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A Comparative Study and Parametric Analysis of Phase Change Materials Utilization for Interior Heat Gain Reduction

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Abstract

The thermal performances of five different phase change materials (PCM) are evaluated when they are installed in a concrete wall for a particular climatic zone. The incident solar radiation on the wall varies throughout the day which results in variable heat gain into the room through the concrete wall. The PCM panel helps in bringing down heat gain and minimizes temperature fluctuation inside the room by absorbing latent heat and undergoing phase change at a constant temperature. The study involves quantifying the amount of phase transition occurring in the PCM throughout a day and also estimating the temperature fluctuation with and without PCM inside concrete wall. Finally, for the given ambient condition the best PCM is chosen which will minimize the temperature inside the room and reduce temperature fluctuation.

Keywords: Phase Change Materials, Incident Solar Radiation, Latent Heat, Heat Gain, Temperature Fluctuation.

1. Introduction

After the realization of PCMs potential of producing thermal comfort inside buildings by passive means, many methods of incorporating PCM in building walls have been widely studied [1,2]. In addition to this, the thermal performances of different types of walls having different quantities of PCM were investigated [3-6]. Alqallaf et al [7] studied the thermal performance of building roofs with cylindrical holes containing PCM. Maximum reduction in heat flux (inside the room) with cylindrical holes containing PCM was reported to be 17.26%. In addition to building walls and roofs, the potential of PCM has also been tested to be used in building windows and floors. Ismail & Henriquez [8] discussed incorporating a moving curtain of PCM in building windows. In the study made by Barzin et al [9], PCM was incorporated under the floor of a room along with an electrical heating element to maintain the floor temperature of the room within the comfort zone. A similar study of PCM based underfloor heating system was made in [10]. These studies showed PCMs change the thermal inertia of buildings by acting as energy storage media which facilitate shifting the electrical load from high demand hours to low demand hours. A detailed study on changing the thermal inertia of different types of buildings by incorporating PCM was made by Hed [11].

The thermal insulation enhancement of buildings by using PCM was studied in both cold and hot environments. Waqas & Kumar [12] discussed the use of PCM in cold climate to minimize the use of conventional fuel for indoor space heating which can also minimize pollution created by the conventional fuel usage. The main parameters affecting the performance of PCM in a cold environment are found to be melting point of PCM, the rate of flow of air and mass of PCM. A similar study was made in [13] where the use of PCM in hot and dry climate is studied. This study infers that the PCM gives maximum thermal performance in hot and dry climate when the melting point of the PCM is equal to the comfort temperature of the hottest month of summer.

There were few other studies made in tropical climatic conditions explaining the efficacy of PCM utilization in buildings. Pasupathy et al [14] did a study where the experimental investigation involved utilization of PCM embedded roof demonstrating their significance as roof insulation. However, the study did emphasize the PCM utilization in tropical climate but a comprehensive mapping of different PCMs in hot and dry climate of South East Asia is still a less explored area. From the critical review of the present state of the art of PCM utilization in buildings, it can be concluded that further studies on PCM utilization in buildings with consideration of hot and dry climatic conditions of South East Asia will reveal promising outcomes.

This study aims in evaluating the thermal performance of a rectangular panel of PCM packed inside a concrete wall under known variations of incident solar radiation and outside ambient condition of a room enclosed by the PCM embedded wall. For the given ambient condition and incident radiation along with their respective variations, the relative performances of five different PCMs (Table 1) are compared to find the best PCM for the given ambient condition.

Table 1: Properties of PCM used in the study [9, 11, 12]

PCM	Melting point (Tm) K	Latent heat of fusion (L_f) kJ/kg	Density of solid phase (ρ_s) kg/m^3	Density of liquid phase (ρ_l) kg/m^3	Thermal conductivity of solid phase (k_s) W/m K	Thermal conductivity of liquid phase (k_l) W/m K	Specific heat of solid phase (C_s) J/kg K	Specific heat of liquid phase (C_l) J/kg K
n-Eicosane	310	241	778	856	0.15	0.15	2010	2040
Calcium Chloride Hexahydrate (CCH)	303	187	1710	1530	1.09	0.53	2200	1400
Paraffin Wax	305	251	830	830	0.514	0.224	1920	3260
Gallium	303	80.16	6095	6093	33.5	32	340	382
Sodium Hydrogen Phosphate Dodecahydrate (SHPD)	309	280	1520	1446	0.514	0.476	1690	1940

2. Modeling of PCM embedded building wall

The physical system for the current study is comprised of a PCM layer sandwiched between two layers of concrete as shown in Figure 1. Dimensions of the system are taken from [14].

