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# TRANSIENT ANALYSIS OF HEAT TRANSFER ACROSS THE RESIDENTIAL BUILDING ROOF WITH PCM AND WOOD WOOL- A CASE STUDY BY NUMERICAL SIMULATION APPROACH

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In this paper, transient analysis on heat transfer across the residential building roof having various materials like wood wool, phase change material and weathering tile is performed by numerical simulation technique. 2-dimensional roof model is created, checked for grid independency and validated with the experimental results. Three different roof structures are included in this study namely roof with (i). Concrete and weathering tile, (ii). Concrete, phase change material and weathering tile and (iii). Concrete, phase change material, wood wool and weathering tile. Roof type 3 restricts 13% of heat entering the room in comparison with roof having only concrete and weathering tile. Also the effect of various roof layers' thickness in the roof type 3 is investigated and identified that the wood wool plays the major role in arresting the entry of heat in to the room. The average reduction of heat is about 10 % for an increase of a unit thickness of wood wool layer.

*Keywords*: Heat transfer, Residential building roof, Phase change material, Wood wool, Numerical simulation

## 1. Introduction

Nowadays people spent majority of their times inside the building and facing many health related symptoms due to high indoor temperature especially for the buildings without air conditioning system. This symptom rate will be higher for the occupants living in the hot region. However, the high symptom rate is mainly due to enormous amount of heat transferring through the roof structure. Vijayakumar et al [1] stated that the heat transmission across the building roof is about 50-70% of the total heat entry for the room below the exposed roof. Chou et al [2] also stated that heat gain through the roof due to solar radiation incident on the roof reaches to more than 1000 W/m$^2$ in clear sky condition and this radiation may be absorbed by 20 to 95%.

In this contest, many research works has been made to reduce the heat transmission across the roof that includes the roof with phase change material, reflective coating, green roofs and etc. Several promising developments were made in the application of PCM for heating and cooling of buildings. Pasupathy and Velraj [3] studied the effect

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of double layer phase change material in building roof, increases the thermal storage capacity of the building and enhances the human comfort by decreasing the frequency of internal air temperature swing. Alqallf and Alawdin [4] made a thermal analysis on a building concrete roof with cylindrical holes filled with PCM and reduce the heat flux at the indoor surface of the roof in the range of 9 % to 17%. Also for the conical holes, the heat flux is reduced up to 39 % (Alqallf and Alawdin [5]). Similarly, the roof with green vegetation is also playing a good role in reducing the heat gain. Olivieri et al [6] analyzed the thermal energy behavior of a green roof during the summer and stated that the incoming thermal gain is about 60% lower than for the roof having no vegetation. Dvorak and Volder [7] investigated the under surface and membrane level temperature of an un irrigated green roof and found that the un irrigated succulent based green roof can provide significant roof top temperature reduction during hot dry summer condition. Also the grassed roof produces a significant cooling effect through evaporative cooling when compared to different colored paint surfaces (Takebayashi [8]). Even though, some advanced cool colored materials have been available along with NIR reflective pigments to cool the roof. Synnefa et al [9] estimated the effect of cool coating on thermal comfort and stated that increasing the roof solar reflectance reduces the cooling load by 18-93% and the indoor thermal comfort is improved by decreasing the hour of discomfort by 9-100%. Harry Suehrcke et al [10] has stated that light color coating may help to reduce 30% total heat gain in the weather condition of Australia since the roofing may have much lower absorptivity.

Even though the above methods are more suitable in reducing the heat gain to the room, the cost incurred for the making such a roof should be considered. The initial cost associated for making the green roof is higher and it is difficult to maintain properly. It also requires stronger roof beam to support the various roof layers of the green roof. Also in the roof with roof coating, the detoriation of roof coating over the time is a major setback. The settlement of dust over the roof coating may completely spoils the performance of the roof coating (Vijayakumar et al [1]). With all these information present work proposes and analyzes a new type of roof to reduce the entry of heat gain in to the room with the aid of PCM material along with wood wool through numerical simulation technique. Numerical simulation technique is the most widely used method to simulate the heat transfer across the building (Zhang et al [12] David et al [13]), building indoor thermal comfort (Ravikumar et al [14, 15]) and also it is the cost effective tool.

## 2. Residential building roof- heat transfer analysis

The heat transfer due to solar radiation across the roof is analyzed by Numerical simulation technique. The 2 dimensional geometry of the roof is modeled in GAMBIT software. For all the analyzed cases the thickness of the concrete layer is taken as 15cm. Three different types of roof structures are included in this study. In the first type, the roof comprises only concrete and weathering tile in which the thickness of the weathering tile is taken as 6cm. In the second type, the phase change material is added in between the weathering tile and concrete layer for a thickness of 4cm by changing the weathering tile layer thickness to 2 cm. In the third type of roof structure, wood wool is included below the weathering tile and all the roof layers except concrete is taken as 2 cm. The schematic representation of the tree types of roof structures included in this study are shown in figure 1.

