and discussed.
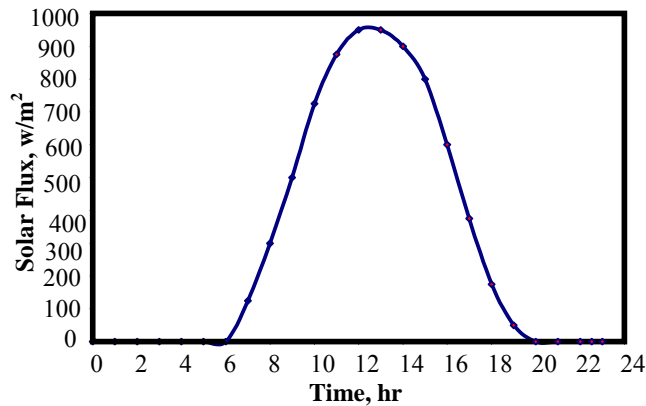
RESULTS AND DISCUSSION

Figure 4: Solar Flux

The thickness of all the three roof structures are different, so the distance is normalized (Y*=Y/Ymax) with Y=0, Y*=0 referring to the bottom of the roof and Y=Ymax and Y*=1.0 referring the top surface of the roof. The solar radiation data for Coimbatore during June 2006 was recorded as shown in the fig 4.

TEMPERATURE DISTRIBUTION ACROSS THE ROOF STRUCTURE

At τ =0 hr to τ =6 hr, there is no solar radiation on the building surface. But the heat accumulated in the middle structure travels on both the sides of the roof.

a) τ = 0 hr

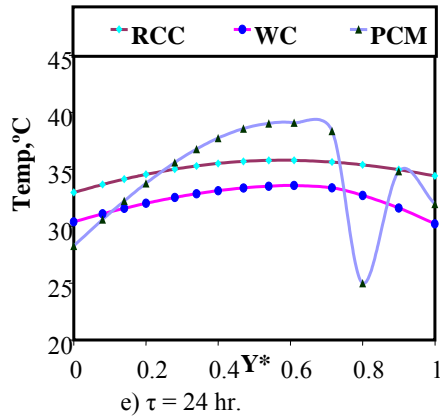b) τ = 6 hr

c) τ =12 hr

d) τ = 18 hr
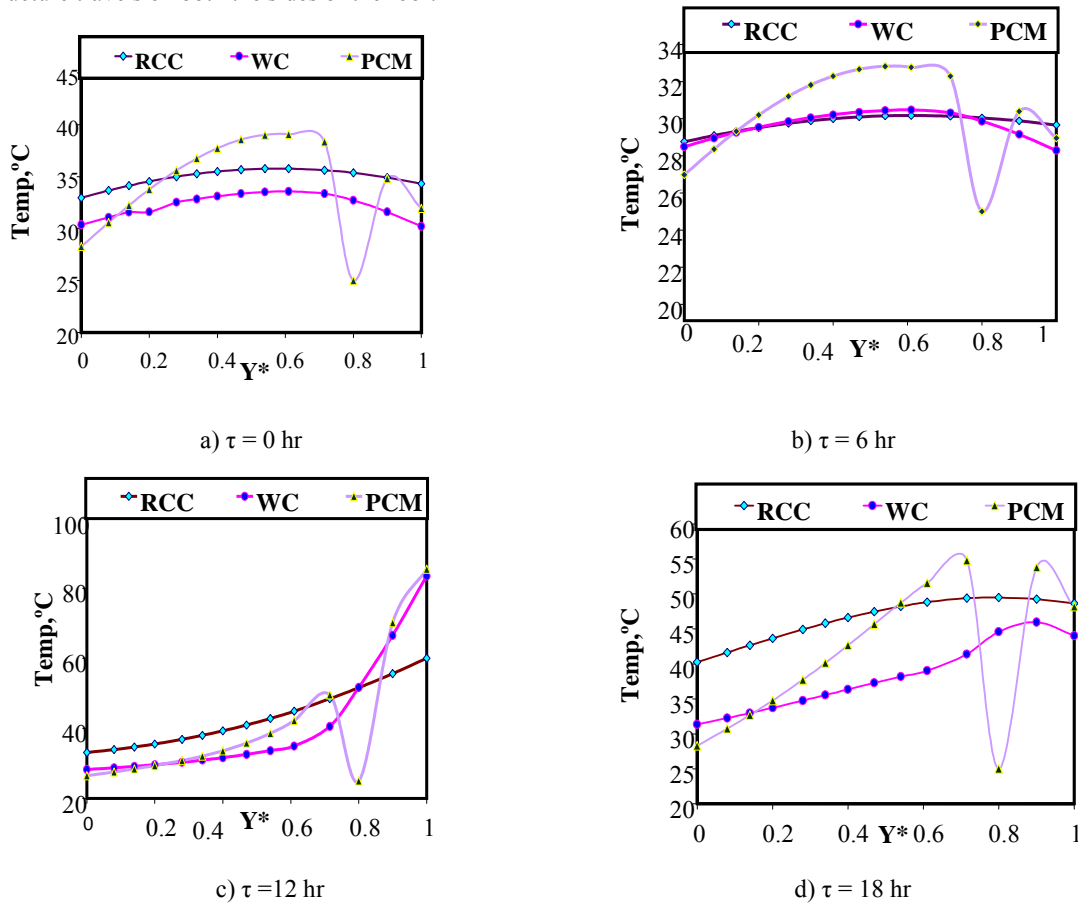
Figure 5(a-e): Temperature distribution across roof structure for various times of the day

