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# Numerical investigation on the thermal performance of a hospital ward roof incorporating phase change material (PCM)

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## ABSTRACT

Overheating is a common phenomenon in a tropical country like Bangladesh. So, ensuring the thermal comfort of hospital patients is necessary for proper health treatment. But in Bangladesh, the thermal comfort of the patient is compromised as installation of the air conditioning system in every general ward of the hospital is impossible due to economic constraints. So, a cheap but effective solution is badly needed to cope with this situation. In that case, PCM (phase change materials) can be an alternative to improve the thermal condition and reduce temperature fluctuation in hospitals in Bangladesh. Phase changing ability at a constant temperature and latent heat storage property of PCM have been proved very effective for the improvement of building thermal condition over the years. In this study, the improvement of thermal condition of the general ward of Patuakhali Medical College (PkMC) is analyzed using PCM as a retrofitting option. A numerical simulation work is performed to analyze and compare the effect of three different PCMs on the enhancement of thermal comfort hours. Finally, based on the result, the best PCM is chosen for optimum thermal management.

Keywords: Hospital general ward, Thermal comfort, Phase change material, Numerical simulation.

## 1. Introduction

Over the last few years the demand for air conditioning has greatly increased in Bangladesh resulting in increased energy consumption. In public health sector, hospital is one of the most energy consuming areas which lacks facilities for thermal comfort due to economic constraints. For this reason, ensuring thermal comfort of patients and searching for more energy efficient building model have become important criteria for Bangladesh nowadays. The use of thermal energy storage has a great importance in this regard as it can control the daily temperature fluctuation and decrease the energy demand for heating and cooling. As a latent heat TES(thermal energy storage) system there are several research going on in the application of phase changing materials (PCM) [1] which can store 5-15 times more heat per unit volume than sensible heat storage materials(rock, water, masonry).

Researches have been conducted for over two decades to find potential PCM in residential building heat comfort applications. Cabeza et al.[2] reviewed the categories of PCM (organic, inorganic, eutectics) with their most possible problems or solutions during application in building and found two PCM-based TES systems. Among them, active systems require an additional fluid loop to charge or discharge a storage tank but passive systems don’t require that heat exchanger and store energy in the form of latent heat. There are also several studies on the incorporation of PCM in roof, wall, floor, window glazing by using micro or macro encapsulation. Cabeza et al. [3] discussed the effectiveness of using microencapsulated PCM within concrete wall to control building temperature and how it can help to minimize the temperature fluctuations. There was 1.15°C reduction in room temperature during winter while using PCM wallboard [4]. In another study, Alqallaf et al. [5] used PCM containing cylindrical holes in roof which causes maximum reduction in heat flux of about 17.26%. Pasupathy and Velraj also discussed how integration of PCM on the roof could narrow down the indoor air temperature swings [6]. Ismail and Henriquez [7] gave a different idea of incorporating a moving curtain of PCM for thermally effective windows. Barzin et al. [8] proposed an experimental investigation by comparing two small room. The first room was comprised of ordinary gypsum board while the second one included PCM (paraffin) boards on the floor. In another experiment, A.G. Entrop et al.[9] discussed the method of storing thermal energy by using PCM layer in concrete floor and how this energy can be utilized to ensure thermal comfort. Again another study revealed a new kind of underfloor electric heating system with shape-stabilized phase change material (PCM) plates [10].

Besides these experimental studies, there are few studies on the use of PCM in tropical climate area. Pasupathy et al. [11] performed a study where PCM is used in roof in tropical climate. But in tropical climate like Bangladesh, there is still less work on PCM to maintain thermal comfort in buildings, especially in health sector.

This study aims at analyzing the feasibility of using PCM to improve thermal condition in hospital general wards of Bangladesh. A numerical simulation work is performed to analyze and compare the effect of three different PCMs on thermal comfort of the patients of Patuakhali Medical College, Bangladesh (PkMC) hospital general ward. Based on the simulation result, PCM with the best thermal performance is suggested.

## 2.Modelling of PCM embedded hospital roof system

The dimension of the roof of PkMC is taken for modelling purpose. A composite roof comprised of PCM

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layer in the middle sandwiched between two layers of concrete is modelled as shown in Fig.1.