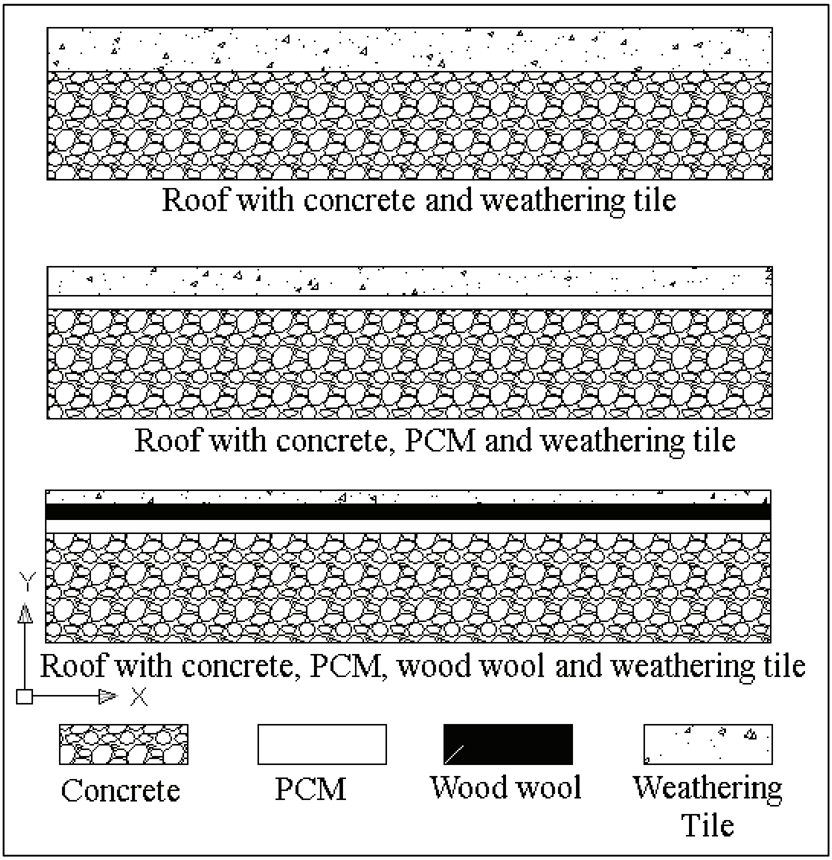


Fig. 1. Schematic representation of residential building roof with various layers

## 3. Numerical simulation methodology

In the numerical simulation of heat transfer across the roof, the required geometry of the roof structure is modeled in GAMBIT software.  The assumptions involved in this numerical simulation of heat transfer across the roof are given below:

(i) The heat conduction in the composite roof is one dimensional and the end effects are neglected.
(ii) The thermal conductivity of roof materials is considered as constant and not varying with respect to temperature.
(iii) The Phase change material is homogeneous and isotropic.
(iv) The convection effect in the molten PCM is neglected.
(v) The interfacial resistances are negligible.

For the above mentioned assumptions the governing equation for the heat transfer is given in Eq. (3.1).

$$k_m \frac{\partial^2 T_m}{\partial y^2} = \rho_m c_{p_m} \frac{\partial T_m}{\partial t} \qquad [0 < y < L]; m = 1,2,3 \dots . n \tag{3.1}$$

Where, k is the thermal conductivity of the material, T is the temperature, density, $\rho$ and $C_p$ is the specific heat.

The material properties for various roof constructing materials included in this investigation are given in table 1.

**Table 1**

Material properties of the roof constructing materials

| Roof material | Density Kg/m$^3$ | Thermal conductivity W/m.K | Specific heat J/Kg.K |
|---|---|---|---|
| Concrete | 2300 | 1.279 | 1130 |
| Weathering tile | 1300 | 0.25 | 1300 |
| Wood wool | 500 | 0.1 | 1000 |
| Phase change material | 1640 (Pasupathy et al [11]) | 1.09(0-27° C); 0.54(28-60°C) (Pasupathy et al [11]) | 1440(0-26.5°C); 125,000 (26.5-28°C); 1440 (28-60°C) (Pasupathy et al [11]) |

### 3.1. Boundary conditions and solution methodology

Roof Top: Solar radiation data for the month of May at Chennai are specified at the roof top. This solar radiation value is converted into $T_{solair}$ through the Eq. (3.2). The variation of solar radiation and the calculated $T_{solair}$ for the month of May at Chennai is shown in figure 2.

$$T_{solair} = T_a + (\alpha q / h_o) \tag{3.2}$$

Where $T_a$ is the ambient temperature, α , absorvity, $q$, solar radiation and $h_o$ convective heat transfer coefficient at the outer surface.

Roof bottom surface: Temperature is assumed constant as 298K with a convective heat transfer coefficient of $10W/m^2K$.