The temperatures at the top and bottom surfaces are lower compared to the temperature inside the roof. The average temperature for the concrete structure is the highest among all the other types of roofs as the thermal conductivity of RCC is more compared to the WC, WC with PCM. As the thermal conductivity of RCC is higher, more heat will be stored during the previous day. The thermal conductivity of WC with PCM is lowest compared to WC and RCC. The curve for Roof 3 falls below the other curves because PCM absorbs maximum heat energy passing through that roof. It brings down the temperature to the room temperature, where the PCM is located.

At τ = 6hr to τ =12hr, as the solar radiation falling on the surface increases, the heat transfer characteristics varying from the previous time period. As the thermal conductivity of the RCC is highest, whatever the heat enters all the heat will be transferred to the bottom so the curve is linear and average. The curve for the Roof 2 is also similar to the Roof 1 curve but slightly falls below the Roof 1 curve at the bottom and peak at the top. The curve for the Roof 3 reaches the least value at the bottom and it reaches the peak value in the top layer.

At τ =12hr to τ =18hr, the solar radiation falling on the roof decreases but the heat that has already entered travels inside the roof. The mid plane temperature values are higher than the τ =12hr.As the heat flux during this τ =18hr is very small value, so the convection at the roof top dominates during this period. Compared to the Roof 1,Roof 3 has reduced the temperature at the bottom of the roof by 12º.

During τ =18hr to τ =24 hr, there is no solar radiation entering to the roof. So the temperature at the top and bottom of the roof is nearly at the same temperature. For the Roof 3, temperature reaches peak value at the middle and in the WC region where PCM is located temperature falls suddenly to room temperature as the PCM absorbs all the heat passing through the roof. And it reaches almost least value at the bottom as the PCM installed region acts as thermal energy storage.
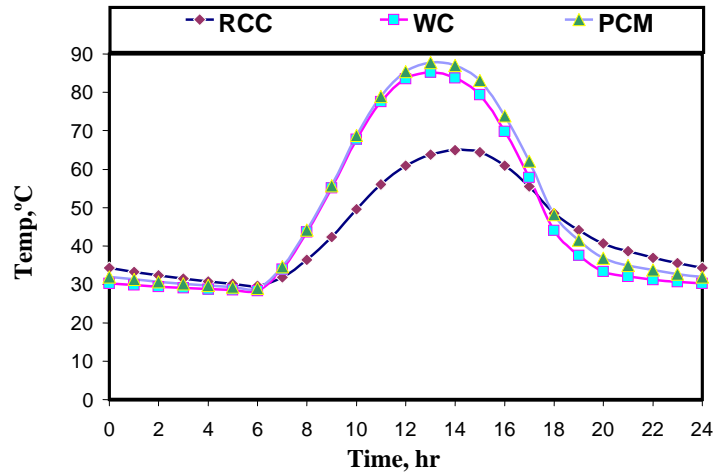
VARIATION OF ROOF TOP SURFACE TEMPERATURE

Figure 6: Roof top surface temperature

Fig.6. shows the variation of top surface temperature throughout the day. During $\tau = 0$hr to $\tau = 6$hr and $\tau = 18$hr to $\tau = 24$hr the top surface temperature reaches the low values. The temperature for the Roof 2 attains the lowest value and Roof 3 attains the highest value, because even though in the absence of solar radiation the PCM has stored heat energy during the previous day releases the energy to the top surface. During $\tau = 6$hr to $\tau = 18$hr the solar radiation initially increases and drops later, the top surface temperature for all the roofs increases initially and drops later. The least value is observed for the Roof 1 structure and highest value for the Roof 3 structure. This is because Roof 2 and Roof 3 structure offers more resistance for the heat flow than the Roof 1 structure makes the top surface temperature to go high for these two structures.

