Project Report

on

"Experimental and numerical investigation of cooling of building room using phase change material"

SRPG-PG GRANT

by

Mr. Achyutananda Swain
ISHRAE Membership No: S00106082

Faculty Guides

Dr. S. P. Kar (Membership No. 56615)

Dr. R K Sarangi (Membership No. 39133)

Dr. A Swain (Membership No. 56298)

SCHOOL OF MECHANICAL ENGINEERING
KALINGA INSTITUTE OF INDUSTRIAL TECHNOLOGY(D.U)
BHUBANESWAR, ODISHA

CONTENTS

COMPUTATIONAL MODEL

For the purposes of the current investigation, a commercial CFD package called ANSYS FLUENT v19.2 is employed for simulation. The next section discusses the discretization of the governing equations using the Finite Volume Method (FVM) and the enthalpy porosity technique for capturing the solid-liquid interface.

Discretization using Finite Volume Method (FVM):

The following equations are crucial for creating the numerical models:

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \tag{1}$$

Energy Equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho V H) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \tag{2}$$

Governing Equation:

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial x^2} - \rho L_f\frac{\partial g_L}{\partial t} \tag{3}$$

According to Patankar's description of FVM, the aforementioned equations are discretized.

Enthalpy -porosity approach:

This method is used to determine the enthalpy content of each control volume from its temperature readings. The latent heat value shifts from 0 to latent heat of fusion when a control volume begins to melt. The liquid fraction may be determined based on its latent heat value. Also, the melt fraction becomes 1 and the latent heat of fusion takes the place of the enthalpy content when the control volume melts entirely.

The governing equation (3.3) is written considering the enthalpy content

$$H = CT + \Delta H \tag{4}$$

$$\frac{\partial}{\partial t}[(\rho C)T] = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + S \tag{5}$$

$$S = -\frac{\partial}{\partial t}(\rho\Delta H) \tag{6}$$

The liquid fraction can be calculated as $g_L = \frac{\Delta H}{L}$. A control volume can be considered melt completely when, $\Delta H = L$ and solidified completely when $\Delta H = 0$.

The liquid fraction in the PCM layer is updated as

$$g_L^{n+1} = g_L^n + \frac{\lambda a_p \Delta t}{\rho_{PCM} L_{f_{PCM}} \Delta V_P}(T_P^n - T_m) \quad (7)$$

where λ1 is the under-relaxation factor.

Here it is to be noted that for the analysis of temperature field, the term $\rho L_f \frac{\partial g_L}{\partial t}$ becomes zero for the concrete slab whereas the liquid volume fraction g_L is updated in the PCM layer.

When g_L =1, a control volume is said to have melted entirely. As a result, it has the ability to capture the melting front in the domain implicitly at any moment. In the current simulation, the tolerance limit for [13] convergence of the iterative solution is set at

10^{-6}

Initial Condition:

$T(t = 0) = T_0$---(1)

Boundary Condition:

$k\frac{\partial T}{\partial y} = 0$ for both left and right wall--(2)

Top Wall:

$-k\frac{\partial T}{\partial y}_{topwall} = Q_r + h_{amb}(T - T_{amb})$ ---(3)

Bottom Wall:

$-k\frac{\partial T}{\partial y}_{bottomwall} = h_{room}(T - T_{room})$ --- (4)

DESCRIPTION OF THE MODEL:

A concrete domain with a dimension of 1 m long by 11 cm thick is depicted in Fig. 1. The arrangement of a single layer of PCM sandwiched between two concrete slabs is shown in Fig. 2. At various positions between two concrete slabs, a layer of PCM is introduced. In scenario A, the PCM layer is situated 6 cm above the bottom concrete domain. The PCM layer is present in cases B and C at a distance of 8 cm and 4 cm, respectively, above the lower concrete domain.

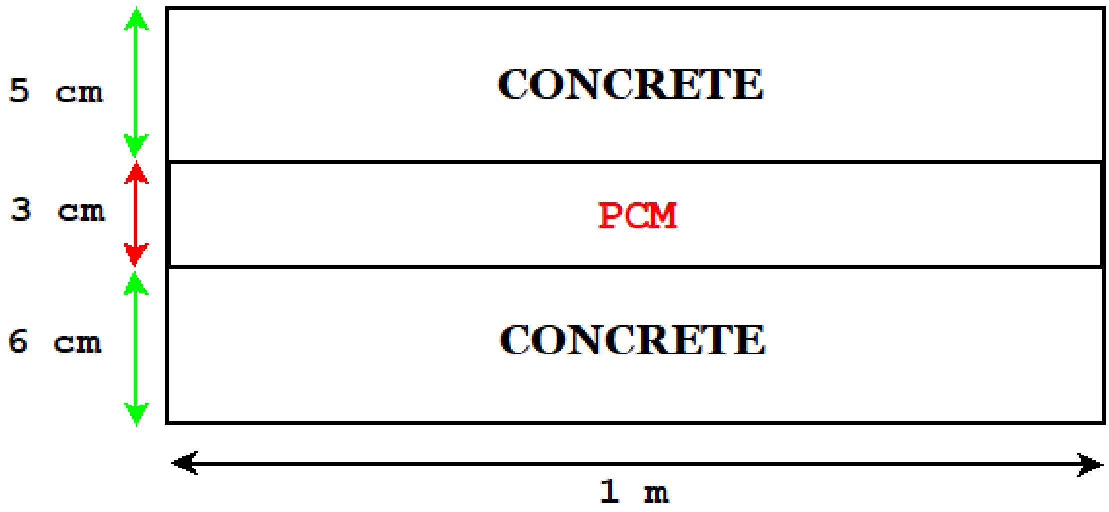


Figure 1: Concrete layers with single layer PCM (Model A)

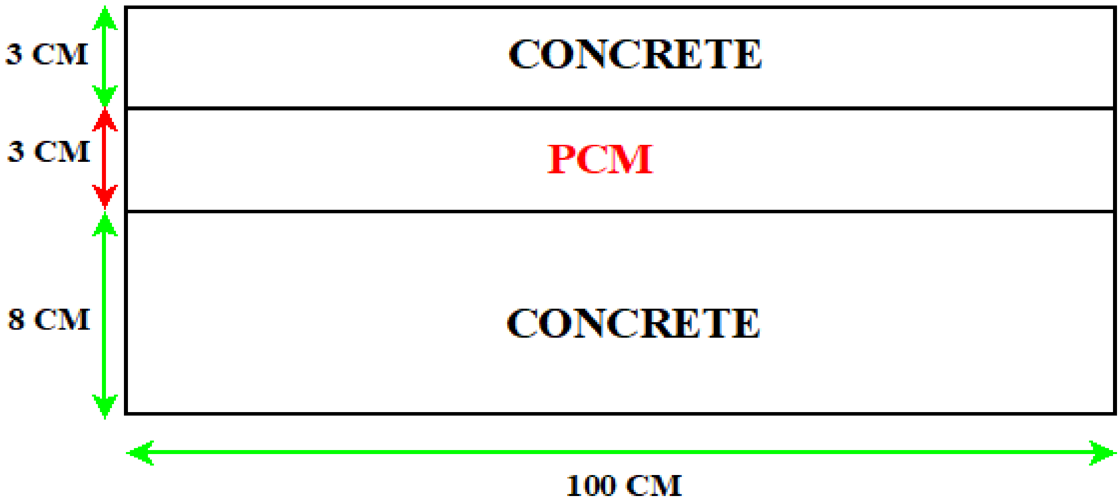


Figure.2: Concrete layers with single layer PCM (Model B)

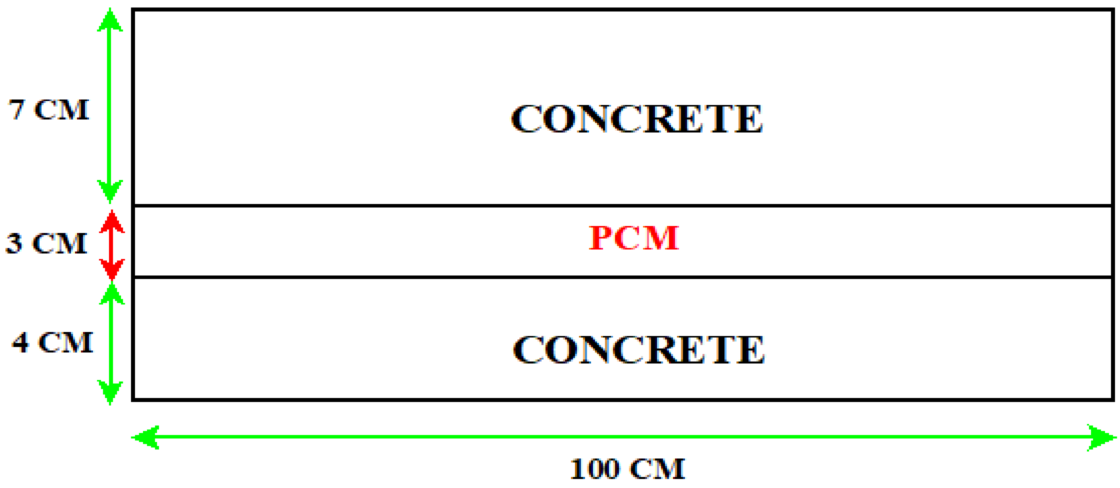


Figure 3: Concrete layers with single layer PCM (Model C)

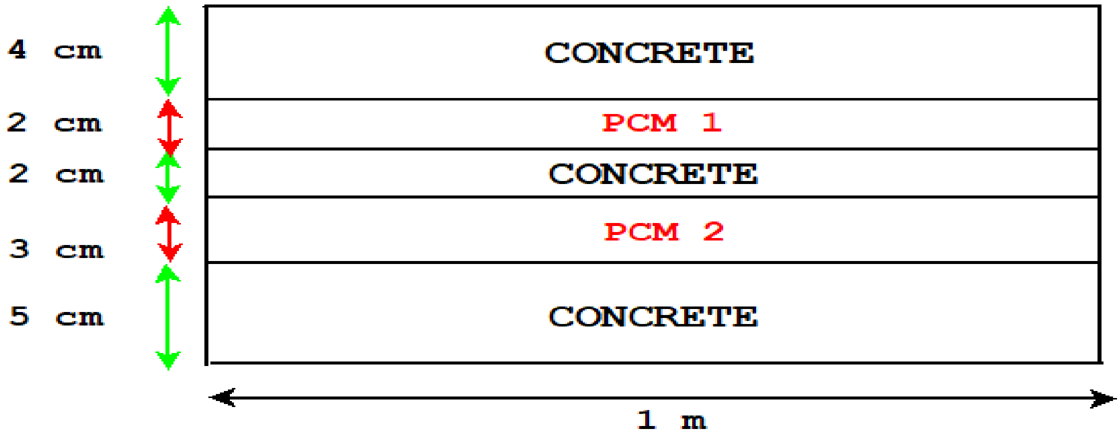


Figure 4: Concrete layers with double layer PCM

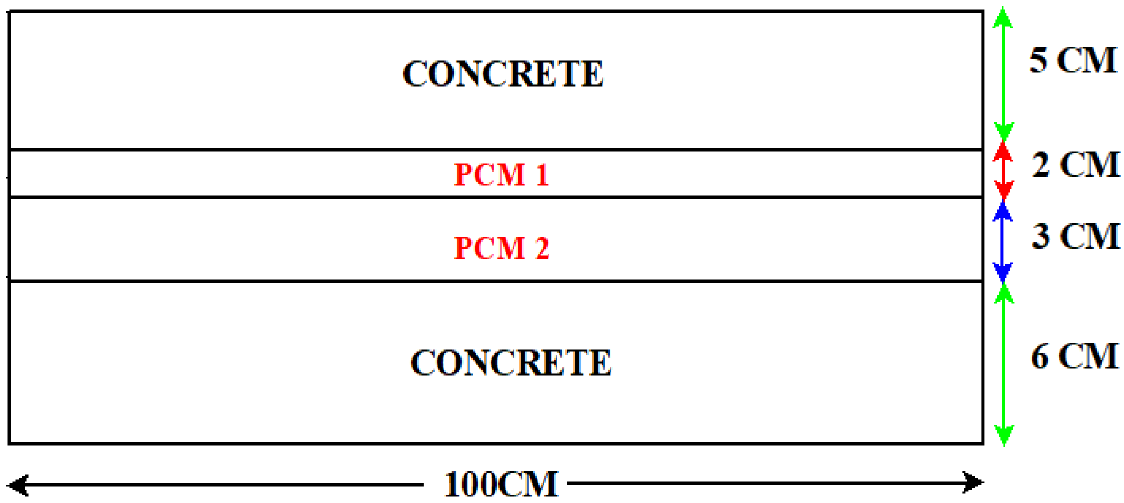


Figure 5: Concrete layers with double layer PCM

THERMOPHYSICAL PROPERTIES	CONCRETE	RT 28 HC	CLIMSEL C 32
Density (kg/m^3)	2500	880	1485
Melting temperature	920	28	32
Heat capacity(J/kg)	1.74	2000	3600
Latent heat of fusion (KJ/kg)	--	250	264000
Thermal conductivity (W/m k)	--	0.2	0.7

Table 1 : Thermo physical properties of materials

INITIAL CONDITIONS:

In the simulation of constant heat flux boundary conditions on the top roof and convective conditions on the ceiling, the temperature of both the concrete and PCM domains is kept at 25 °C, which defines the PCM as being in the solid phase. In the case of convective boundary conditions on both the top roof and ceiling, the initial temperature of the domain is taken as 27 °C.