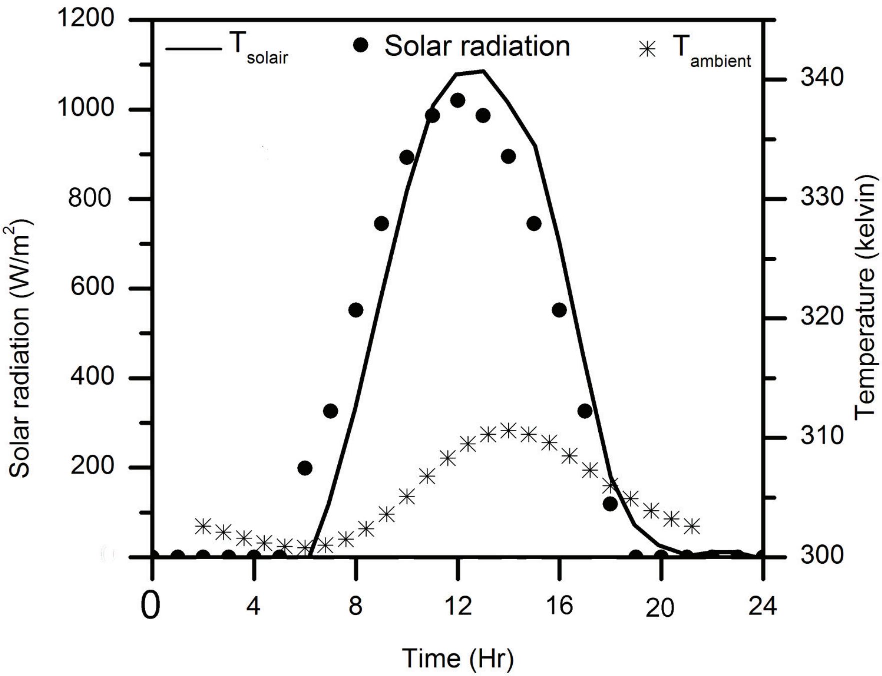


Fig. 2. Solar radiation and the calculated $T_{solair}$ temperature data for the month of May at Chennai

The roof domain is initially analyzed under steady state with double precision segregated solver. Later it is solved under transient state for one complete cycle of 24 hrs with second order implicit method. To avoid the effect of initial condition on the result, the solution has been marched in time repeatedly over the days till the temperature distribution at the end of the two consecutive days will be same. All the cases are iterated up to the convergence level of $10^{-6}$. The above numerical simulation is validated with the experimental predictions made by Pasupathy et al [11]. In this validation, the same roof model made by Pasupathy et al [11] is modeled in GAMBIT software and the same boundary conditions are applied. The numerically simulated temperature at the bottom of the roof surface is compared with the experimental predictions (Pasupathy et al [11]) and is shown in figure 3. This figure 3 infers that the numerical simulation of thermal behavior across the roof is having a good agreement with experimental results.

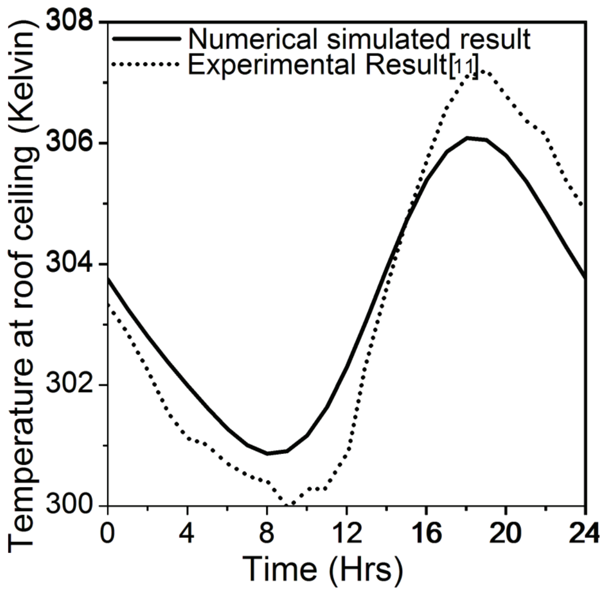


Fig. 3. Validation of Numerical simulation of heat transfer across Roof with Experimental results (Pasupathy et al [11])

## 4. Thermal behavior of roof structures

The thermal behavior for the three types of roof structures are analyzed for one complete 24 hours and their corresponding temperature plots at the time of 14hr is shown in figure 4. At time =14hr, the average temperature at the bottom of the roof is predicted as 301.32K, 301.9 K and 300.8 K for the three roof structures respectively. This shows that the second type structure stores enormous amount of heat that causes the ceiling temperature to get increase in comparison with the first type. Hence additional layer wood wool is provided below the weathering tile that reduces the ceiling temperature to a value of 300.8K. Also it is well identified that for the roof type 3, the temperature below the wood wool layer is comparatively lower than the rest of the roof structures.

In the figure 5, the variation of temperature across the roof is plotted for the time 6, 10, 12, 14, 18 and 24 hrs. At the time of 10 hr, the temperature lowers drastically and linearly from y=0.21 to 0.15m for the roof type 1. The weathering tile reduces the temperature from 325K to 305K. For the roof type 2, the temperature is reduced from 322K to 312K by weathering tile and PCM layer reduces the temperature from 312K to 305K. For the roof type 3, weathering tile reduces the temperature from 325K to 320 K, wood wool reduces from 320 to 305K and PCM reduces the temperature from 305K to 303K. By using the wood wool layer, the top face of the PCM layer is exposed