VARIATION OF ROOF BOTTOM SURFACE TEMPERATURE

The bottom surface temperature for three different roof structures are plotted for different time period during the day along with the room temperature (Tr). The net heat entering in to the room is mainly determined by the bottom surface temperature. In the case of Roof 1, it has good thermal conductivity, so the heat travels freely into the room and the room temperature is remarkably high value.
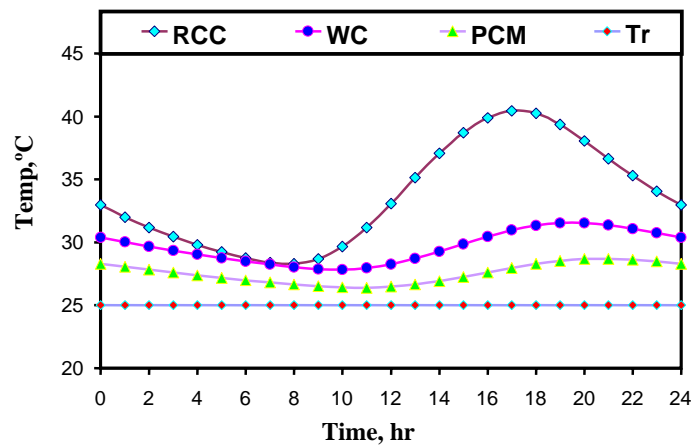

Figure 7: Roof bottom surface temperature

The Roof 2 structure offers some resistance so the bottom temperature drops significantly. For the Roof 3 structure, as the thermal conductivity of PCM is very low it offers high resistance for heat flow, so the bottom temperature is nearly maintained constant.

VARIATION AT THE MIDDLE OF THE STRUCTURE

In the Roof 1, the middle surface temperature goes on decreasing up to τ =7hr. As the solar radiation increases later the temperature starts increasing up to τ =16hr and then drops later.
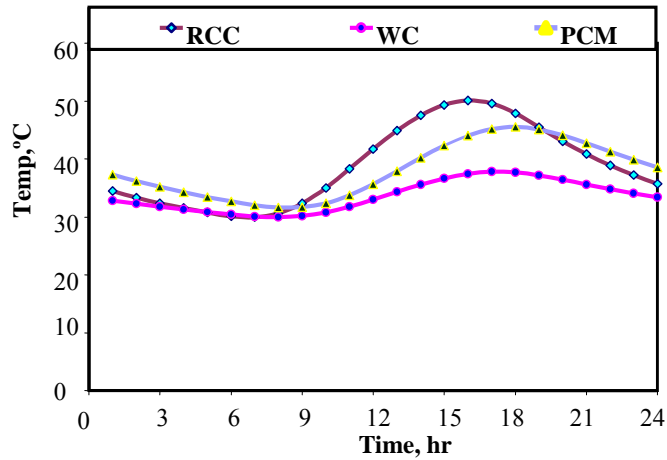

Figure 8: Middle surface temperature

For Roof 3 the surface temperature goes on decreasing up to τ = 9hr as these roofs offer some resistance to heat flow compared to the Roof 1.Up to τ =18hr, both the curves are linearly increases and then drops later.

HEAT FLUX ENTERING INTO THE ROOM

From the Fig.9 it clearly states that Roof 3 is better than the Roof 2 and Roof 1. If the roof is installed with PCM it can reduce the heat entering the room about more than two-third than the RCC laid roof. When compared with the Roof 1, the Roof 2 and Roof 3 reduces the heat transfer by 46.88% and 71.16%.As compared to Roof 2 with Roof 3, reduction in net heat transfer was found to be 45.71%. The reduction in heat transfer is directly proportional to the corresponding reduction in the electrical energy consumption for to maintain the room at 25ºC.
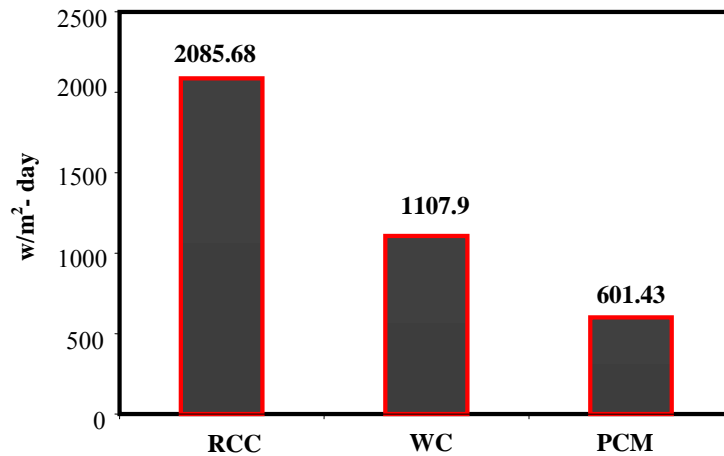

Figure 9: Heat Flux Entering the room

FOR WINTER CONDITION

The effect of temperature in the top and bottom surface of the roof was studied by using the solar radiation data for Coimbatore during December 2006.