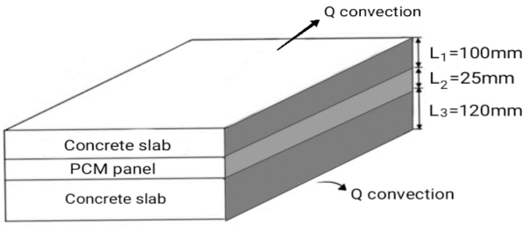

**Fig.1** Building roof layout

Initially a uniform temperature is maintained throughout the wall except at two boundary surfaces. Convective heat transfer with environment and room air is considered at outer and inner wall surface respectively. The heat transfer coefficient at the outer and inner surface is considered as $h_0$=$h_i$=8.3 W/m$^2$k respectively from similar work of [12]. Ambient temperature of Patuakhali for the month of June, 2020 is chosen for analyzing thermal performance of PCM.

Following assumptions are made for calculation purpose:

1. Heat conduction along the wall is one dimensional (occurs along the thickness direction of the wall).
2. Wall material (concrete) has constant and homogenous thermal property (thermal conductivity) and density.
3. The PCMs are homogenous and isotropic.
4. The thermal resistance at the concrete-PCM interface is neglected.
5. The room temperature is kept constant at 27 ºC.
6. The specific heat value, $c_p$, of PCM is taken as stated below:

$c_p = c_{ps}$ when temperature $T < T_m - \Delta T$
$c_p = c_{pl}$ when temperature $T > T_m + \Delta T$
$c_p = h_{sl} / 2\Delta T$ when $T_m - \Delta T < T < T_m + \Delta T$

### 2.1 Numerical Formulation

The governing equation of one directional heat conduction with no internal heat generation is given by,

$$\alpha\frac{\partial^2 T}{\partial x^2}=\frac{\partial \mathrm{T}}{\partial \mathrm{t}} \tag{1}$$

Where α is the thermal diffusivity. This equation is applicable for three material layer regions (concrete, PCM and concrete) individually. A finite difference explicit scheme is used to calculate temperature at different nodes. For interface heat conduction, compatibility equation considering matching thermal diffusivities is used.

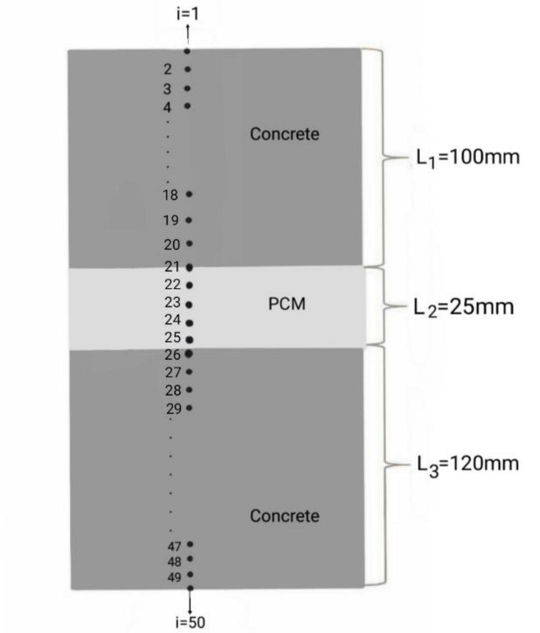

**Fig.2** Finite difference discretization of the roof

The composite wall is subdivided into 50 nodes as shown in Fig.2 for calculation purpose. Governing equations and boundary conditions are considered for three cases as stated below:

#### 2.1.1 For Nodes at two boundaries

For the exterior node (node 1) which lies at outer concrete surface, the boundary condition is

$$k\frac{\partial T}{\partial x}=h_0(T_\infty-T_{x=0}) \tag{2}$$

Here radiation heat transfer effect is neglected for the insufficiency of data at described region and for its insignificance in comparing the effect of various PCMs. For the node which lies at bottom layer of the concrete slab (node 50), the boundary condition is

$$k\frac{\partial T}{\partial x}=h_\mathrm{i}(T_{\mathrm{x=L}}-T_{\mathrm{room}}) \tag{3}$$

#### 2.1.2 For inner nodes of concrete and PCM layer

For inner nodes lying inside PCM and concrete layer, Eq. (1) is applicable for suitable value of thermal diffusivity. By standard forward first order time and central second order space finite differencing, Eq. (1) can be expressed as.

$$\alpha\frac{T_{\mathrm{i+1,t}}-2T_{\mathrm{i,t}}+T_{\mathrm{i-1,t}}}{\Delta x^2}=\frac{T_{\mathrm{i,t+1}}-T_{\mathrm{i,t}}}{\Delta t} \tag{4}$$

Which can be rearranged as,

$$T_{\mathrm{i,t+1}}=T_{\mathrm{i,t}}+\lambda(T_{\mathrm{i+1,t}}-2T_{\mathrm{i,t}}+T_{\mathrm{i-1,t}}) \tag{5}$$

Where $\lambda=\frac{k\Delta t}{\Delta x^2}$

Eq. (5) provides an explicit way to calculate temperature at any inner node in PCM and concrete layer.