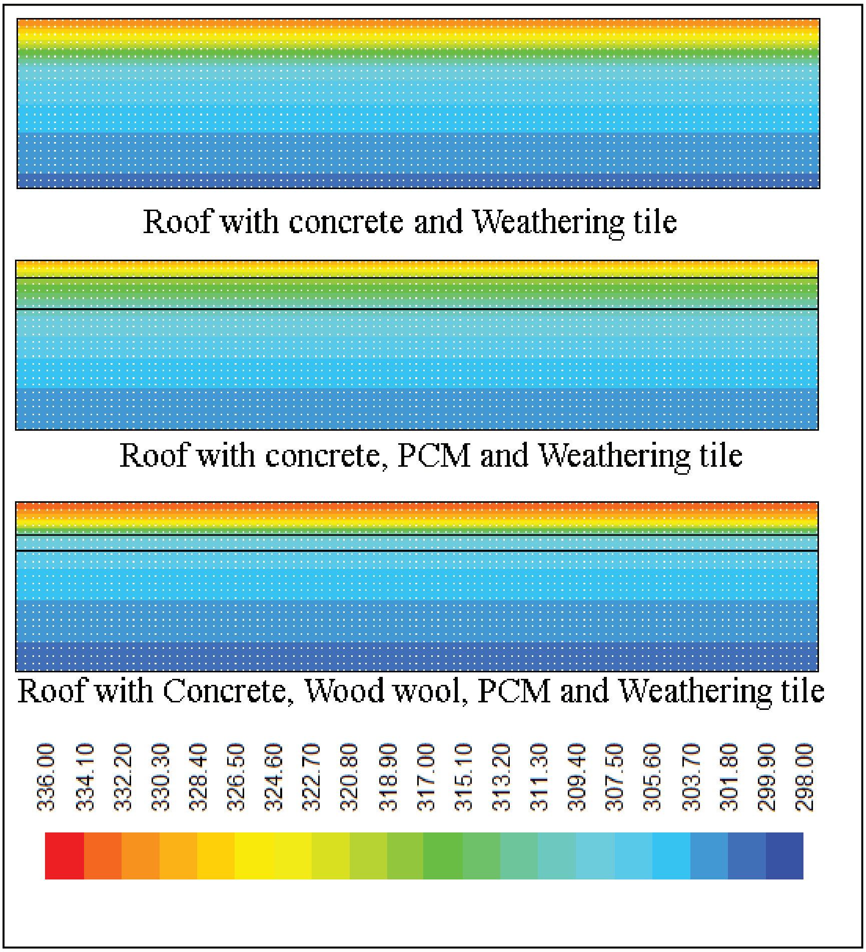


Fig. 4. Temperature plots across the roof at time =14 hr

to a temperature of 305K where as the roof without wood wool causes the top face of the PCM to expose with a temperature of 312K. This 7°C variation causes the PCM to accumulate more amount of heat energy.

At time of 12 and 14 hr, the temperature variation follows a similar trend. In the roof type 1, the weathering tile reduces the temperature from 332K to 310K. However, in roof type 2, the weathering tile reduces the temperature from 328K to 320K and PCM layer reduces the temperature from 320K to 310K. For the roof type 3, the weathering tile reduces the temperature from 335K to 327K, wood wool reduces the temperature to 310K and the PCM layer further reduces the temperature to 305K. For the time of 18hr, the temperature gradually reduces from Y= 0.21m to 0m for the roof type 1 and 2, whereas for the roof type 3, the reduction in temperature is identified as piecewise linear. The temperature along the weathering tile is almost constant, followed by a drastic reduction across the wood wool and gradually falls along the PCM and concrete. However for the time of 6 and 24hr the variation in temperature across the roof is not appreciable and almost constant about 302K. From this figure it is very clear that the roof with PCM layer along with weathering tile increases the ceiling temperature and hence an insulator like wood wool is required to reduce the ceiling temperature.