VARIATION OF ROOF TOP SURFACE TEMPERATURE

Fig.10. shows the variation of top surface temperature throughout the day. Initially during $\tau = 0$hr to $\tau = 6$hr the temperature reaches the lowest values for all types of roof. During $\tau = 6$hr to $\tau = 18$hr the solar radiation increases and drops later, the top surface temperature for all the roofs increases initially and drops later.
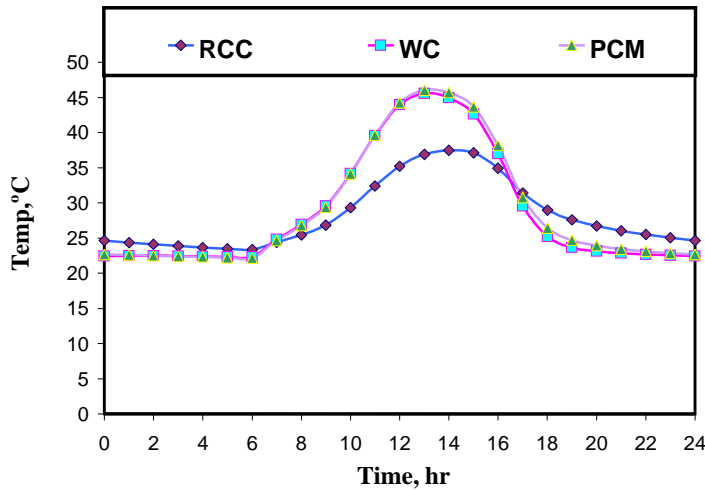

Figure 10: Roof top surface temperature

The least value is observed for the Roof 1 structure and highest value for the Roof 3 structure. This is because Roof 2 and Roof 3 structure offers more resistance for the heat flow than the Roof 1 structure makes the top surface temperature to go high for these two structures as like during summer conditions. The Peak temperature attained by the Roof 3 structure is 46ºC.

VARIATION OF ROOF BOTTOM SURFACE TEMPERATURE

Fig 11 shows the bottom surface temperature for three different roof structures plotted for different time period during the day. In the case of Roof 1, the temperature during $\tau = 0$hr to $\tau = 10$hr drops lower than the room temperature and reaches higher value later. The Roof 2 structure offers some resistance so the bottom temperature drops significantly compared to the Roof 1. For the Roof 3 structure, the temperature is always maintained closer to the room temperature.
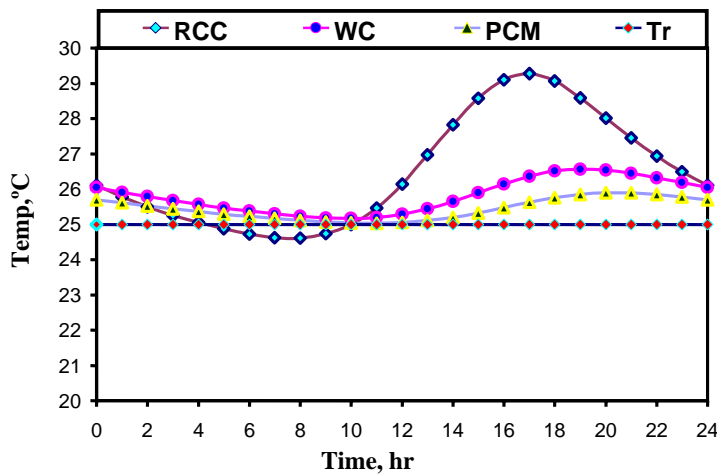

Figure 11: Roof bottom surface temperature

CONCLUSION

 Natural Cooling of building with phase change material was studied. The heat entering in to the room was maximum with RCC laid roof, because the thermal conductivity of RCC is high value. So almost all the heat entering the roof was transferred to the room. In Roof 2 and Roof 3 the heat entering the room was reduced by 46.88% and 71.16%.As the PCM is having low thermal conductivity, it offers the resistance for the heat flow and heat transfer was reduced by 45.71 compared to the Roof 3. With various combinations of PCM, the test can be repeated to find the best and effective material for cooling application. The effects of thermo physical properties of PCM, installation methodology, location of PCM are the scope for future work.

ACKNOWLEDGEMENT

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NOMENCLATURE

T_{sol} = Sol temperature (ºC)
T_{amb} = Ambient temperature (ºC)
α = absorption coefficient
q_s = heat flux in (w/m^2)
h_0 = room outside heat transfer coefficient (W/m^2.K)
h_i = room inside heat transfer coefficient (W/m^2.K)
A_r = cross sectional area of the room in (m^2)
T_R = room temperature (ºC)