### 2.1.3 For nodes at concrete-PCM interface

Various finite difference schemes are available for modelling node at multilayer interface. This work adopts the scheme of Hickson[13], where continuity in temperature and flux at the interface is assumed. In this scheme, one grid point lies on the interface for the spatial discretization for any layer. Continuity of temperature and heat flux is maintained for these two adjacent additional grid points.

Using this scheme the numerical discretization equation at the first concrete-PCM interface can be written as,

$$\frac{\alpha_{\mathrm{PCM}}T_{22,\mathrm{t}}-(\alpha_{\mathrm{PCM}}+\alpha_{\mathrm{Concrete}})T_{21,\mathrm{t}}+\alpha_{\mathrm{Concrete}}T_{20,\mathrm{t}}}{\Delta x^2}=\frac{T_{21,\mathrm{t+1}}-T_{21,\mathrm{t}}}{\Delta t} \qquad (6)$$

Similarly for the second concrete-PCM interface, numerical discretization equation can be written as,

$$\frac{\alpha_{\mathrm{Concrete}}T_{27,\mathrm{t}}-(\alpha_{\mathrm{PCM}}+\alpha_{\mathrm{Concrete}})T_{26,\mathrm{t}}+\alpha_{\mathrm{PCM}}T_{25,\mathrm{t}}}{\Delta x^2}=\frac{T_{26,\mathrm{t+1}}-T_{25,\mathrm{t}}}{\Delta t} \qquad (7)$$

### 2.2 Selection of PCM and thermal characteristics:

Selection of suitable PCM for thermal enhancement is another goal of this work. For the selection of PCM, different criteria is considered such as cost, availability, thermal property etc. In this work three common PCMs, Octadecane, Paraffin wax, and Calcium Chloride Hydroxide ($CaCl_2.6H_2O$) are primarily selected for their thermal performance analysis. Several related properties of them are listed in Table 1 to Table 3

**Table1** Thermal Properties of Octadecane

| Description | value |
|---|---|
| Phase changing temperature((°C) | 28-28.2 |
| Latent Heat(kJ/kg) | 189 |
| Density**(**Kg/$\mathbf{m^3}$) | |
| Solid | 814 |
| Liquid | 774 |
| Thermal conductivity (W/mK) | |
| Solid | 0.358 |
| Liquid | 0.152 |
| Specific Heat(kJ/kg K) | |
| Solid | 2.15 |
| Liquid | 2.18 |
| Thermal diffusivity ( $m^2$/s) | |
| Solid | $1.49\times10^{-7}$ |
| Liquid | $1.47\times10^{-7}$ |

**Table2** Thermal Properties of Paraffin Wax

| Description | value |
|---|---|
| Phase changing temperature((°C) | 32-32.2 |
| Latent Heat(kJ/kg) | 251 |
| Density**(**Kg/$\mathbf{m^3}$ **)** | |
| Solid | 830 |
| Liquid | 830 |
| Thermal conductivity (W/mK) | |
| Solid | 0.514 |
| Liquid | 0.224 |
| Specific Heat(kJ/kg K) | |
| Solid | 1.92 |
| Liquid | 3.26 |
| Thermal diffusivity ($m^2$/s) | |
| Solid | $2.44\times10^{-7}$ |
| Liquid | $2.26\times10^{-7}$ |

**Table3** Thermal Properties of $CaCl_2.6H_2O$

| Description | value |
|---|---|
| Phase changing temperature((°C) | 29-30 |
| Latent Heat(kJ/kg) | 170 |
| Density**(**Kg/$\mathbf{m^3}$ **)** | |
| Solid | 1706 |
| Liquid | 1538 |
| Thermal conductivity (W/mK) | |
| Solid | 1.09 |
| Liquid | 0.546 |
| Specific Heat(kJ/kg K) | |
| Solid | 2.06 |
| Liquid | 2.23 |
| Thermal diffusivity ($m^2$/s) | |
| Solid | $2.31\times10^{-7}$ |
| Liquid | $1.36\times10^{-7}$ |

## 3. Result and Discussion

The governing equations and boundary conditions are discretized using finite difference explicit method. The composite wall is divided into 50 number of nodes as shown in Fig.2. The simulation is performed in Python programming language maintaining a 2s time step. At first initial temperature throughout the wall is considered to be 0 ºC and the simulation is continued for 5 days to get realistic initial values. Using this initial values, a full day simulation starting from 6 am is performed.