BOUNDARY CONDITIONS:

There are various boundary conditions used to define the issue quantitatively;

Constant heat flux boundary condition on top of the Roof:

In this simulation, the roof top is subjected to a continuous heat flux of 350 W/m2, while the bottom of the roof is subjected to a convective boundary condition with a heat transfer coefficient of 1 W/m2K. The insulation is present on the left and right walls.

Convective boundary condition :

The convective heat loss is taken as boundary condition in the roof. Similarly, as the room ceiling is at higher temperature than inside of the room, there is convective loss from the room ceiling to the inside of the room. This is considered as the convective boundary condition at the room ceiling. The other two walls are considered as adiabatic.

Assumptions:

For this simulation, the following assumptions are made: - The thermo physical characteristics are constant. It is expected that densities, thermal capacities, and thermal conductivities remain constant and temperature-independent while being different in the liquid and solid phases.

- Left and right walls of the domain is considered to be adiabatic.

- Isothermal phase transition is present.

- The amount of liquid velocity-induced flow in the melted PCM is minimal.

- Only conduction heat transfer is considered through the domain.

MATHEMATICAL PROCEDURE:

ANSYS, a commercial CFD package, is used to execute the simulation. The evaluation of the PCM's melting properties is done using Fluent software. The mushy zone is defined as a porous material in the computational approach using the enthalpy porosity method. For the pressure-velocity coupling in this simulation, the SIMPLE algorithm is used. The selected values for the underrelaxation factors for pressure, density, momentum, liquid fractions, and energy are 0.3, 1, 0.5, 0.2, and 1 correspondingly. The convergence limit for the equation combining momentum and energy is set at an order of 10-6.

Overall Solution Procedure:

Following is a summary of all aspects of the solution process:

1. Equation discretizations are carried out.
2. Consider starting with a liquid fraction of '0' and an initial temperature of T_o.
3. Go to the next time step.
4. Compute all of the terms contained in the governing equation.
5. Obtain the temperature field solutions.
6. The liquid percentage is modified in accordance with the updated equation
7. Check for convergence.

   a) If the solution is found, then check if the required number of time steps has been reached. If yes, stop. If not, repeat (4) to (7).

b) If the solution is not converged, then repeat steps (5) to (7).

RESULTS AND DISCUSSIONS

COOLING OF BUILDING ROOM WITH SINGLE LAYER PCM

GRID INDEPENDENCE TEST:

A grid independency test, as seen in Figure 6, is conducted to support the optimal grid size. It displays the difference in temperature with PCM. Three different grid sizes with 1519 nodes, 4831 nodes,8231 nodes and 10847 nodes have been chosen for the analysis of the concrete layer with PCM. Timestep size of 10s is considered during this simulation.

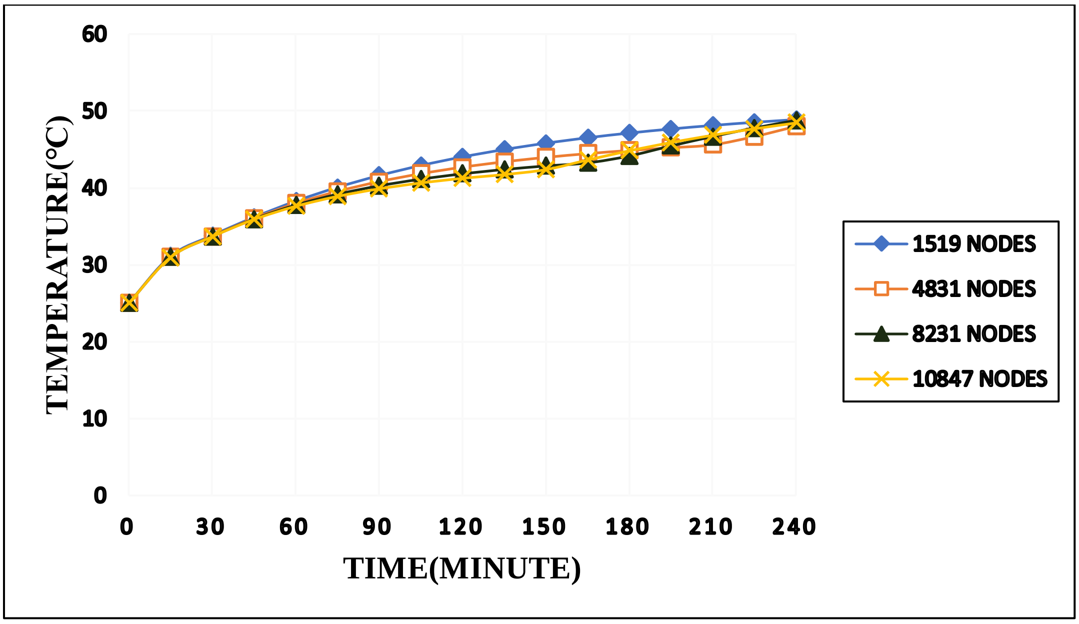


Fig.6. ROOF TEMPERATURE WITH SINGLE LAYER OF PCM

TIMESTEP INDEPENDENCE TEST:

The timestep independence test is carried out as depicted in Figure 7 using two distinct timestep sizes of 30s and 60s at a grid size with 8231nodes in order to get the optimal value of timestep size. For showing the other findings, a 10-second time step is selected.

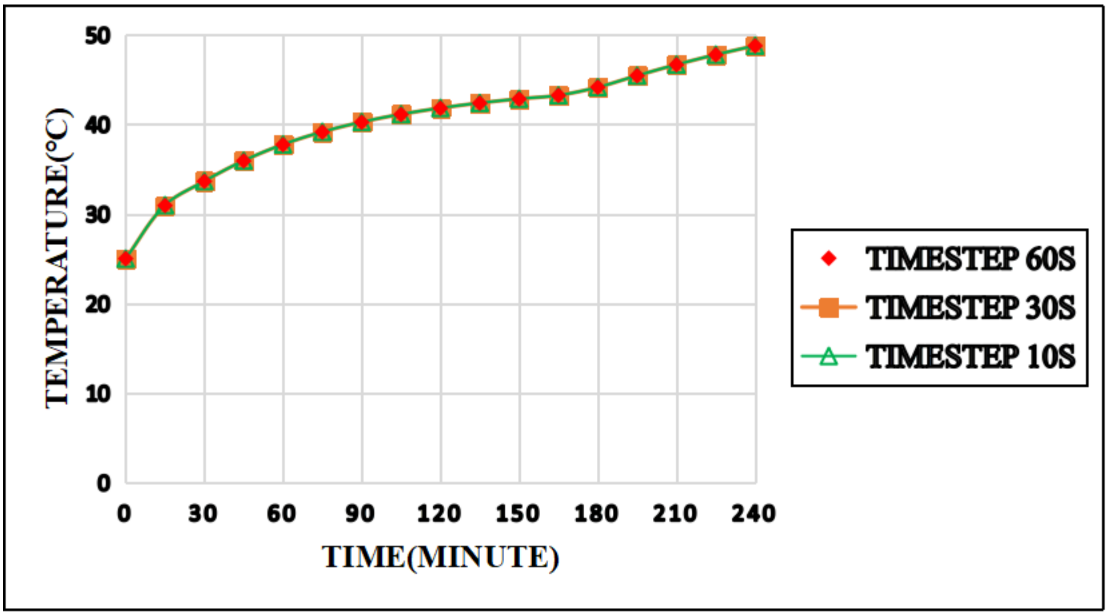


Fig.7. ROOF TEMPERATURE

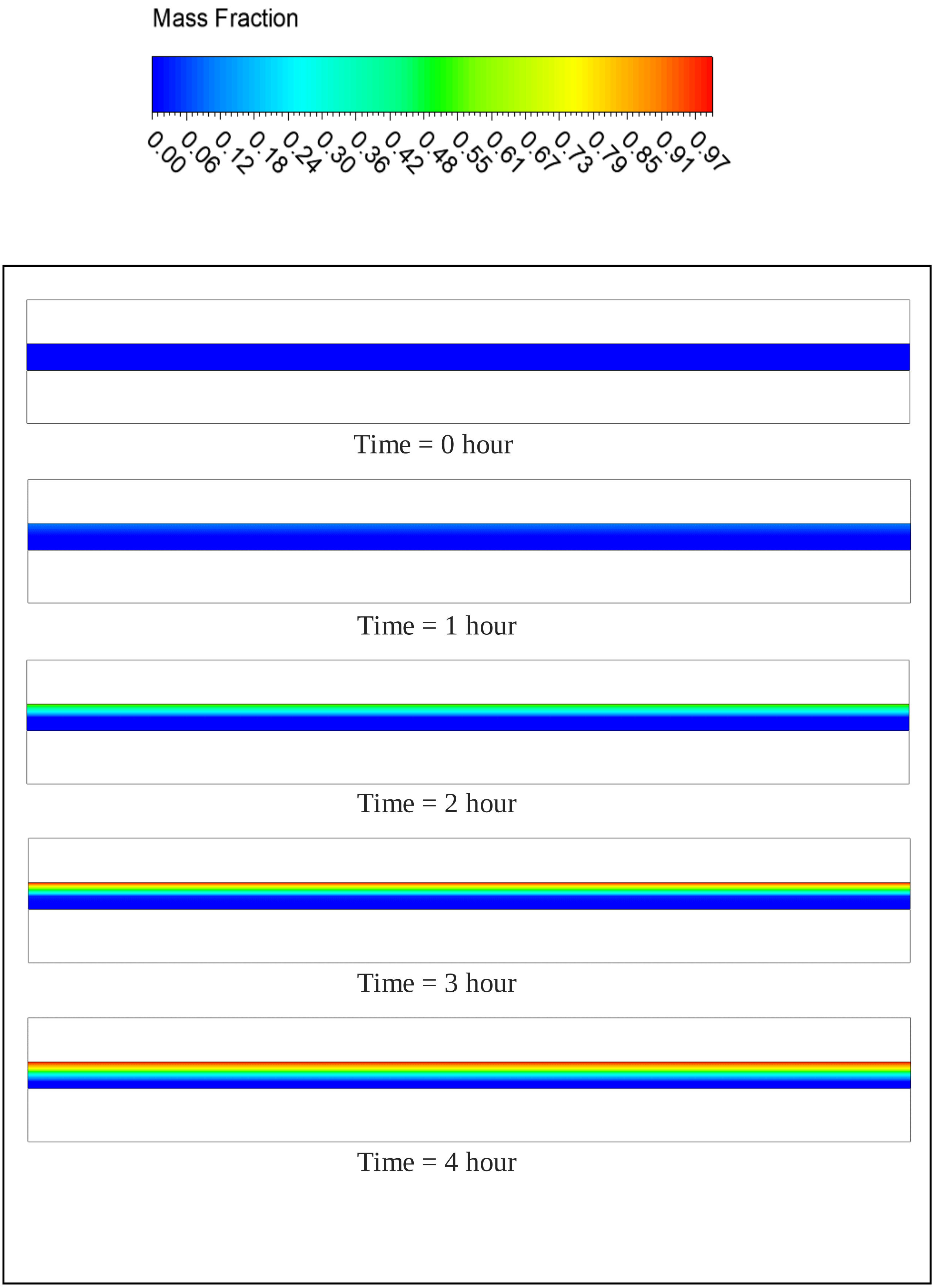
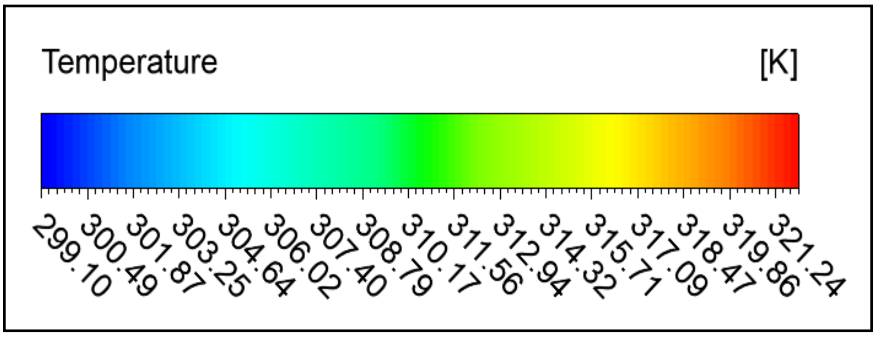
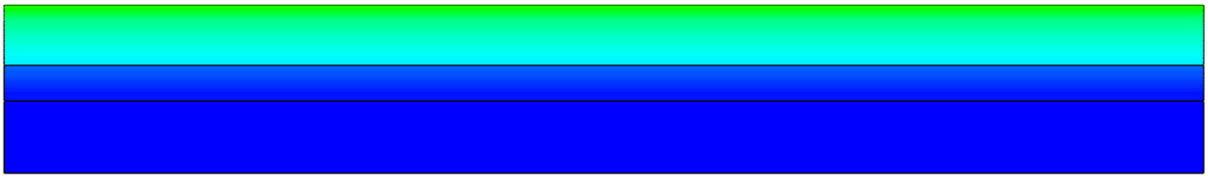