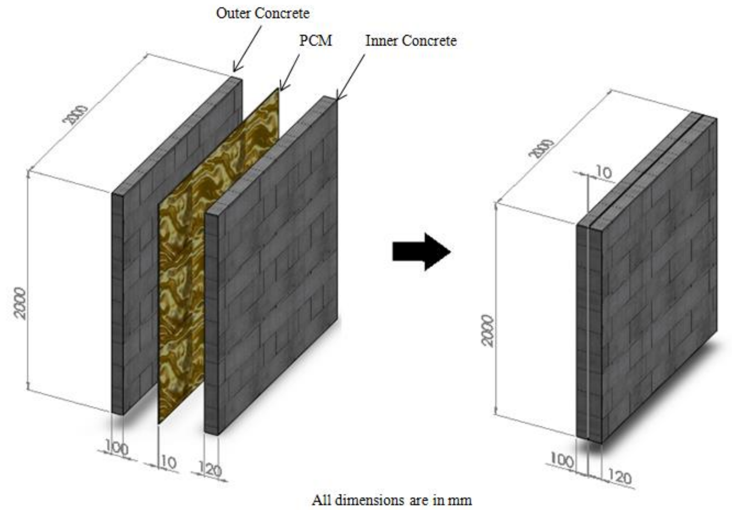

Figure 1: Schematic of the physical system

The outer concrete layer is exposed to solar radiation and ambient climate while the inner layer of concrete is facing the room interior. From [15] value of convective heat transfer coefficient for air and PCM wall can be conveniently taken as h_i=h_o=h=8.3 W/m^{2}K. Also from [16] incident solar radiation and ambient temperatures are taken for a wall facing East in the city Jodhpur. The month of May is chosen for the assessment of the thermal performance of the PCM. The variation of ambient temperature and sol-air temperature during a diurnal cycle have been depicted in Figure 2.

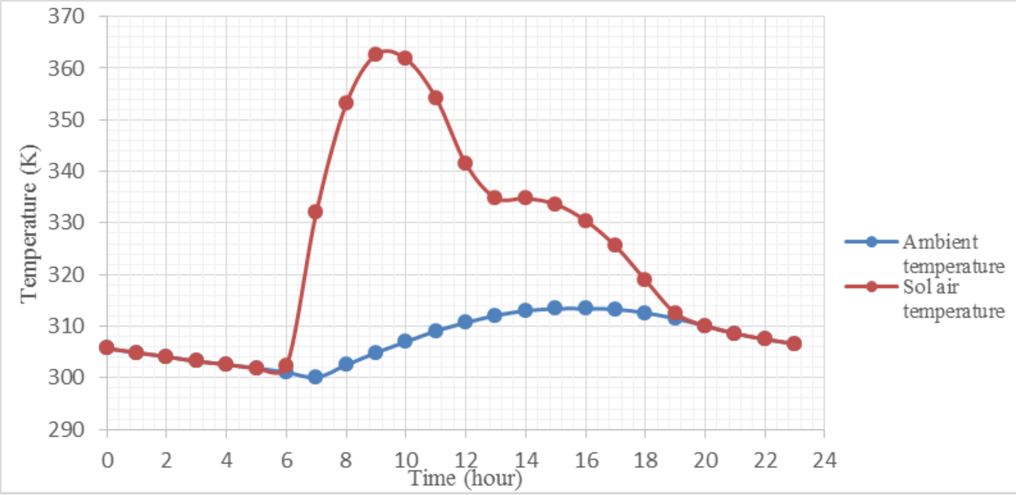

Figure 2: Variation of ambient temperature and sol-air temperature with time

Governing equation of heat transfer (in one direction) by conduction with no internal heat generation is given by

$$\frac{\partial^2 T}{\partial x^2} = \rho C dT / k dt \qquad (1)$$

Where x denotes the thickness direction of the concrete wall. T is the temperature of the solid through which heat flows by conduction, ρ is the density, C is specific heat capacity and k is thermal conductivity of the material. dT is the change in temperature of the solid in time dt.

2.1 Assumptions

Following are the assumptions considered in the study.