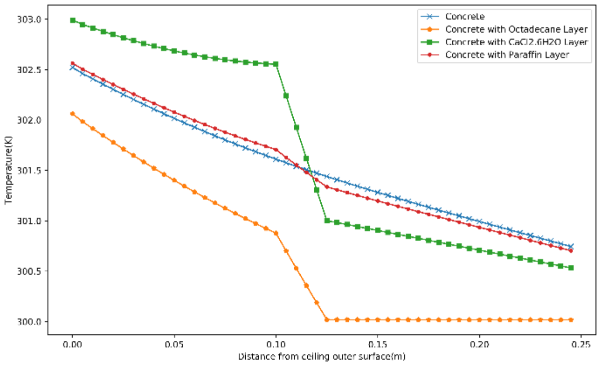

**Fig.3**(a) Variation of temperature with distance from the outer concrete layer at 12 pm.

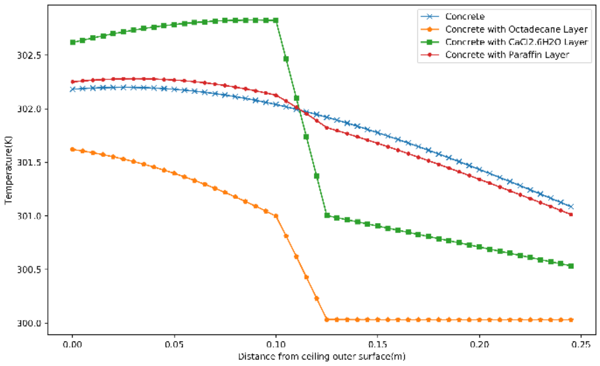

**Fig.3**(b) Variation of temperature with distance from the outer concrete layer at 6 pm.

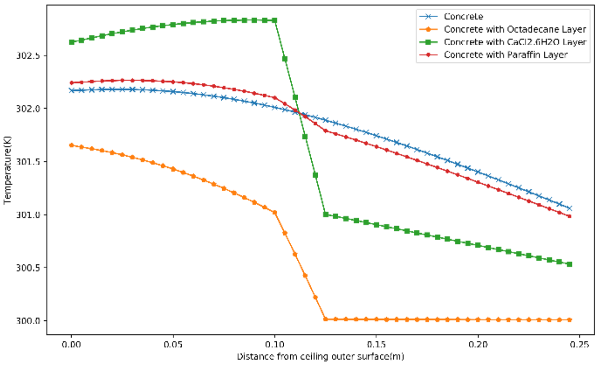

**Fig.3**(c) Variation of temperature with distance from the outer concrete layer at 12 am.

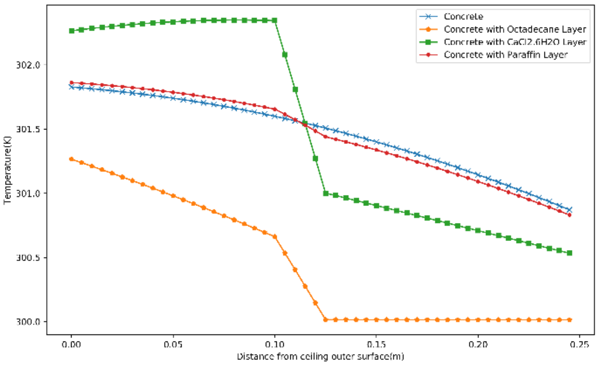

**Fig.3**(d) Variation of temperature with distance from outer concrete layer at 6 am.

The results from the simulation at 6 hours interval are shown in Fig.3(a), Fig.3(b), Fig.3(c), and Fig.3(d). From Fig.3 (a) (after 6 hours at 12 pm), it is observed that concrete with calcium chloride hydroxide(CCH) layer produces the highest temperature (about 30 ºC) at the first node ( at outer concrete surface), while concrete with Octadecane produces the lowest temperature there ( about 29.06 ºC). Normal concrete and concrete with Paraffin wax layer produce approximately same temperature at node 1(29.52 ºC and 29.56 ºC respectively). Throughout the PCM layer, CCH layer produces the highest temperature drop (about 1.55 ºC). Paraffin shows the lowest temperature drop among the PCMs (0.37 ºC) which is higher than that of concrete (about 0.17 ºC). As a result, temperature is slightly lower than that of concrete in this region. Octadecane produces a temperature drop of about 0.85 ºC, which is between the value of CCH and Paraffin. Below the PCM layer, temperature curve of concrete with Octadecane layer becomes flatter and parallel to x axis, which interprets least heat flux gain through the room. Temperature value at last node on the wall with CCH layer has a smaller value than that of Paraffin and concrete (about 300.53 ºC). Paraffin produces slightly less temperature than concrete (300.70 ºC) and the temperature profile is approximately similar to concrete. Paraffin and CCH are in solid and saturated state respectively and Octadecane is mostly in liquid state (negligible portion is in solid state) at this time (12 pm).

Fig.3(b) shows the temperature profile after 12 hours (at 6 pm). From this figure, it is observed that heat conduction occurs from PCM layer towards outer concrete surface for wall with CCH and Paraffin layer, but heat convection to environment doesn’t occur because of higher environment temperature than concrete outer surface. But for wall with octadecane layer, heat conduction direction doesn’t change. The phase of CCH and Paraffin don’t change while Octadecane completely converts into liquid phase. The style of temperature profile below PCM layer remains same for three PCMs as stated in Fig.3(a).

Fig.3(c) and Fig.3(d) (after 18 hours and 24 hours respectively) show similar trend as stated in Fig.3(b) for three PCMs except heat is convected from upper concrete surface to environment for wall with CCH and Paraffin layer for Fig.3(c). The style of temperature profile remains same for Octadecane integrated wall but negligible portion of Octadecane turns into solid.