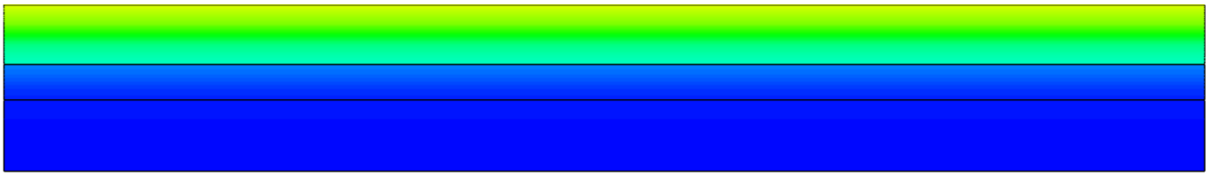
Fig.8. CONTOUR OF MELT FRACTION



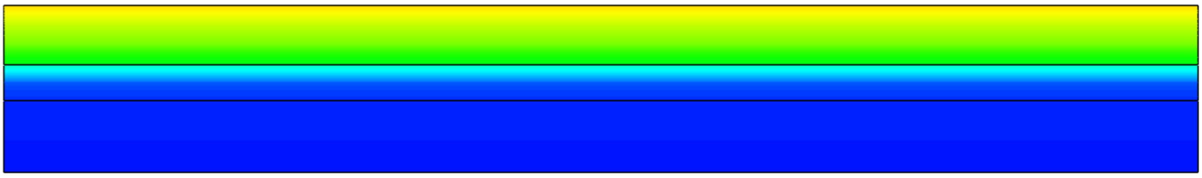
Time = 0 hour



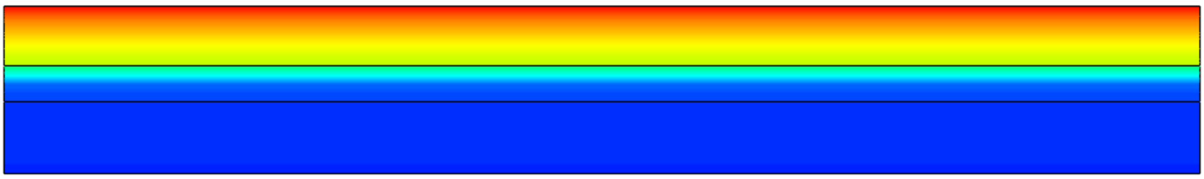
Time = 1 hour



Time = 2 hour



Time = 3 hour



Time = 4 hour

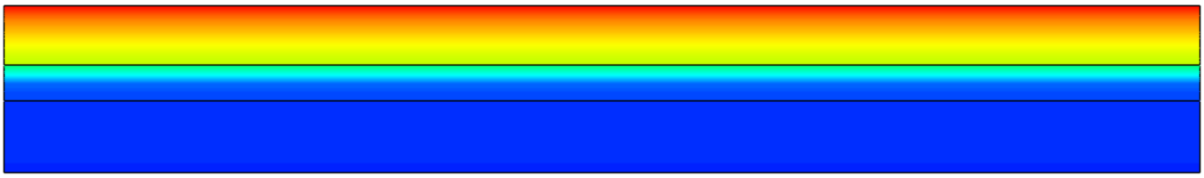


Fig.9. ROOF TEMPERATURE

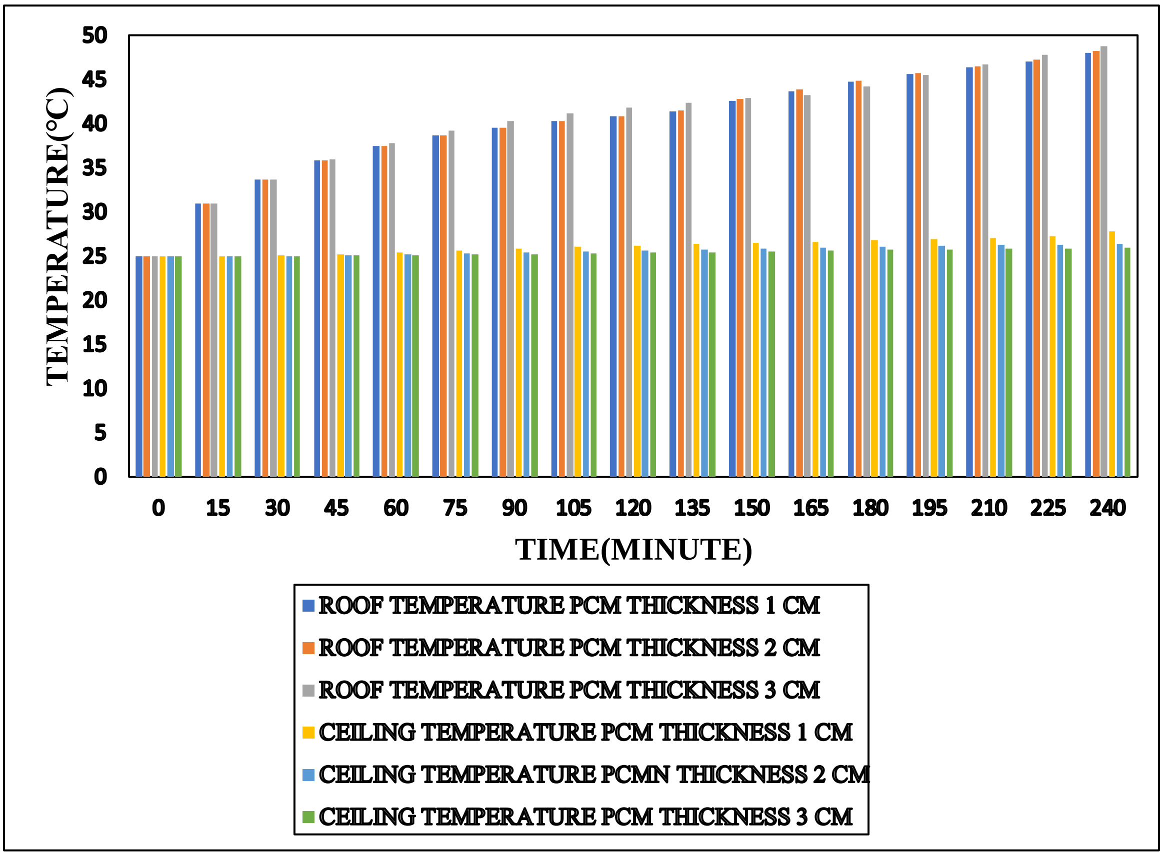


Fig.10. ROOF TEMPERATURE FOR DIFFERENT PCM THICKNESS

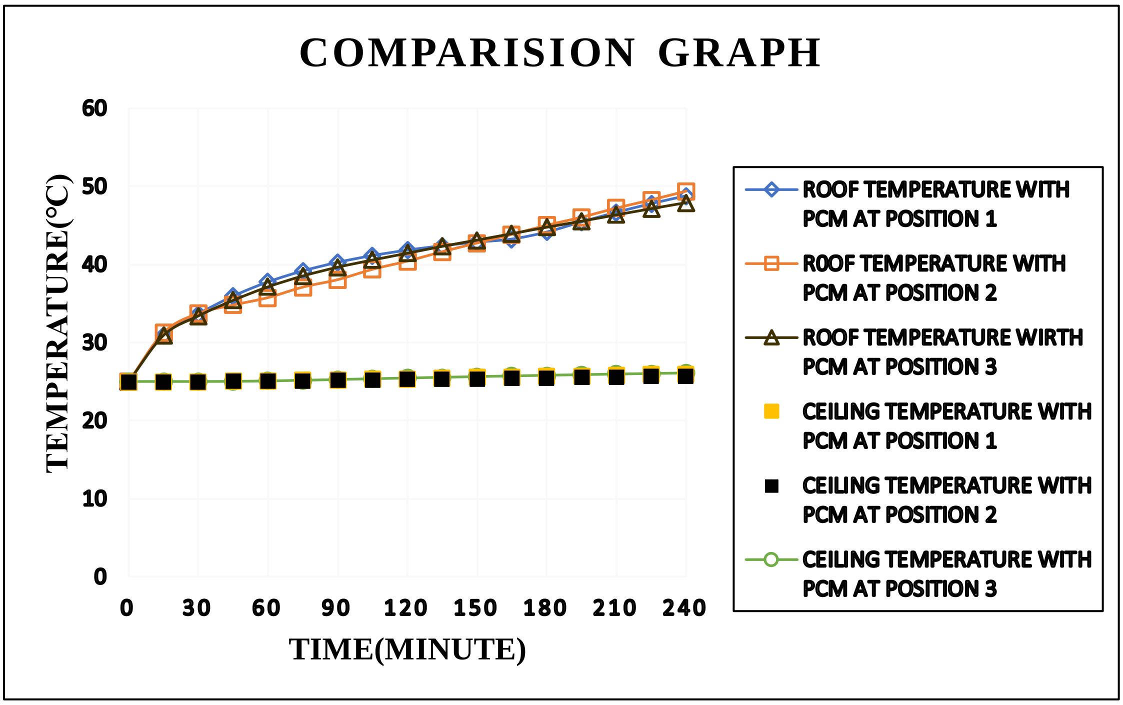


Fig.11. COMPARISON OF ROOF AND CEILING TEMPERATURE

Case-2

Convective boundary conditions are employed in this instance to simulate concrete with and without PCM at both the ceiling and the top of the roof. At the roof top, boundary conditions with a free stream temperature of 45^{0}C , a heat transfer coefficient of 5 W/m2K, and a heat generation rate of 790 W/m3 are taken. Another boundary condition with a heat transfer coefficient of 1 W/m2K and a 27°C free stream temperature is used at the ceiling for the numerical study. An initial temperature of 27°C is used to initialise the entire domain.

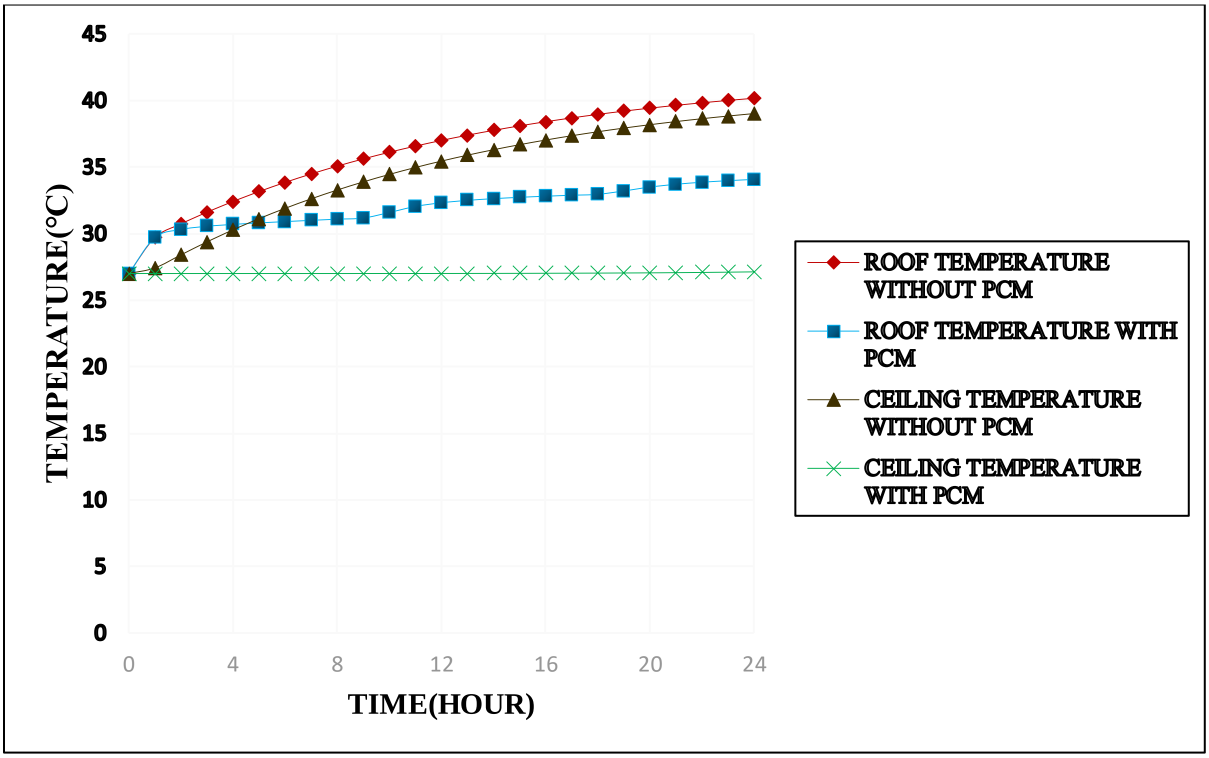


Fig.12. ROOF TEMPERATURE WITH AND WITHOUT PCM

COOLING OF BUILDING ROOM WITH DOUBLE LAYER PCM

Numerical simulation with constant heat flux boundary condition at roof and convective boundary condition at ceiling:

For cooling the building room, a double layer of PCM is implemented for investigation purposes. A double layer of PCMs having different thermophysical properties is incorporated between concrete layers at different orientations.

