Mathematical Modeling and Experimental Study on Building Ceiling Using Phase Change Material for Energy Conservation

Avadaiappa P. Pasupathy1 and Ramalingom Velraj2,*

1 Department of Mechanical Engineering, Jayamatha Engineering College, Aravonmoozh, Kanyakumari – 629301, India
2 Department of Mechanical Engineering, College of Engineering, Anna University, Chennai-600025, India

Abstract: Thermal storage plays a major role in wide variety of industrial, commercial and residential application when there is a mismatch between the supply and demand. Several promising developments are taking place in the field of thermal storage using phase change materials (PCMs) in buildings. In the present paper, a detailed study on the thermal performance of a PCM 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 of the building. One room is constructed without PCM on the roof to compare the performance of the experimental room that with the PCM on the roof which has melting temperature in the range of 26 - 28°C. A mathematical model has been developed and the finite volume method is used for the computational thermal behavior of the ceiling incorporating PCM. Several simulation runs are made for a given ambient conditions by varying the heat transfer co-efficient on both sides of roof. A comparison with the experimental results is also made.

Keywords: Building Energy Conservation, Encapsulation, Latent Heat, Thermal Energy Storage, Phase Change Material

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. Infact, 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 when it was extensively research 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 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. Stritih and Novak [1] 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 [2-5] in wallboards. Lee et al. [6] and Hawes et al. [7] presented the thermal performance of PCM’s in different types of concrete blocks. They studied and presented covered the effects of concrete alkalinity, temperature, immersion time and PCM dilution on PCM absorption during the impregnation process. Ismail et al. [8] proposed a different concept for thermally effective windows using a PCM moving curtain. UniSA (University of South Australia) [9] 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 [10] put forward a new kind of under-floor electric heating system with shape-stabilized phase change material (PCM) plates. Hed [11] 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 B. Zalba [12]. The objective of the work was to design and construct an experimental installation to study PCMs with a melting temperature between 20-25°C.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 Koschens and Beat Lehmann [13] to incorporate this system in a light weight building that can be retrofitted. Velraj et al. [14] 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 [15] 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. Athienitis et al. [16] 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.

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% CaCl₂ + 4.3 % NaCl + 0.4%KCl + 47.3% H₂O), 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.

2. MODELING OF PCM INTEGRATED BUILDING ROOF SYSTEM

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. As melting requires a large quantity of heat at its phase change temperature, the temperature of the concrete slab normally will not exceed the PCM temperature. 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 described in Fig. 1 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 [17] 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. 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 less, 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.

2.2 Mathematical formulation

For the mathematical formulation of the above-mentioned problem shown in Fig. 2, the following assumptions are made:

1. The heat conduction in the composite wall is one-dimensional and the end effects 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 effect in the molten PCM is neglected.
5. The interfacial resistances are negligible.
6. The ‘c_p’ value of the PCM in the panel is considered as follows.
   
   \[ T < T_m - \phi \quad c_p = c_{ps} \]
   
   \[ T > T_m + \phi \quad c_p = c_{pl} \]
   
   \[ T_m - \phi < T < T_m + \phi \quad c_p = \lambda / 2 \varepsilon \]

   where ‘c_p’ is the specific heat capacity, \( \lambda \) is the latent heat capacity, \( \phi \) is half of the temperature range over which the phase change occurs and \( T_m \) 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. In accordance with the above-mentioned assumption, the governing equation and the boundary condition are developed as below.