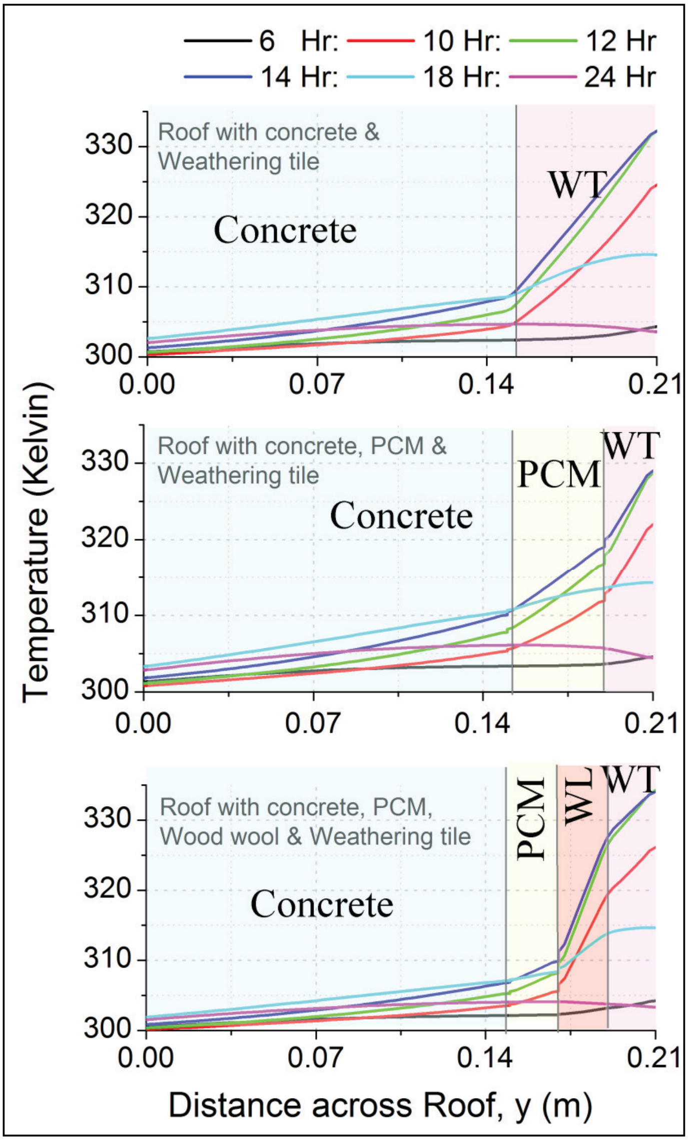


Fig. 5. Variation of temperature across the roof at time = 6, 10, 12, 14, 18 & 24 hr

The figure 6 shows the variation in temperature and heat at the roof bottom (Ceiling) for the three types of roof structure for one complete 24 hrs.

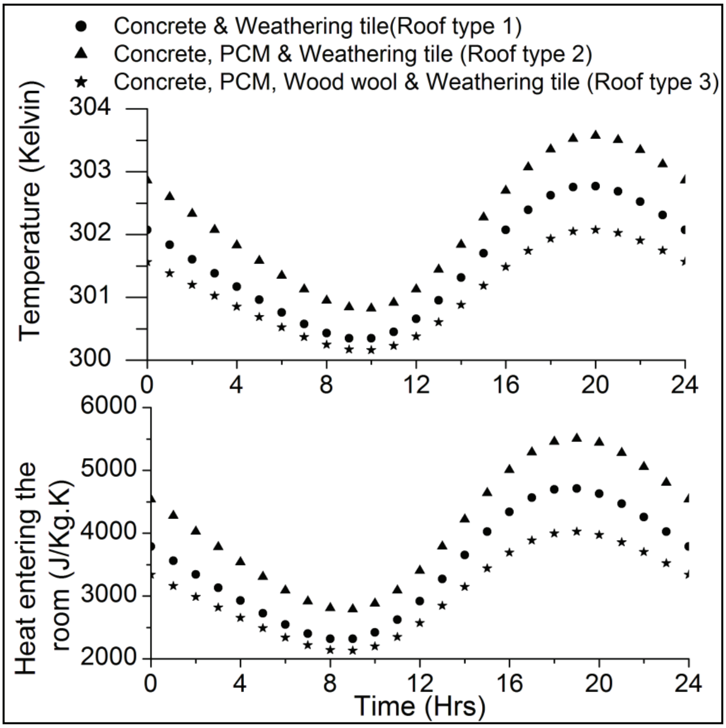


Fig. 6. Variation of temperature and heat at the roof bottom for one complete 24 hrs

The temperature and heat at the roof ceiling decreases gradually from time =0hr to 10hr and rises gradually up to time =20hr and again falls down to the time of 24hr for all the type of roof structure. This figure clearly depicts that roof with PCM and weathering tile (roof type 2) shows comparatively high temperature at the ceiling for complete 24 hrs, whereas the roof with PCM, wood wool and weathering tile (type 3) reduces the average ceiling temperature by 1° C. Also for the roof type 3, the variation of temperature for one complete 24 hrs is noticed as 1.8° C, whereas for the roof type 2 it is 3°C. Similarly, the roof type 3 reduces the average heat that entering the room through the roof ceiling by 1300J/Kg.K in comparison with roof type 2.

In general, roof with PCM material absorbs more amount of heat energy during the day time and this heat energy is released during the night time to make uniform interior condition. However adding the PCM layer and reducing the thickness of weathering tile increases the heat entering the room and thereby causes a rise in ceiling temperature in comparison with the roof without PCM. Hence additional layer wood wool is laid between the weathering tile and PCM layer that reduces the temperature drastically.

## 5. Effect of roof layer thickness

In this section, the effect of increasing the thickness of roof layers such as PCM, wood wool and weathering tile on heat transfer across the roof is performed. The PCM layer thickness is varied as 2cm, 4cm, 6cm and 8cm by keeping the other roof layers wood wool and weathering tile as constant as 2cm. Similarly, the wood layer and weathering tile layer are varied by keeping other roof layer as constant. The temperature at the bottom of the roof (ceiling) for one complete 24 hrs is plotted for various thickness of roof layer in the figure 7.