CASE-1

In the first case, one layer of PCM having a thickness of 3 cm is at a distance of 5 cm above the bottom concrete domain, and another layer of PCM having a thickness of 2 cm is at a distance of 4 cm below the top concrete domain. In between two PCM layers, a concrete domain with a thickness of 2cm is present. For simulating the model, a constant heat flux boundary condition is taken at the roof top, and a convective boundary condition is taken at the ceiling. In this particular scenario, Rt-28 is used as PCM 2 and Climsel C-32 as PCM 1. An identifiable outcome is shown when double-layer PCM is used.

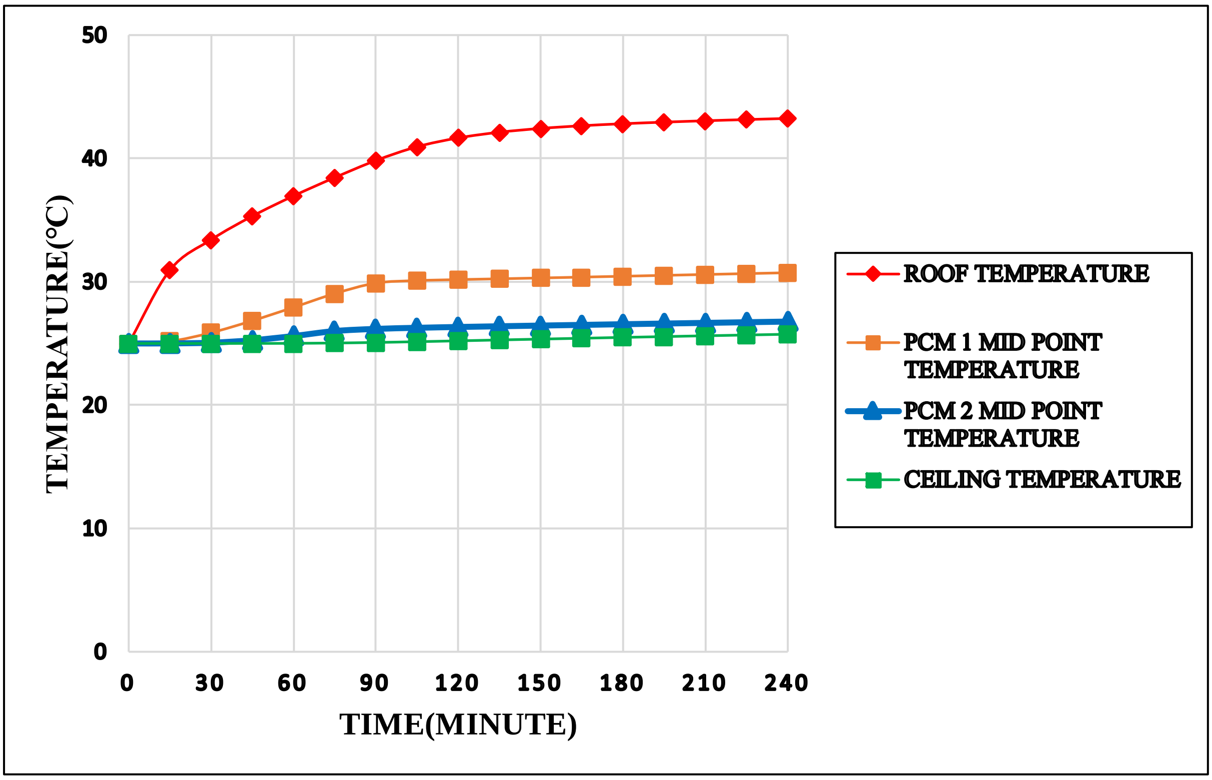


Figure 13: TEMPERATURE VARIATION WITH DOUBLE LAYER OF PCM

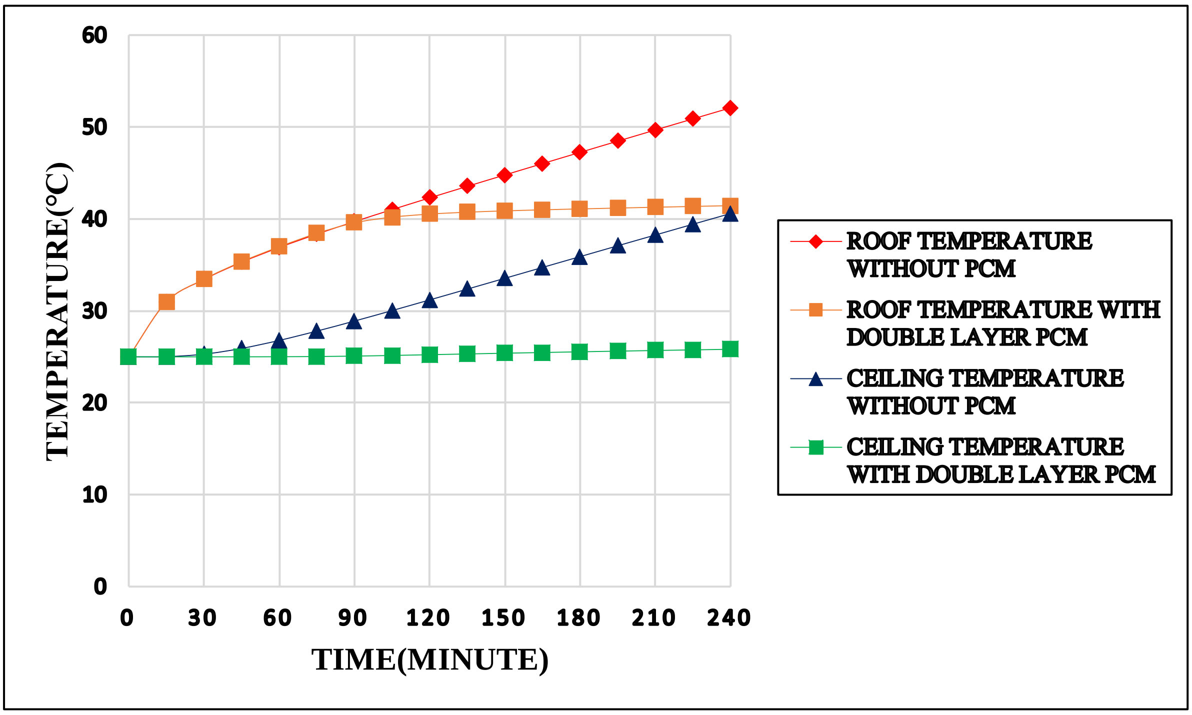


Figure 14: Temperature variation with double layer PCM and without PCM

Figure 13 shows the effect of double layer of PCM on the temperature. The roof temperature is found to be increasing and measures about 41^0C. In comparison to using a single layer of PCM, using two different layers lowers the temperature of the roof. Moreover the temperature of ceiling is maintained at 25^0C within the comfort limit. It is to be noted that the higher melting temperature PCM is kept in the upper layer and the lower melting temperature PCM is kept in the bottom layer. PCM of higher melting point in the top layer can sustain higher roof temperature absorbing the latent heat to convert into liquid form. The less amount of heat conducted through the bottom layer melts the low melting point PCM. Thus, a good balance of heat transfer is maintained between the PCM layers to control the ceiling temperature. It can be concluded here that the choice of PCM can be done to optimise the cost and also the more energy can be stored with proper selection of PCM.

A comparison of the temperature fluctuation over time for single layer and double layer PCM is shown in Figure 16 . It has been discovered that two layers of PCMs consisting of a variety of PCM inputs work best for controlling ceiling and roof temperatures.

GRID INDEPENDENCE TEST:

A grid independency test, as seen in Figure , is conducted to support the optimal grid size. It displays the difference in temperature between those with and without PCM. Four different grid sizes with 1873 nodes, 4231 nodes, 10689 nodes and 13257 nodes have been chosen for the analysis of the concrete layers with double layer of PCM. Time step size of 10s is considered during this simulation.

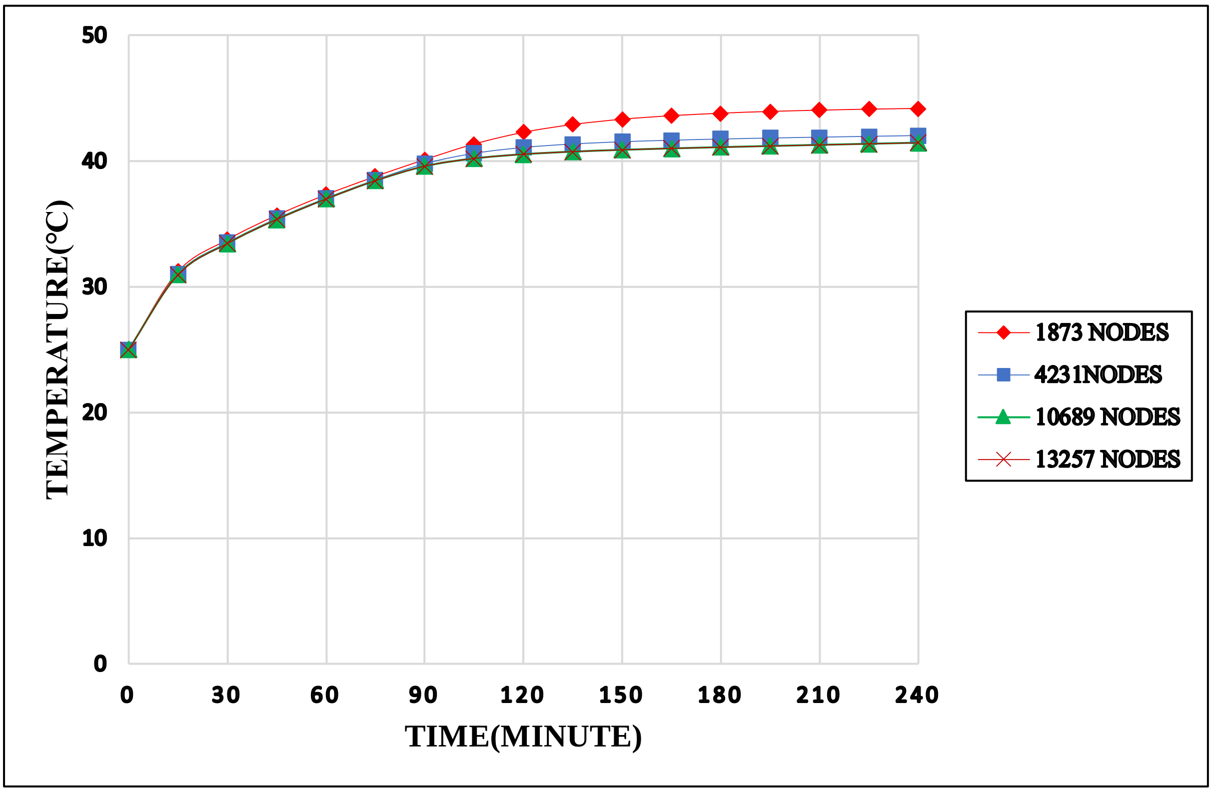


Figure 15: Roof temperature (Case 1)

TIMESTEP INDEPENDENCE TEST:

The timestep independence test is carried out as depicted in Figure using three distinct timestep sizes of 60s,30s and 10s at a grid size with 10689 nodes in order to get the optimal value of timestep size. For showing the other findings, a 10-second time step is selected.

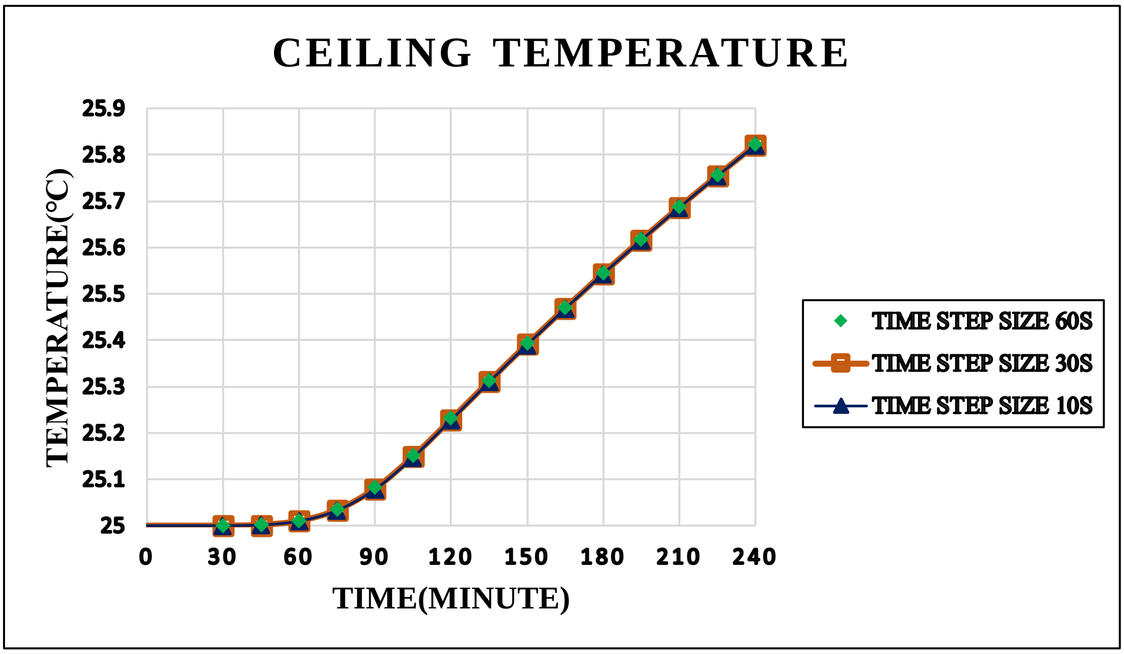


Figure 16: Ceiling temperature (Case 1)