**Governing Equation**

\[
\frac{k_w}{m^2} \frac{\partial^2 T_x}{\partial x^2} = \rho_m c_p \frac{\partial T_x}{\partial t} \quad [0 < x < L] ; \quad m = 1, 2, 3
\]

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 \( k, \rho, c_p \) value. In the exterior boundary \((x=0)\) where the floor is exposed to solar radiation, the boundary condition is,

\[
k_1 \frac{\partial T_1}{\partial x} \bigg|_{x=0} = q_{rad} + h_o (T_\infty - T_{x=0})
\]

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

\[
+ k_3 \frac{\partial T_3}{\partial x} \bigg|_{x=L} = h_i (T_{x=L} - T_{room})
\]

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

![Interfacial resistance](image)

**Fig. 2** Finite volume grid for the analysis

### 2.2.1 Exterior Node

The equation for the top volume cell is written as below

\[
\left( \frac{\rho_o c_i \Delta x_i}{\Delta t} + \frac{f k_o \Delta x_i}{\Delta x_i} + h_o f \right) T_1 - \frac{f k_i \Delta x_i}{\Delta x_i} T_3
\]

\[
= h_o f T_\infty + (1 - f) \left[ \frac{k_i (T_2 - T_1)}{\Delta x_i} - h_o (T_1 - T_\infty) \right]
\]

\[
+ \frac{\rho_o c_i \Delta x_i T_1^0}{\Delta t} (T_1 - \epsilon T_\infty) + \alpha q_{i} + \sigma \left[ \alpha T_{s, i}^4 - \epsilon T_\infty^4 \right]
\]

### 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

\[
-\frac{f k_o \Delta x_i}{\Delta x_i} T_{i+1} + \left[ \frac{\rho_o c_i \Delta x_i}{\Delta t} + \frac{f k_o \Delta x_i}{\Delta x_i} + \frac{f k_i \Delta x_i}{\Delta x_i} \right] T_i - \frac{f k_m \Delta x_i}{\Delta x_i} T_m
\]

\[
= (1 - f) \left[ \frac{k_i (T_{i-1} - T_1)}{\Delta x_i} - k_m \frac{(T - T_1)}{\Delta x_i} \right] + \frac{\rho_o c_i \Delta x_i T_1^0}{\Delta t} \left[ -\epsilon T_\infty + \sigma \left( \alpha T_{s, i}^4 - \epsilon T_\infty^4 \right) \right]
\]

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.

\( m = 1, \quad i = 2, 3, 4; \quad m = 2, \quad i = 7, 8, 9; \quad m = 3, \quad i = 12, 13, 14. \)
2.2.3 Interface Node

The equation for the interface volume cell 5 is written as below

\[
-\frac{f k_i}{\Delta x_i} T_{1i} + \left[ \frac{\rho c_i \Delta x_i}{\Delta t} + \frac{f}{\Delta x_i / 2k_i + \Delta x_i / 2k_i} \right] _T \left[ \frac{\Delta x_i / 2k_i + \Delta x_i / 2k_i}{\Delta t} \right] T_{1i} = \left( 1 - f \right) \left[ k_i (T_x - T_i) \right] / \Delta x_i - \left[ \frac{\rho c_i T_i^3}{\Delta t} \right] T_{1i}
\]

(6)

where \( \Delta x_1 \) and \( \Delta x_2 \) 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 \( \Delta x_2 \) and \( \Delta x_3 \) 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

\[
-\frac{f k_i}{\Delta x_i} T_{15} + \left[ \frac{\rho c_i \Delta x_i}{\Delta t} + \frac{f k_i}{\Delta x_i} \right] T_{15} = f \left[ h_i (T_{15} - T_{15}) \right] + \left( 1 - f \right) \left[ 2h_i - k \left( T_{15} - T_{15} \right) \right] / \Delta x_i + \frac{\rho c_i T_i^3}{\Delta t} \Delta x_i
\]