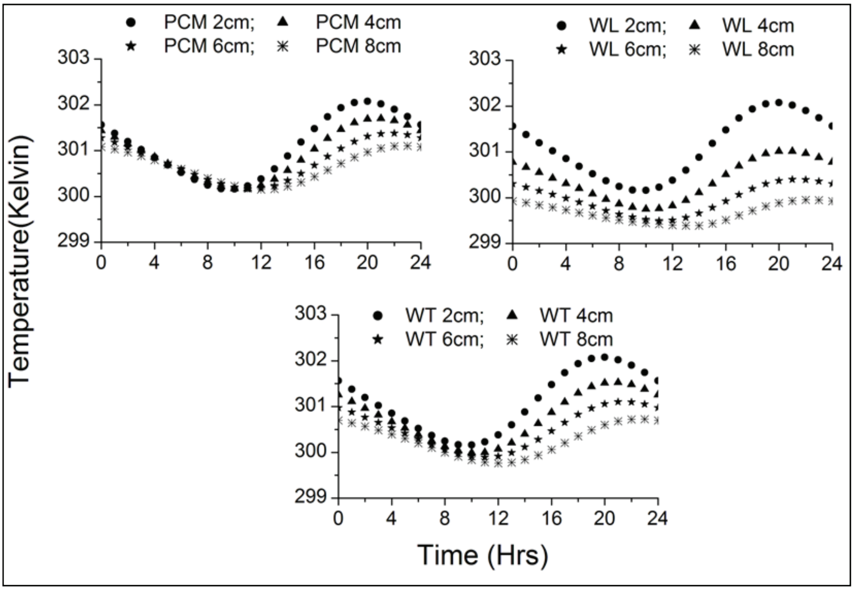


Fig. 7. Variation of ceiling temperature for various roof layer thickness for one complete 24 hrs

From this figure, while changing the PCM layer thickness the temperature is not having significant variation from time =0 hr to 11hr. However from the time of 11hr, the temperature at the roof bottom decreases by increasing the PCM layer thickness. For all the PCM layer thickness, the temperature rises from time =11 hr, attains a maximum value at time =20hr and after the time of 20 hr a marginal fall in temperature is noticed. For the PCM layer thickness of 2cm, the variation in temperature for one complete 24 hours is identified as 2°C. This variation in temperature is gradually reduced by increasing the PCM layer thickness and finally this temperature variation is noticed as 0.65°C for PCM =8 cm. In the next study of varying the wood wool layer thickness from 2cm to 8 cm with an increment of 2cm, the temperature variation is not same during the time between 0hr to 11hr as in the previous case. However the variation in temperature for one complete 24 hrs is decreasing by increasing the wood wool layer thickness. This variation in temperature is predicted as 1.3°c, 0.9°c and 0.55°c for the wood wool layer thickness of 4cm, 6cm and 8cm respectively. For the wood wool layer thickness of 2cm, 4cm, 6cm and 8 cm, the temperature gradually decreases from time =0hr to 10hr, 10.5hr, 11hr and 13 hr respectively. This shows that the wood wool layer of 8 cm extends the temperature fall during the day time by 3hrs and also this thickness reduces the average ceiling temperature by 1.6°C with reference to the wood wool layer thickness of 2cm. In the next case of varying the weathering tile thickness, the difference in temperature up to the time of 10hrs is not significant. Whereas, from the time of 10hr, a drastic reduction in temperature is identified through the rest of the