These stated phenomena can be attributed to the thermal diffusivity and melting point of the studied PCMs. From Table 1,Table 2 and Table 3, Octadecane has the least thermal diffusivity in solid state and slightly higher diffusivity than CCH in liquid state. For its smaller thermal diffusivity value, once it reaches liquid state, it tends to maintain this state with lower temperature variation. CCH has higher diffusivity in solid state but its melting point is very close to Octadecane. So its temperature profile is effected by its periodical change in diffusivity value. On the other hand, Paraffin wax has higher melting point and highest thermal diffusivity in both phases. For this characteristics, it shows temperature profile similar to concrete, which makes it less applicable in heat control area.

From these mentioned results, Octadecane can be chosen as suitable PCM for the stated application of this study because of its lower melting point and lower thermal diffusivity in both phases. On the other hand, Paraffin is less applicable for its higher melting point and thermal diffusivity. CCH also lacks potential because of its higher thermal diffusivity value at solid state.

## 4. Conclusion

In this work, feasibility of using phase change material for hospital ward thermal comfort in Bangladesh is studied. Ambient temperature profile of Patuakhali for the month of June and building roof characteristics for Patuakhali Medical College Hospital ward are considered. The feasibility of three PCM, Paraffin wax, Octadecane and Calcium Chloride Hydroxide, as retrofitting option is analyzed with an explicit numerical finite difference method. From this study it is shown that, Paraffin wax is least applicable because of its higher melting point and higher thermal diffusivity value. Calcium Chloride Hydroxide shows potential for its lower thermal diffusivity at liquid state but isn’t recommended for its higher thermal diffusivity at solid state. On the other hand, Octadecane shows potential for its low melting point and low thermal diffusivity value at both liquid and solid state. For this reason, this study recommends Octadecane out of three stated PCMs for thermal comfort application in the studied region.

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## NOMENCLATURE

| | |
|---|---|
| $c_{\mathrm{p}}$ | : specific heat capacity, kJ·kg$^{-1}$·K$^{-1}$ |
| $c_{\mathrm{ps}}$ | : specific heat capacity of solid PCM, kJ·kg$^{-1}$·K$^{-1}$ |
| $c_{\mathrm{pl}}$ | : specific heat capacity of liquid PCM, kJ·kg$^{-1}$·K$^{-1}$ |
| $T_m$ | : Temperature about which phase change occurs, K |
| $\Delta T$ | : half of the temperature range over which phase change occurs, K |
| $h_{\mathrm{sl}}$ | : enthalpy change of solid-liquid, J/kg |
| $\alpha$ | : thermal diffusivity, m$^2$/s |
| $k$ | : thermal conductivity, W/mK |