(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 second 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 the 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 6mm 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 2m by 2m and thickness of 2.54 cm which accommodates inorganic salt hydrate (48% CaCl₂ + 4.3 % NaCl + 0.4%KCl + 47.3% H₂O) 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 m³.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Technical Specifications of used PCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCM material</td>
<td>(48% CaCl₂ + 4.3 % NaCl + 0.4%KCl + 47.3% H₂O)</td>
</tr>
<tr>
<td>Appearance (color)</td>
<td>Grey</td>
</tr>
<tr>
<td>Phase change temp. (ºC)</td>
<td>26 - 28</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1640</td>
</tr>
<tr>
<td>Latent Heat (kJ/kg)</td>
<td>188</td>
</tr>
<tr>
<td>Thermal conductivity (W/mk)</td>
<td></td>
</tr>
<tr>
<td>Solid</td>
<td>1.09 [0 to 27ºC]</td>
</tr>
<tr>
<td>Liquid</td>
<td>0.54 [28 to 60ºC]</td>
</tr>
<tr>
<td>Specific heat J/ kg. K</td>
<td>1440 [0 to 26.5°C]</td>
</tr>
<tr>
<td></td>
<td>125000 [26.5 to 28°C]</td>
</tr>
<tr>
<td></td>
<td>1440 [28 to 60 ºC]</td>
</tr>
</tbody>
</table>

The PCM salt hydrate mixture is prepared by mixing all the inorganic salts in the appropriate proportion of 48% CaCl₂, 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 prevent incongruent melting and sub-cooling. The total mass of the PCM mixture used is 164 kg and the PCM panel after carefully installing the heat exchanger is filled with the mixture in its liquid state and sealed properly. The RTD (PT 100) are placed in different depths in the PCM panel with perfect sealing. The PCM temperature variation is recorded for every one hour using the 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 the theoretical analysis, the room temperature is maintained constant with convective boundary condition on the inner surface of the concrete slab during a particular trial. Hence, while comparing the theoretical model with the experiment the room temperature is maintained at a constant temperature of 27°C as input in the theoretical analysis. 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 handbook by Tiwari (17) 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 graph 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, 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. This is due to the fact that the ceiling of the roof is highly influenced by the inside room condition which is governed by the ventilation and wall conditions of the room. However, in the experimental trial, a small decrease in ceiling temperature during the day time and small increase in ceiling temperature during the night time is observed in the PCM room which reduces the fluctuation of temperature inside the PCM room. This is due to the large heat storage capacity of the PCM.

The differences in temperature value between the theoretical and experimental results are due to the following reasons.

- 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

Considering the above facts, the trend in the theoretical results is in reasonable agreement with the experimental results. Hence this theoretical analysis is further extended to study the effects during all the seasons in a year and to analyze the effects of other parameters.

6. CONCLUSION

Several promising developments are taking place in the field of thermal storage using PCM’s in buildings. In the present study the thermal performance of an inorganic eutectic phase change material based thermal storage for thermal management in residential and commercial establishment has been carried out. It is quite evident from the preceding modeling and experimentation 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 percentage of PCM mixed with conventional material, 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. Therefore, the information like operational range and limitations evolved in a project with PCMs as heat transport medium and
elaborate calculation for analysis supported by a simulation program would definitely be a remarkable and reckonable guidance for deciding and designing PCMs in building application. Being site specific, a detailed study is required for the selection of material

7. NOMENCLATURE

c1, c2, c3 - Specific heat of Roof top slab, PCM panel, concrete slab (kJ/kgK)
cp - Specific heat of solid (kJ/kgK)
cpl - Specific heat of liquid (kJ/kgK)
f - Fraction
hi - Inside heat transfer coefficient (W/m²K)
ho - Outside heat transfer coefficient W/m²K
k1, k2, k3 - Thermal conductivity of roof top slab, PCM panel, concrete slab (W/m K)
q - Heat flux (W/ m²)
T - Temperature (°C)
Troom - Room temperature (°C)
Ts - Surface temperature (°C)
Tsky - Sky temperature (°C)
Tin - Initial temperature (°C)
Ti - Current time step temperature at i-th volume cell (°C)
T∞ - Ambient temperature (°C)
λ - Latent heat of PCM (kJ/kg)
∈ - Emissivity
α - Absorptivity
σ - Stefan Boltzman Constant
Δ - Time step
Ax1, Ax2, Ax3 - Control volume length of roof top slab, PCM panel, concrete slab (m)
δx1, δx2, δx3 - Nodal distances (m)
ρ1, ρ2, ρ3 - Density of floor tiles, PCM, concrete (kg/m3)

8. REFERENCES