1. Heat transfer occurs only along the thickness direction of the wall (one dimensional heat transfer)
2. Both the PCM and concrete have isotropic material properties.
3. The material properties of PCM and concrete do not change with temperature and time.
4. Inside temperature of the room is kept constant at 300 K [14].

At the time of installation, the PCM is assumed to be in solid state at a temperature of 300 K. However the comparison of the performances of different PCMs is carried out only after their performances become repetitive beyond a certain number of diurnal cycles irrespective of the initial state assumed for the PCMs.

2.2 Mathematical formulation

The outer concrete layer and inner concrete layer are subdivided into smaller nodes of size equal to that of the PCM. Basic energy conservation equation is applied to all the nodes taking into account all the thermal properties of the concrete and PCM. Sol-air temperature is defined as the imaginary temperature of the ambient in contact with the wall surface, which would result in the same amount of heat transfer, by convection as the combined effect of radiation and convection in the actual situation. It is defined in equation (2).

$$T_{sol} = T_o + \frac{abs \times I}{h_o} \qquad (2)$$

The present heat transfer problem involves two independent variables x (along the thickness direction of the wall) and t (time) and a dependent variable T (temperature).

$$T = f(x,t) \qquad (3)$$

For transient one directional heat transfer, the time derivative of temperature is written in the following explicit form.

$$\frac{dT}{dt} = \frac{T(x, t+\Delta t) - T(x,t)}{\Delta t} \qquad (4)$$

The nodal form of equation (4) is

$$\frac{dT}{dt} = \frac{T_{i,j+1} - T_{i,j}}{\Delta t} \qquad (5)$$

where the nodal variable j is defined by as t=(j-1)Δt and j=1 corresponds to t=0.

The x (thickness) derivative of temperature is expressed by the following explicit equation.

$$\frac{\partial^2 T}{\partial x^2} = \frac{T(x-\Delta x, t) - 2T(x,t) + T(x+\Delta x, t)}{\Delta x^2} \qquad (6)$$

The nodal form of equation (6) is

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i-1,j} - 2T_{i,j} + T_{i+1,j}}{\Delta x^2} \tag{7}$$

Combining equation (4) and equation (6) we get the explicit equation (8) which enables calculation of temperature at any node at any time step.

$$T(x, t + \Delta t) = \frac{\alpha \Delta t}{\Delta x^2}\left[T(x - \Delta x, t) + T(x + \Delta x, t)\right] + \left[1 - 2\frac{\alpha \Delta t}{\Delta x^2}\right] T(x, t) \tag{8}$$

The nodal form of equation (8) can be expressed as

$$T_{i,j+1} = \frac{\alpha \Delta t}{\Delta x^2}\left[T_{i-1,j} + T_{i+1,j}\right] + \left[1 - 2\frac{\alpha \Delta t}{\Delta x^2}\right] T_{i,j} \tag{9}$$

For the first element (i=1) which is exposed to ambient following equation is used to calculate the temperature at any time step t.

$$T_{1,j+1} = T_{1,j}\left[1 - 2Fo(1 + Bi)\right] + 2FoBiT_o + 2FoT_{2,j} \tag{10}$$

Where Fo is the Fourier number defined by Fo = $\frac{\alpha \Delta t}{\Delta x^2}$ and Bi is Biot number defined by Bi = $\frac{h\Delta x}{k}$.

3. Results and Discussion:

With the similar inputs (such as geographic condition, PCM properties, dimensions of the wall) used in Pasupathy et al [14] the output obtained from the numerical model showed very close peak temperatures (308 K in [14] and 307.5 K in present study) of the PCM panel (Figure 3). The slight shift in study curve may be attributed to the fact that the solar radiation values for the study are taken from the standard solar radiation data which is available online. But the solar radiation available on the day of experimentation by Pasupathy might differ from the standard value.