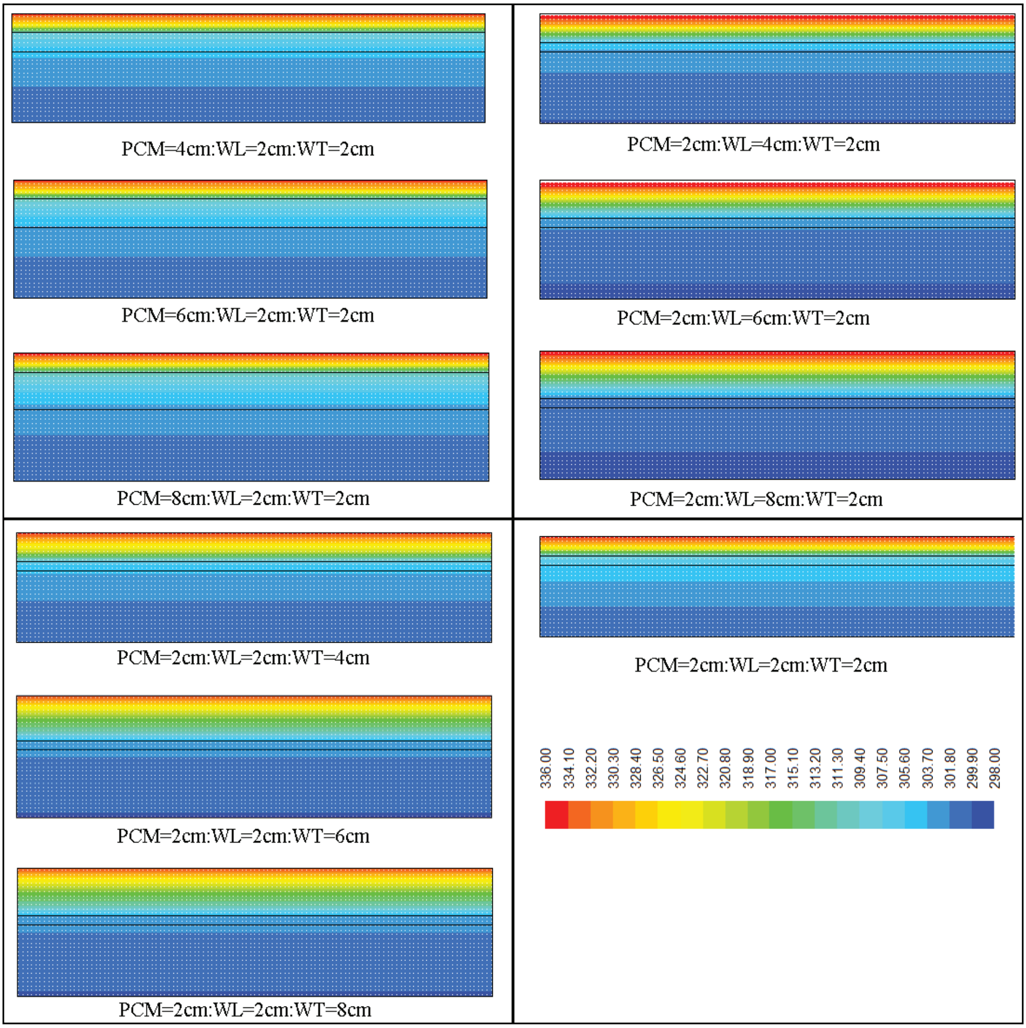


Fig. 8. Temperature plots across the roof various roof layer thickness at time = 14hr

time by increasing the weathering tile thickness. Also the temperature variation for one complete 24 hrs for the weathering tile thickness of 2, 4, 6 and 8cm are determined as 1.9, 1.5, 1.2 and 0.9°c respectively. The reduction in the variation of temperature by increasing the weathering tile thickness is not much appreciable in comparison with the change in wood wool layer thickness. This shows that the change in wood wool layer thickness make a drastic effect in reducing the temperature at the bottom of the roof for one complete 24 hrs in comparison with the change in PCM and weathering tile layer thickness.

The temperature plots in the range of 298K to 336K were plotted across the roof for various thicknesses of roof layers in figure 8. From this figure it is clearly evident that the roof with higher wood wool layer thickness shows comparatively low temperature at the bottom of the roof. This low temperature region extends to a high distance across the roof for the wood wool layer thickness of 8cm. Also for the weathering tile case of 6cm and 8cm a smaller portion nearer to the roof bottom experiences the low temperature.

The heat entering the room through the roof ceiling is shown for various thicknesses of roof layers in figure 9. By varying the PCM thickness the heat at the roof ceiling is similar up to the time =10hr from 0 hr. However, the ceiling heat for the PCM layer thickness of 8cm is higher between the times of 4hr to 10 hr and lower between the

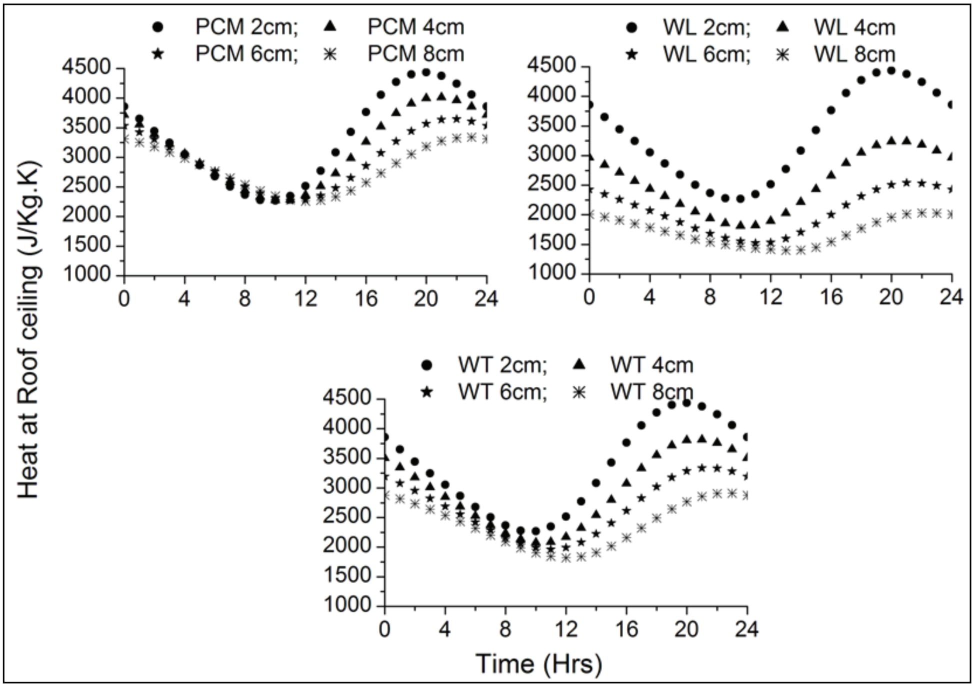


Fig. 9. Variation of Ceiling heat for various roof layer thicknesses for one complete 24 hrs

times of 0 to 4hr in comparison with the PCM thickness of 2cm. Also between the time 12 to 24hr the variation in ceiling heat is drastically reduced for PCM=8cm in comparison with other cases.