CONTOURS OF MASS FRACTION AND TEMPERATURE:

Figure 17: Liquid fraction evolution of the PCM inside concrete from t= 0 hour to t = 4 hour

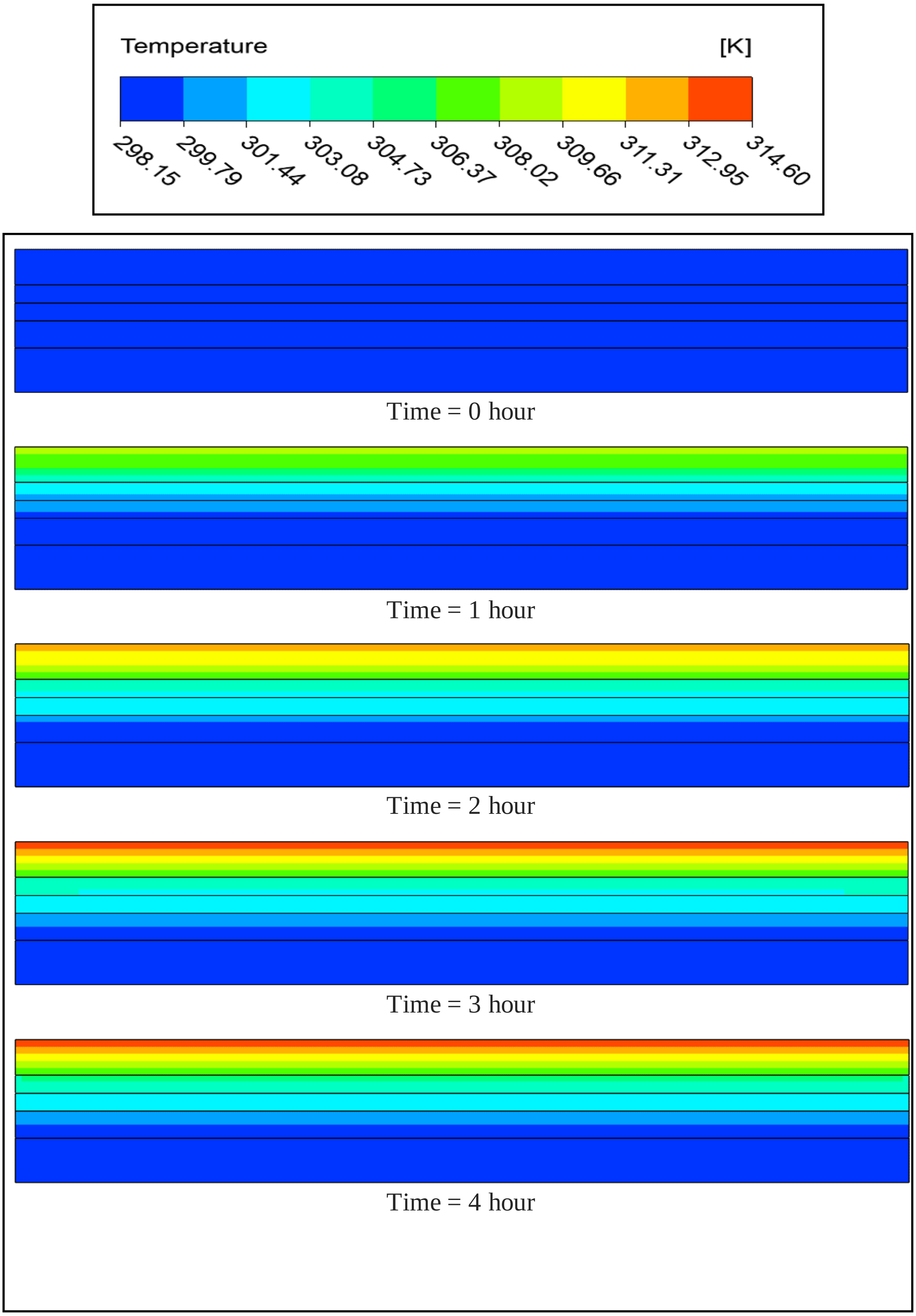


Figure 18: Temperature distribution inside the roof from t= 0 hour to t= 4 hour (Case 1)

CASE-2

In this situation, two adjacent layers of PCM are included between the concrete domain at a distance of 6 cm above the ceiling and 5 cm below the roof, each having differing thermophysical characteristics. A constant heat flux boundary condition is used at the top of the model for simulation, while a convective boundary condition is used at the ceiling. Rt-28 serves as PCM 1 in this scenario, and Climsel C-32 serves as PCM 2. When neighbouring double-layer PCM is employed, a recognisable result is displayed. In order to figure out the outcomes and ensure the impact of adjoining PCM layers, this model is also simulated over a period of 4 hours.

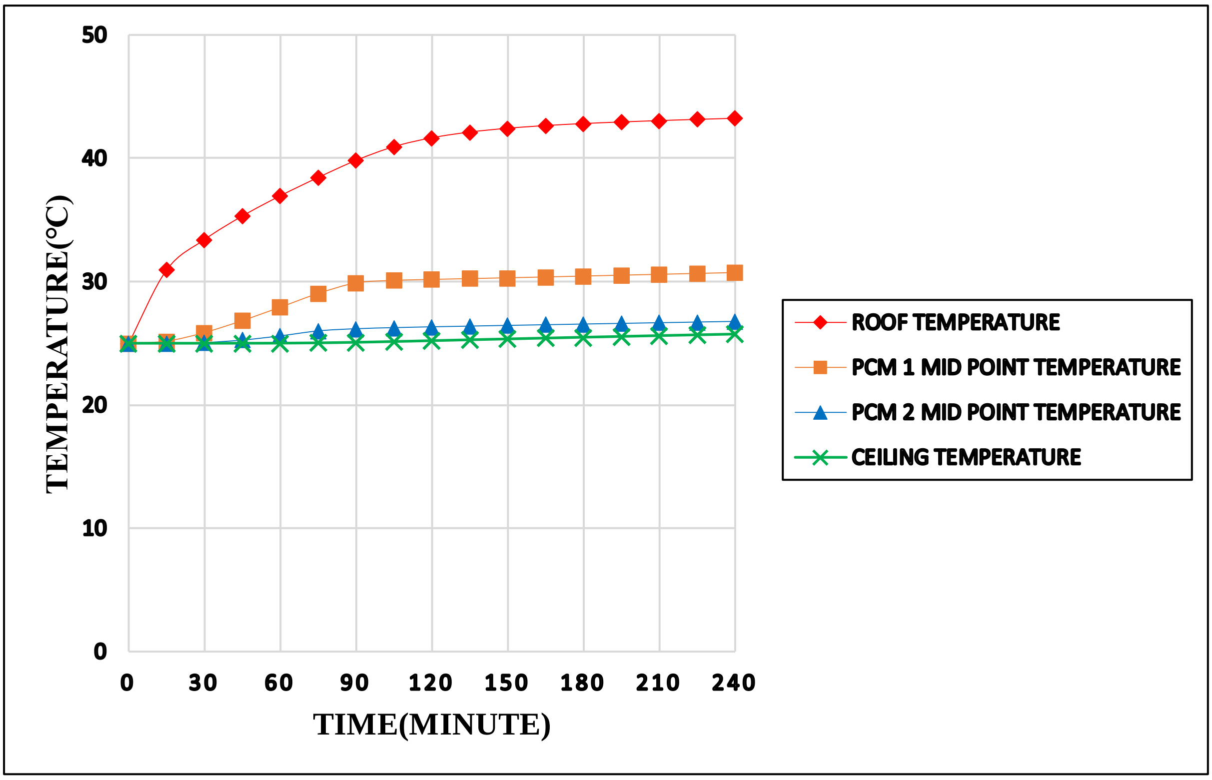


Figure 19: Temperature variation with two adjacent layer of PCM

Figure 19 shows that a concrete roof with two adjacent layers of PCM increases the temperature of the roof to 43.3 °C in 4 hours but keeps the ceiling temperature between 25 and 26 °C. The PCMs can melt due of heat transmission through the roof, with PCM 1 melting first and PCM 2 melting concurrently.

GRID INDEPENDENCE TEST:

A grid independency test, as seen in Figure 22, is conducted to support the optimal grid size. It displays the difference in temperature between those with and without PCM. Four different grid sizes with 1772 nodes, 5636 nodes, 9652 nodes and 12504 nodes have been chosen for the analysis of the concrete layers with two adjacent layers of PCM. Timestep size of 10s is considered during this simulation.

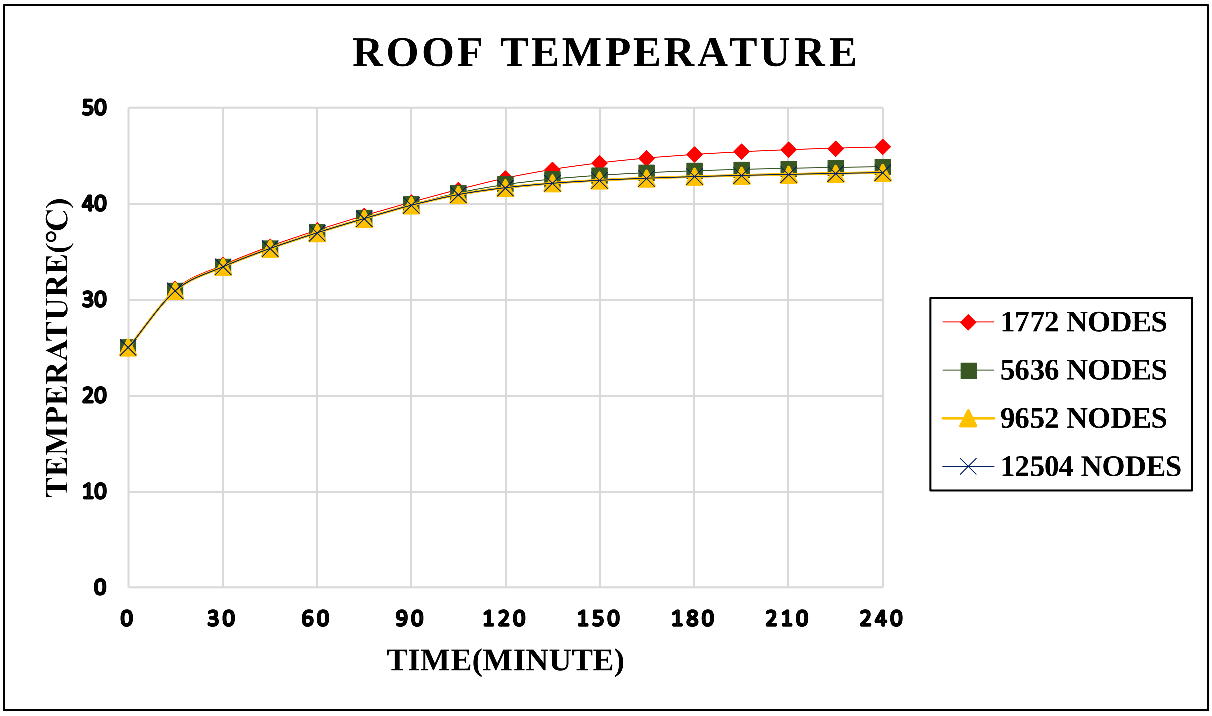


Figure 20: Roof temperature (Case 2)

TIMESTEP INDEPENDENCE TEST:

The timestep independence test is carried out as depicted in Figure using two distinct timestep sizes of 60s,30s and 10s at a grid size with 9652 nodes in order to get the optimal value of timestep size. For showing the other findings, a 10-second time step is selected.

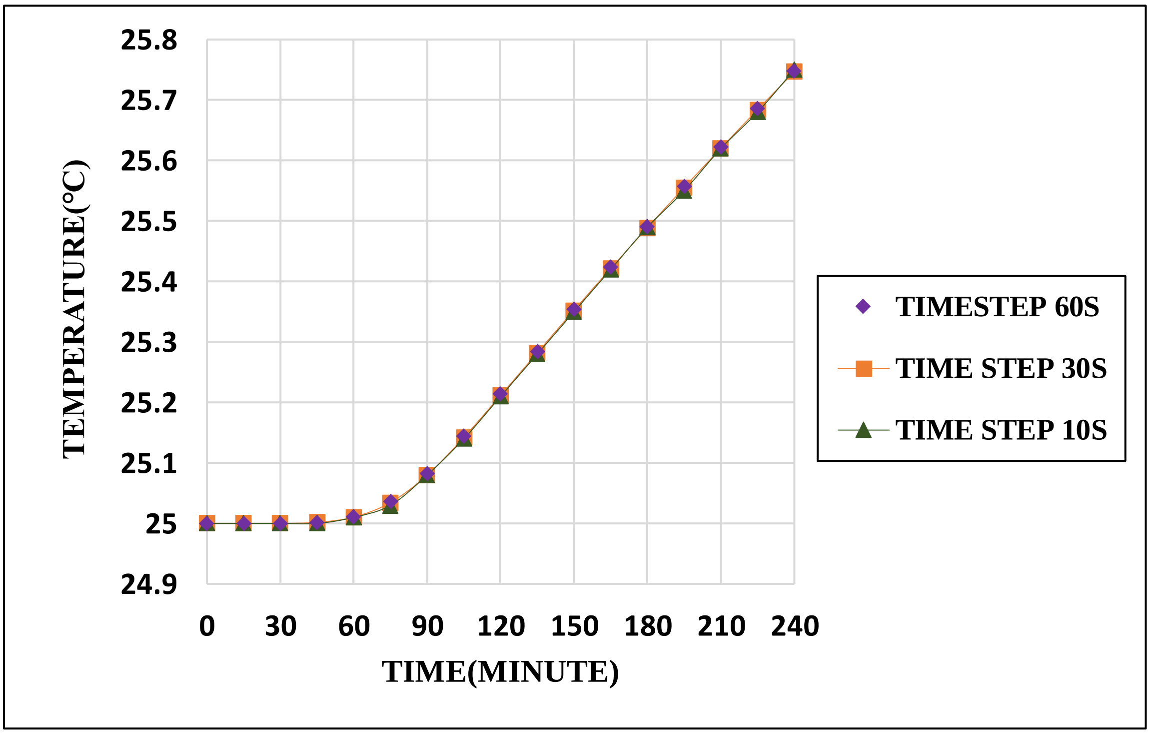


Figure 21: Ceiling temperature (Case 2)

CONTOURS OF MASS FRACTION AND TEMPERATURE:

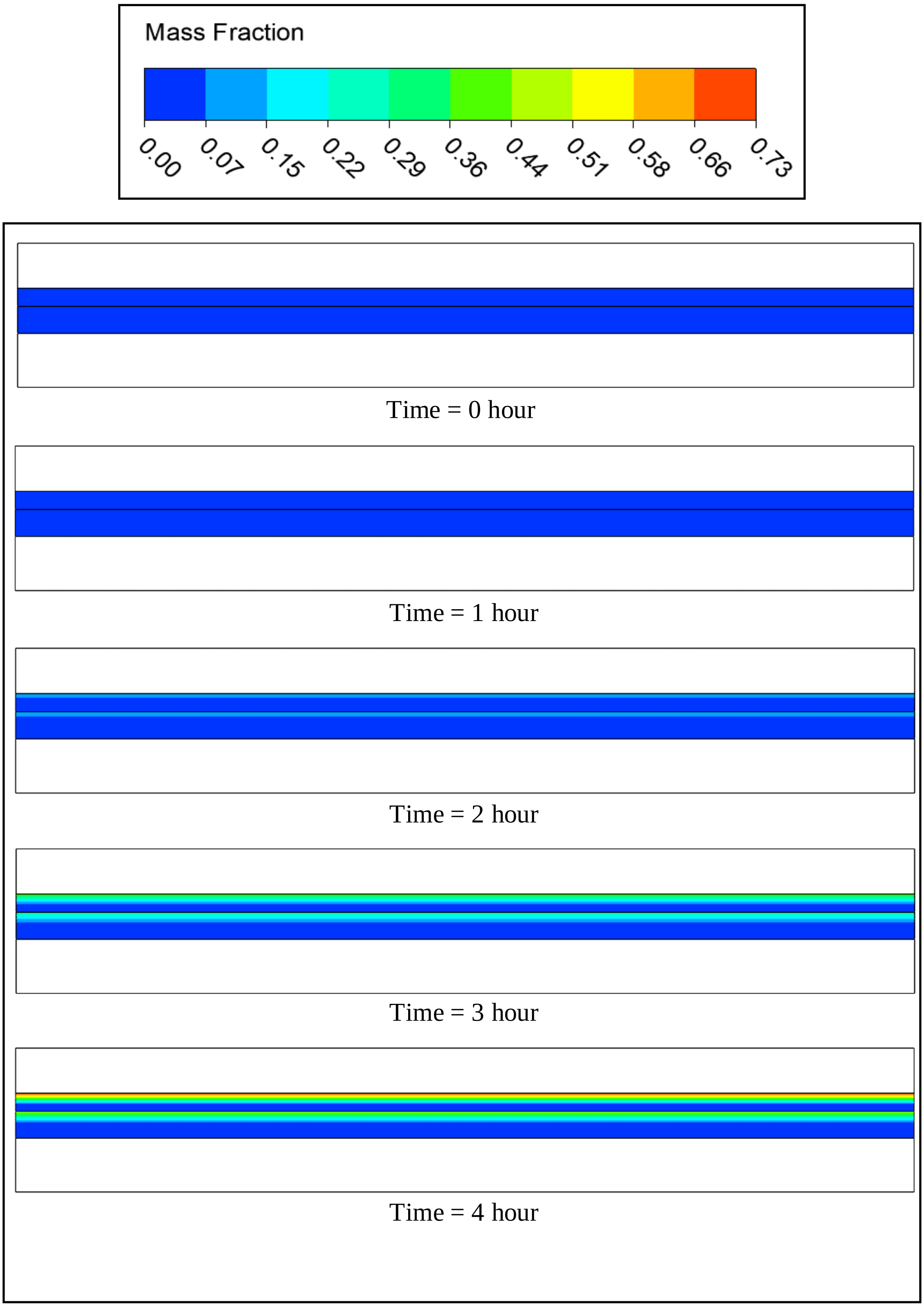


Figure 22: Liquid fraction evolution of the PCM inside concrete from t= 0 hour to t = 4 hour

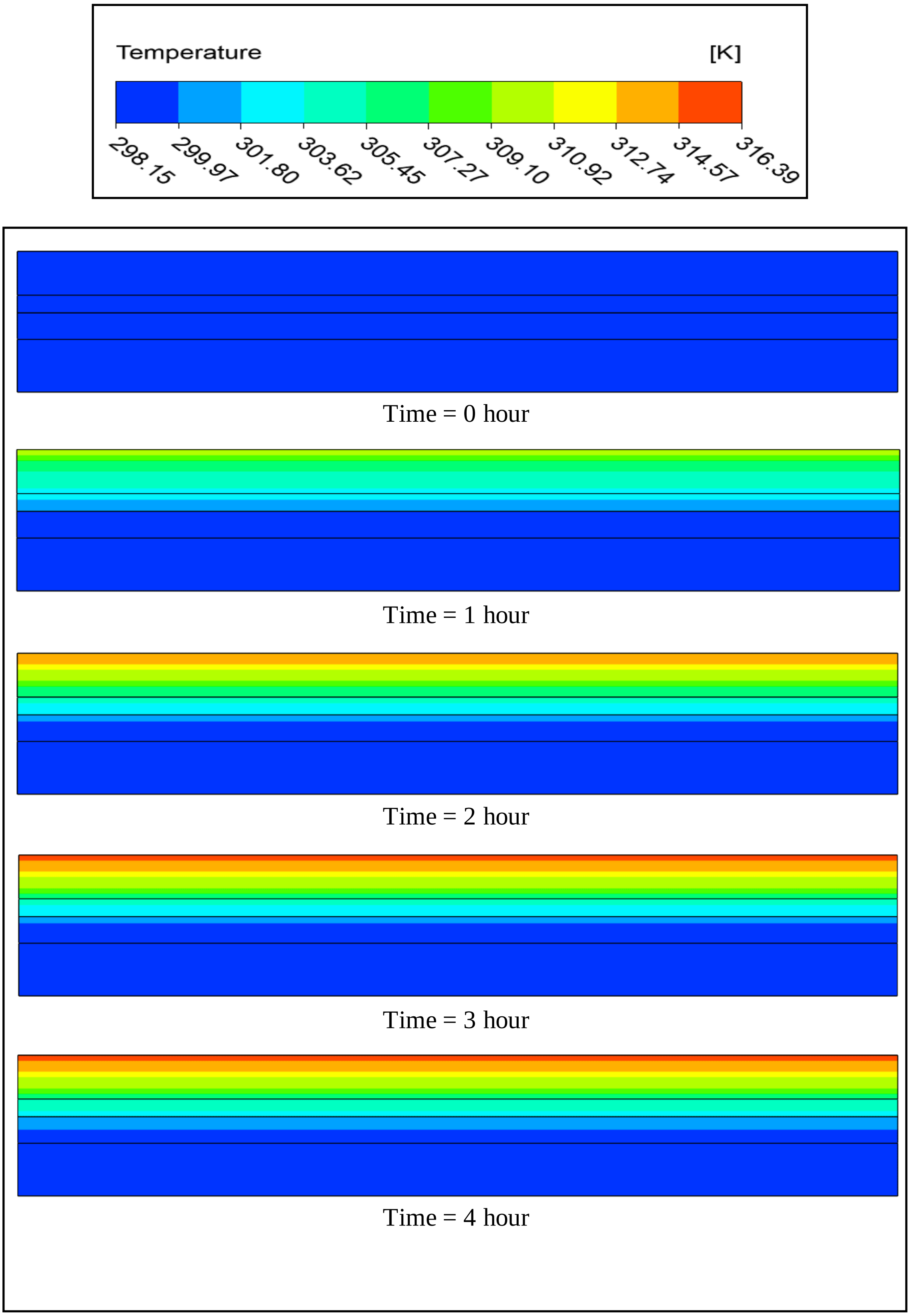


Figure 23: Temperature distribution inside the roof from t= 0 hour to t= 4 hour (Case 2)

COMPARISION CHARTS:

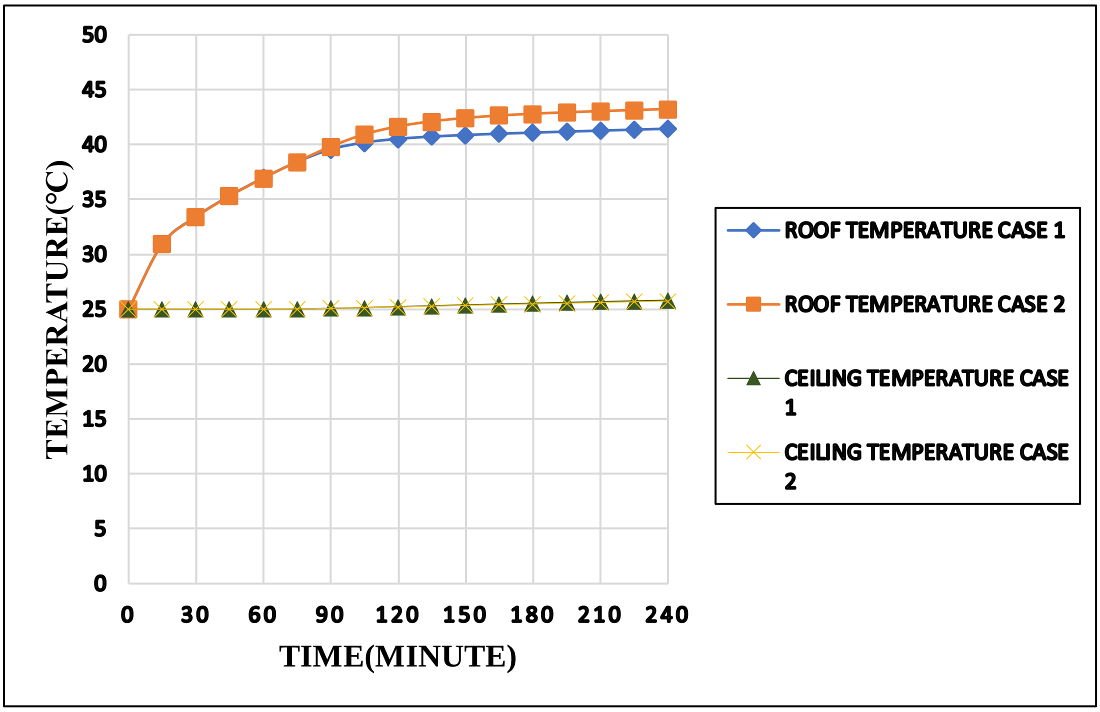


Figure 24: Temperature difference between case 1 and case 2

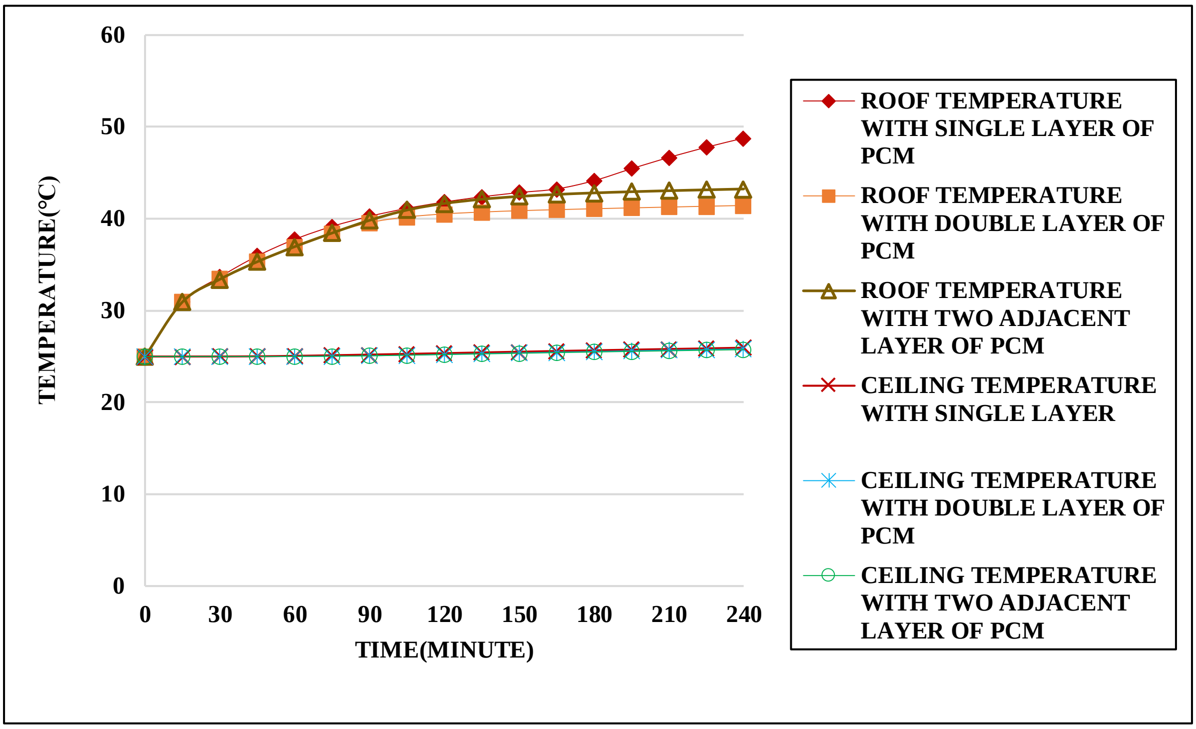


Figure 25: Comparison of temperature variation in concrete roof with respect to addition of different layers of PCM