This shows that by increasing the PCM layer thickness the heat at the ceiling can be maintained at constant value and provides a uniform indoor comfort condition for one complete 24hrs. In the case of varying the thickness wood wool layer, a drastic variation in ceiling heat is noticed for a complete 24 hrs. For wood wool of 2cm thickness, the ceiling heat reduced from 4000J/Kg.K to 2500 J/Kg.K between the time 0hrs to 10hrs and increases up to 4250 J/Kg.K at time 20hr and from time =20hr a short fall in ceiling heat is noticed. However by increasing the wood wool layer thickness, a drastic reduction in ceiling heat is identified and for the wood wool layer thickness of 8cm, the heat at the ceiling is almost constant around 2000 J/Kg.K. By varying the thickness of weathering tile from 2cm to 8cm the reduction in ceiling heat is smaller between the times 0 to 10 hr in comparison with the time between 12 to 24 hr. This shows that increasing the thickness of weathering tile reduces the ceiling heat effectively between the time 12 to 24hr. From these figures it is well identified that increasing the wood wool layer reduces the ceiling heat drastically in comparison with other roof layers.

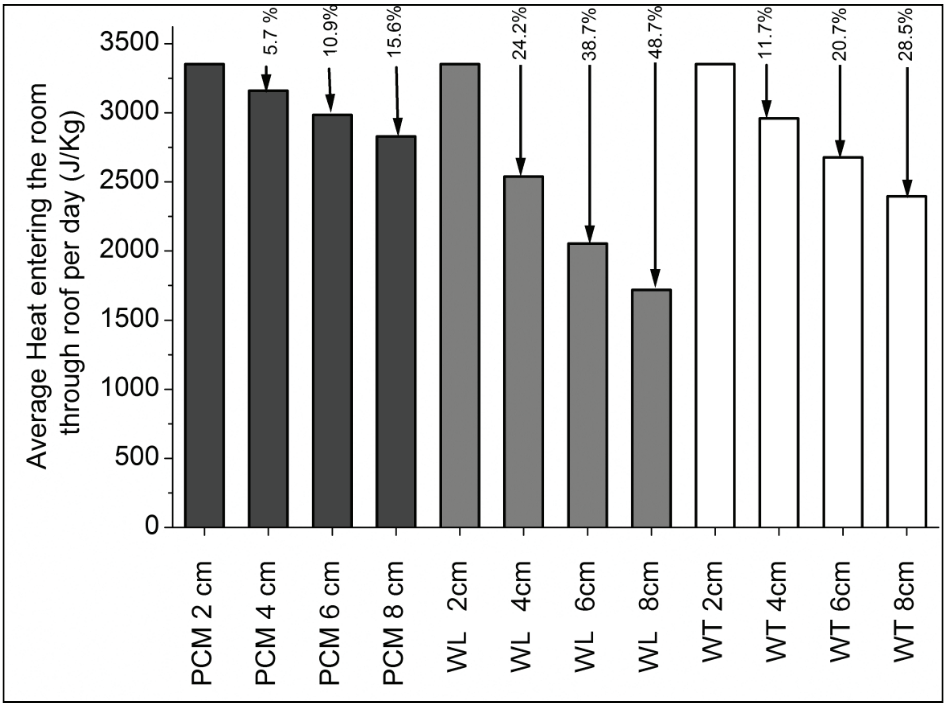


Fig. 10. Average heat entering the room for various roof layer thicknesses

This is also evident from the figure 10 which shows the average amount of heat entering the room through the ceiling for various roof layer thicknesses.

By increasing the PCM layer thickness as 4cm, 6 cm and 8 cm the reduction in heat entering the room is predicted as 5.7%, 10.9% and 15.6% with reference to the PCM layer thickness of 2cm. However this reduction in heat entering the room is drastic by increasing the wood wool layer thickness. By changing the wood wool layer thickness of 4cm, 6cm, 8cm the average heat entering the room is reduced by 24%, 38% and 48% with reference to the wood wool layer thickness of 2cm. Similarly, the weathering tile of thickness 4cm, 6cm and 8cm reduces heat by 11.7%, 20.7% and 28.5% with reference to the thickness of 2cm. It is clearly noticed that a unit increase in the wood wool layer thickness reduces the heat entering the room in a drastic quantity as 10% where as by increasing the PCM and weathering tile layer thickness the average reduction in heat is 2.8 and 5.3% respectively per unit thickness.

## 6. Conclusion

In this paper the conventional type of roof with concrete and weathering tile is modified by providing additional material namely phase change material and wood wool to reduce the heat entering the room. The heat transfer across the roof with (i). Concrete and weathering tile, (ii). Concrete, phase change material and weathering tile and (iii). Concrete, phase change material, wood wool and weathering tile are analyzed through numerical simulation technique under transient approach. The numerical simulation method is validated with the experimental result and found that it is having good agreement. The temperature, heat at the bottom of the roof and across the roof is predicted and the thermal behavior for the three types of roofs is discussed. Roof with phase change material, wood wool and weathering tile reduces the average heat that entering the room through the roof ceiling by 500 J/Kg.K and 1300J/Kg.K in comparison with roof type 1 and 2 respectively. Finally, the effect of increasing the thickness of various roof layers of the roof type 3 is studied. Among the varied roof layers, wood wool plays the major role in arresting the entry of heat in to the room and the average reduction of heat entering the room is about 10 % for an increase of a unit thickness where as by increasing the PCM and weathering tile layer thickness the average reduction of heat is predicted as 2.8 and 5.3% respectively per unit thickness.

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