According to figure 25 , there is no discernible change in the ceiling temperature between cases 1 and 2 working with double-layer PCM, while case 2 has a higher roof temperature than case 1. The position of double-layer PCM inclusion in concrete roofing is thus proposed for further study. The use of double-layer PCM over single-layer PCM is strongly advised for the following reasons, as illustrated in Figure 5.13: In the case of two layers of phase change materials, the most amount of heat is absorbed by the PCM from the roof top, resulting in a lower roof temperature than when applying one layer. However, it suggests using PCM in the upper PCM layer as opposed to the other layer with a higher melting point. As a result, heat may be absorbed more quickly than if lower melting-point PCM were used in the top layer.

EXPERIMENTAL MODEL

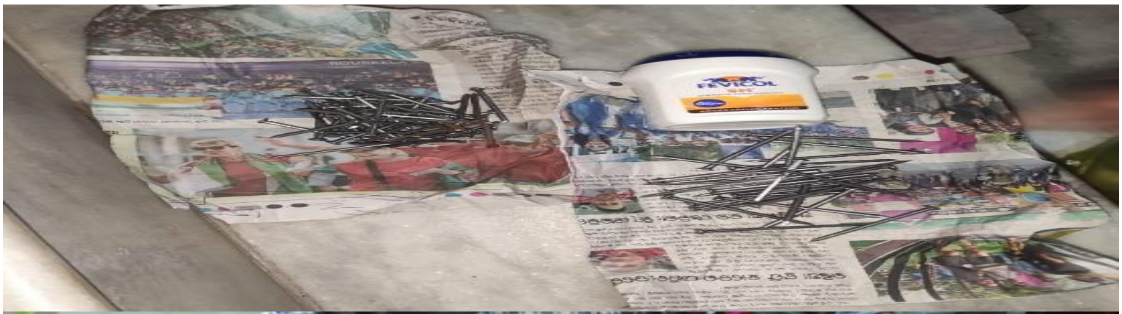
DESCRIPTION OF THE MODEL:

An experimental prototype consisting of a test room with a dimension of (1 m * 1 m * 1 m) has been fabricated. All the walls of the test room are fabricated with plywood, and there is an iron structure around the walls for strengthening the room. Two concrete slabs have been fabricated with the incorporation of GI rods, ultratech cement, chips, and sand particles with dimensions of 0.06m and 0.05m. phase-change material has been macro-encapsulated with prefabricated aluminium panels (having a 3mm thickness). The panel is leak-proof.

To examine the only impact of the PCM panel on the roof, all interior walls of the rooms aside from the ceiling are entirely insulated with 19 mm thick plywood on all four sides. The thermocol is used as insulation on the sidewalls of the PCM-concrete domain.

Figure 26: Winding of GI rod for slab fabrication

Figure 27. Fabrication of two concrete slab




NAGA PINE
PLYWOOD, BLOCK BOARD & FLUSH DOOR

Figure 28: Test room with plywood(wall) and iron structure(pillar)

Figure 29: Aluminium panel

Figure 30: Thermocouple placed within in the aluminium panel

Figure 31: K-type thermocouple

Figure 32: Plate heater (1m*1m)

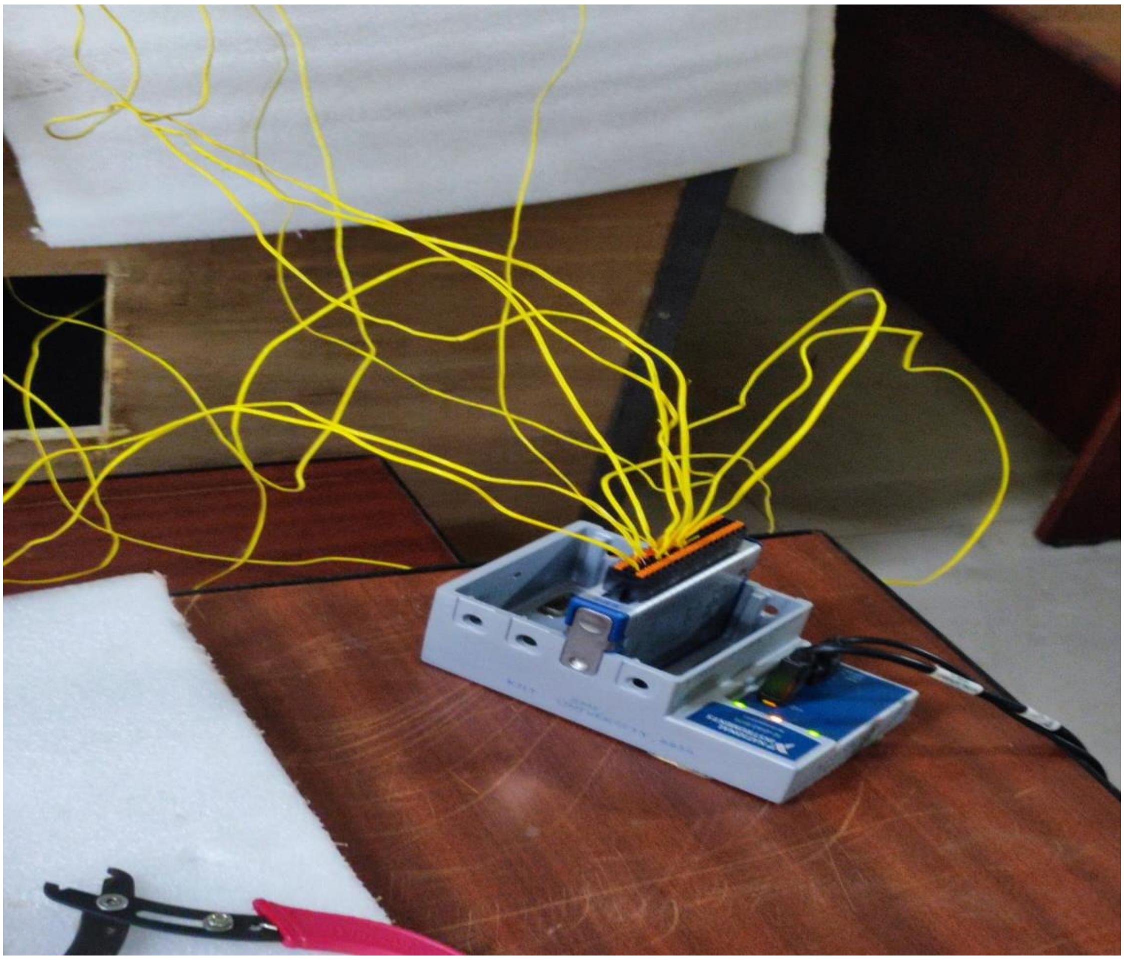


Figure 33: Thermocouples connected with C DAQ

Figure 34: Initialization of experimental Investigation

EXPERIMENTAL PROCEDURE:

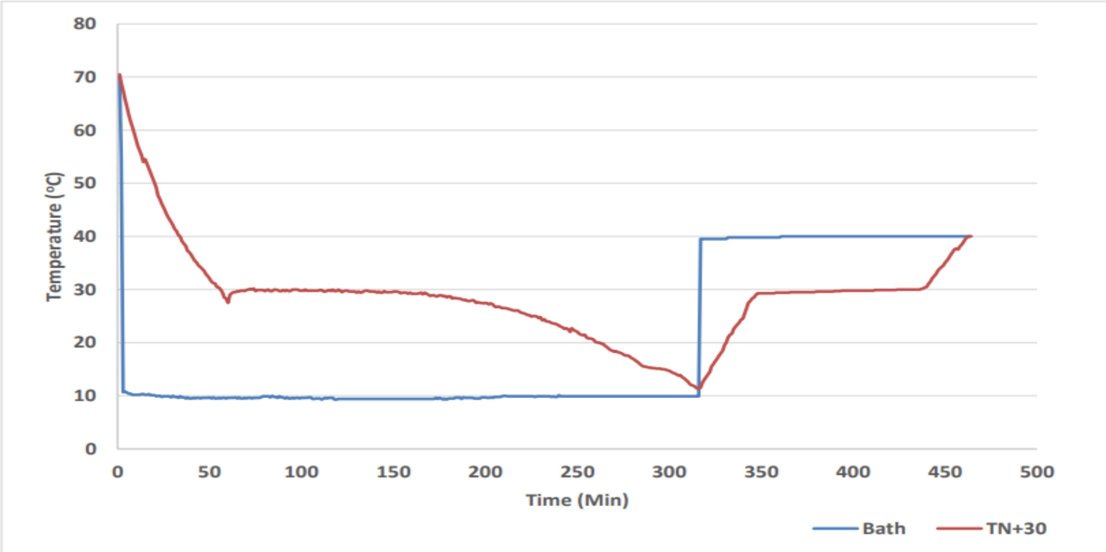
The concrete slab is heated using a mica plate heater, which is installed at the top of the slab using thermal paste. In order to encapsulate the TN+30 phase change material, it is poured inside a prefabricated aluminium panel that is sandwiched between two slabs of concrete.

Temperature measurements are performed using K-type thermocouples. Three thermocouples are mounted on the top slab of the roof at equal distances to measure the temperature of the roof, and three more thermocouples are placed in the ceiling, or the bottom slab, at an equal interval. In order to measure the temperature between the PCM, three thermocouples are attached at positions shown in Figure 36. . Then a temperature detector instrument is mounted in the room, which is enclosed by the walls. A total of nine thermocouples are connected to a data acquisition system, which is linked to a computer to display the temperature readings. After the experiment is finished, the temperature data are collected, and an analysis is performed using MS Excel.

Properties	**value**
Melting Point	30 ℃
Latent Heat	202 kJ/kg
Density	1535 (liquid) 1706 (solid) kg/m^3
Specific Heat	2.08 (liquid) 1.42 (solid)kJ/Kg.K
Thermal Conductivity	0.546 (liquid) 1.088 (solid) W/mK
Max Operating Temperature	100 ^{0}C
Safety	Non-Toxic, Safe to Handle
Flammability	NO

Table: thermophysical properties of TN+30 PCM

Temperature curve of TN+30 PCM:



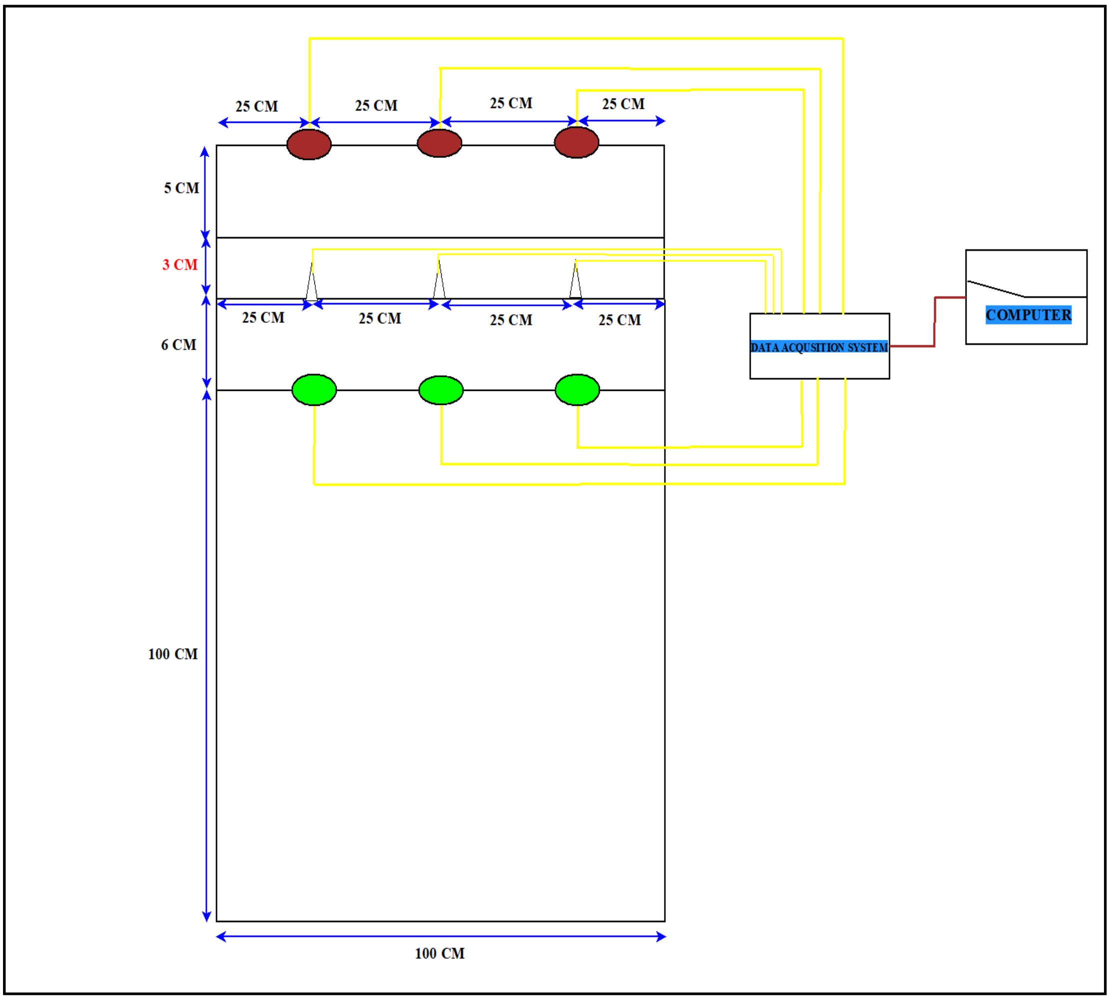


Figure 35: Schematic of experimental prototype

SPECIFICATION OF MATERIALS:

- Aluminium sheet thickness - 3mm
- Plate Heater- 1500 W, 220 V
- Ply wood thickness- 19 mm
- PCM - TN+30 (melting point 30^0C)
- K-type thermocouple – range (0 - 1000^0C)

EXPERIMENTAL RESULTS AND DISCUSSION

RESULTS AND DISSCUSION:

In this case, a concrete layer without PCM is being simulated using a constant heat flux boundary condition at the top of the concrete layer and a convective boundary condition at the bottom of the concrete layer. Similarly, these boundary conditions are taken for the numerical analysis of concrete layer with single layer of pcm. A constant heat flux of 350 W/m2 is taken, and a convective loss of 1 W/m2k is taken for the analysis. The entire domain is initialised at a temperature of 25°C.

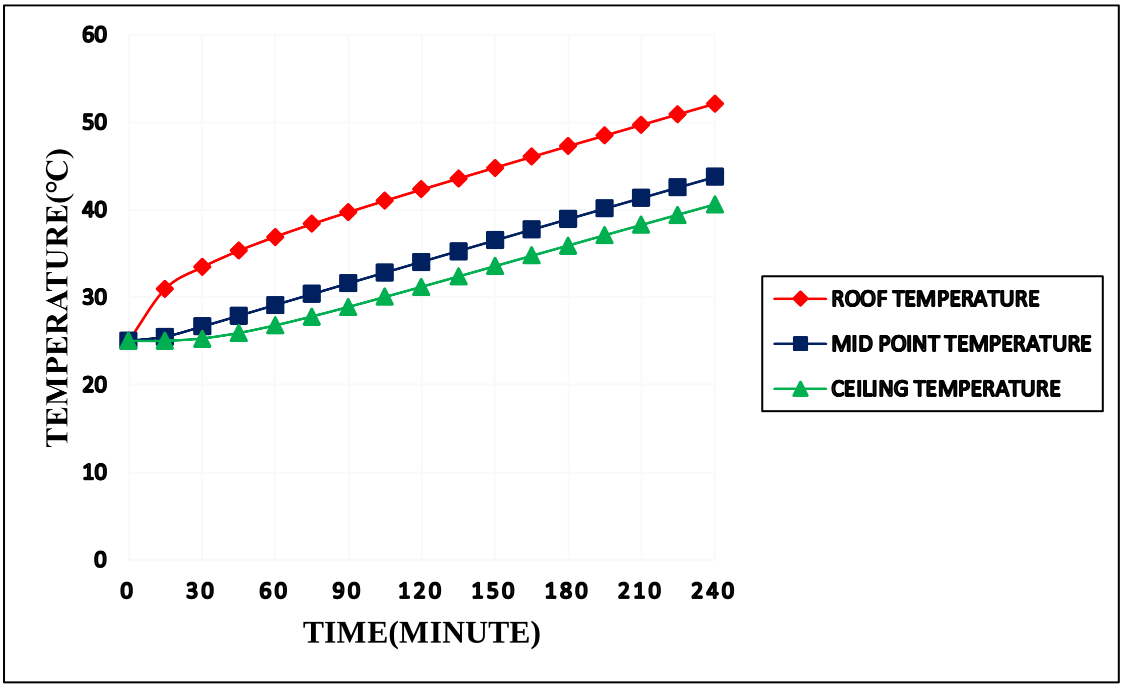


Fig.36. TEMPERATURE VARIATION WITHOUT PCM

From the fig.36, it is shown that the roof temperature gradually increases from 25 °C to 52 °C without the implementation of PCM, and the ceiling temperature goes up to 40 °C in 4 hours. The non-PCM room's ceiling shows a significant variation since the outside surroundings have an instantaneous impact on it.

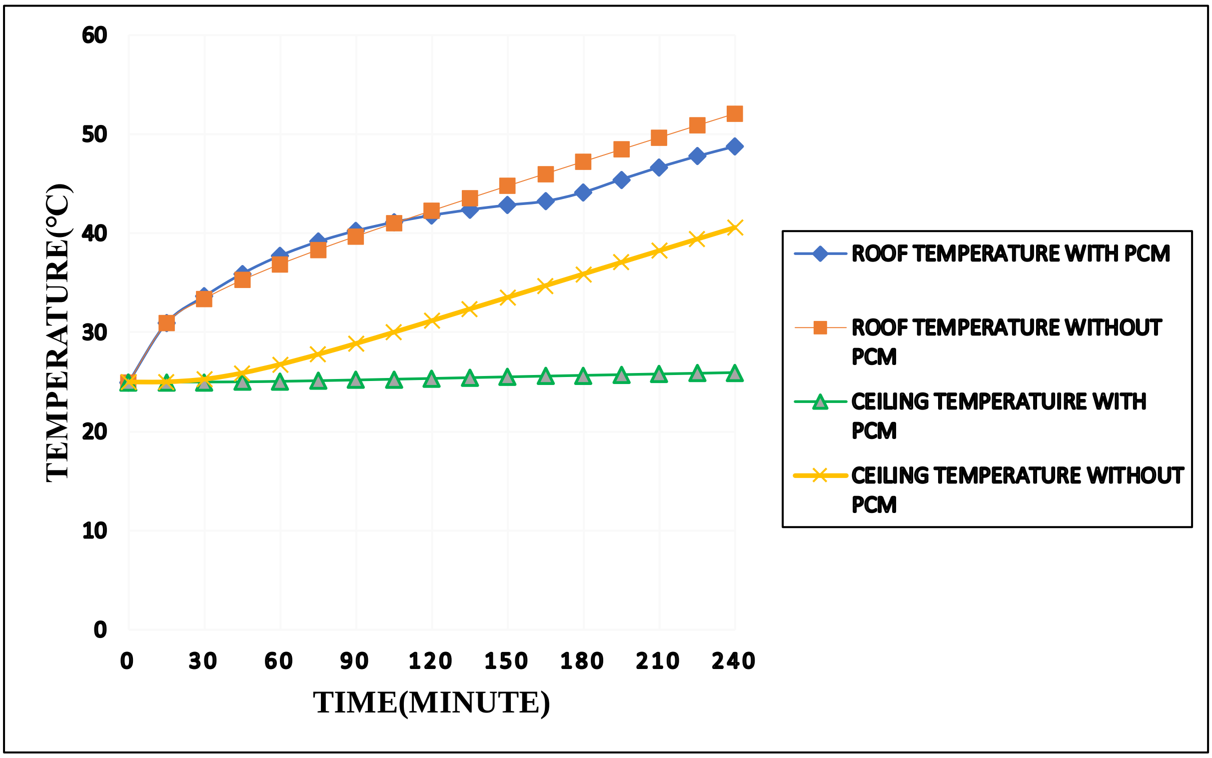


Fig.37. TEMPERATURE VARIATION WITHOUT PCM AND WITH PCM

With the use of PCM the roof temperature reduces to about 48 ^{0}C. However, the ceiling temperature is controlled within the comfort limit of about 25^{0}C using PCM. If PCM is not used, the temperature of the ceiling increases significantly to 40^{0}C. Therefore, use of PCM is recommended to control the temperature. The heat conducted through the concrete layer from the heating of roof is absorbed by the PCM. The PCM thus melts and keep the temperature within the limit.

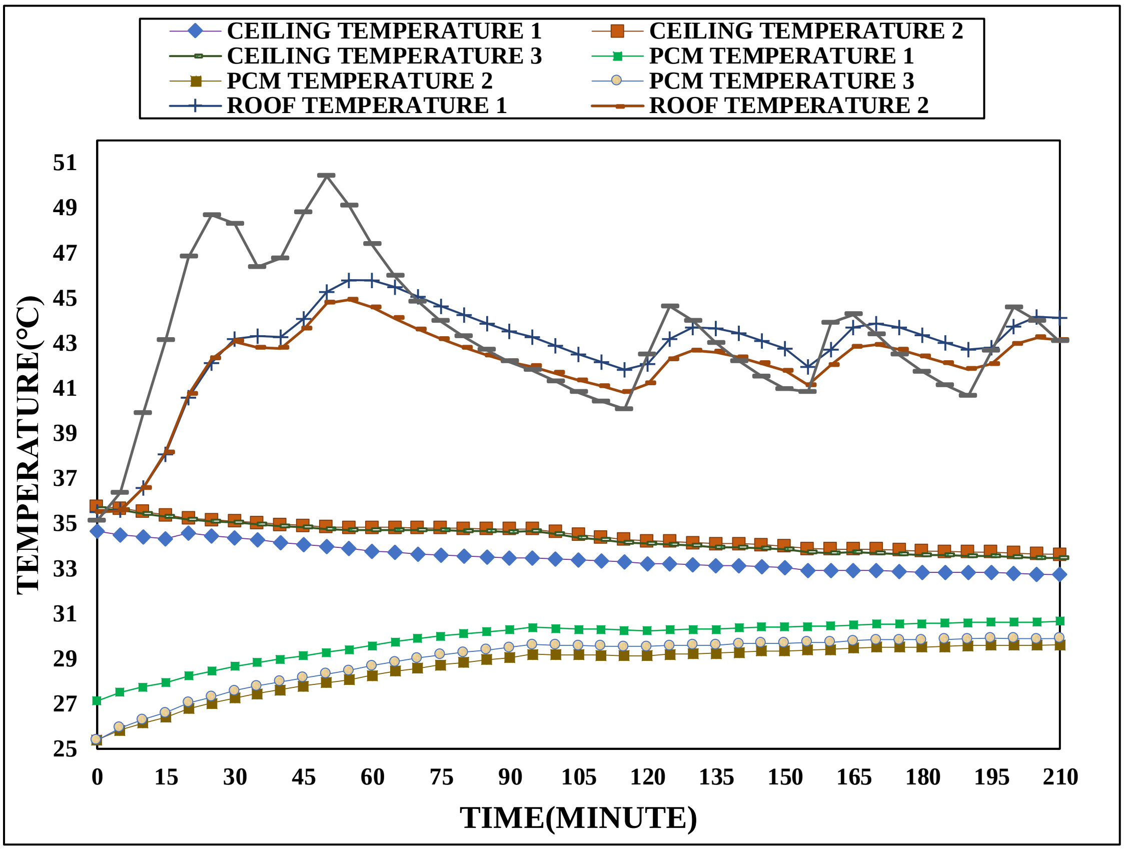


Figure 38: Temperature Variation of PCM along the roof and ceiling

Figure 38 describes the temperature variation along the roof and ceiling using PCM. The ceiling temperature reduced to 32^0C. The roof temperature is about 45^0C. The PCM absorbs the heat released by the roof and the ceiling temperature is reduced.

CONCLUSIONS

Conclusion

The temperature of the hot roof can be controlled and thus the temperature inside the room can be maintained in thermal comfort zone by using PCM. It can be concluded from the analysis that the roof temperature decreases with the use of two types of PCMs in two layers as compared to using single layer of PCM. The thickness of PCM is varied to control the temperature inside the room.. So, in view of the above analysis, the present article can be helpful in the following manner.

- The proper PCM can be chosen to fit into the concrete slab to control the temperature inside the room in the comfort zone
- The location of PCM is to be decided for accurately predicting the temperature as per the climatic conditions
- The no. of layers of PCM can be optimized to keep inside the concrete for maintaining the thermal comfort in less time