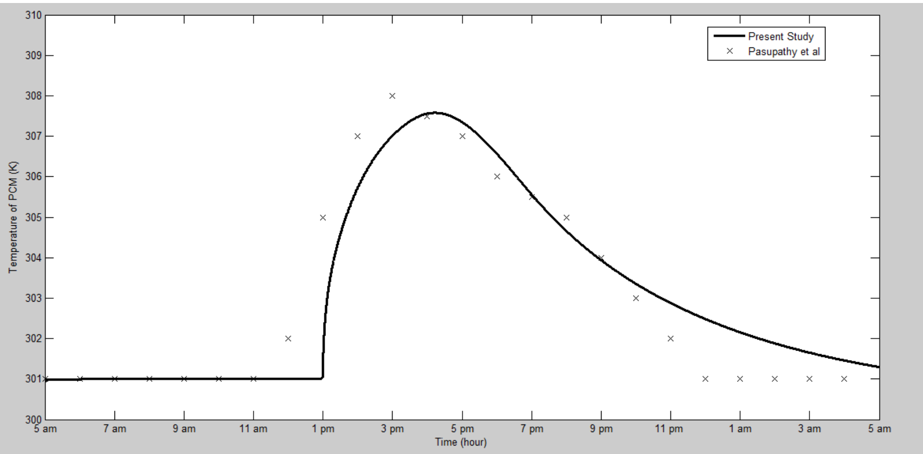

Figure 3: Validation of results of simulation

Firstly, a study is carried out for the concrete wall without any PCM packed inside it. The study showed a high degree of variation of temperature on the inner surface of the concrete wall with a peak temperature of 309.4 K. After this, further analysis is carried out for the same wall with different PCMs packed inside. The temperature variations of different PCM and inner concrete surface are shown in Figure 4.

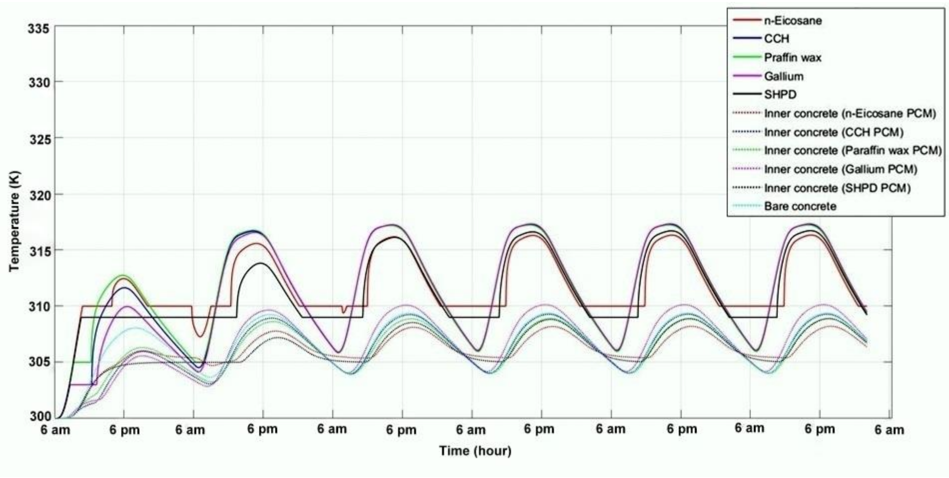

Figure 4: Variation of Temperature with time

For the first diurnal cycle, Sodium Hydrogen Phosphate Dodecahydrate (SHPD) gives minimum inner concrete peak temperature of 306 K. But in the following cycles, the performance of SHPD gradually deteriorates. When the behaviour of all the PCM becomes repetitive after fourth diurnal cycle then n-Eicosane gives minimum peak temperature of inner concrete (308.2 K). Hence for a cycle independent state, n-Eicosane is the most suitable PCM for the given ambient condition followed by SHPD. It is also observed that when Gallium is used as PCM, the inner concrete peak temperature rises above the temperature the wall would have achieved without any PCM. This is justified by the fact that Gallium starts behaving as a superheated liquid with a thermal conductivity higher than an equivalent layer of concrete. This reduces the thermal insulation of the wall and raises the peak temperature of inner concrete. Calcium Chloride Hexahydrate (CCH) and Paraffin Wax work in the superheated liquid regime after their behavior become repetitive from the 4th cycle. It is because they have lower melting points. The density of Gallium is very high compared to the other PCMs. This means more mass of PCM can be packed inside concrete wall and more heat will be required to melt the PCM panel. However, the latent heat of fusion and specific heat of Gallium are low compared to the other PCMs used in the study. This will reduce the heat storage capacity of the PCM panel. The overall effect is, Gallium behaves in a similar manner as Paraffin Wax and CCH. Due to the inability to return to solid phase during night hours Gallium, Paraffin Wax and CCH are not suitable for the given ambient conditions.

The solid phase mass variation curve (Figure 5) clearly indicates that only two PCM (n-Eicosane and SHPD) are able to go back to solid phase (charging of PCM during night hours) out of the five PCMs studied as indicated by the positive peaks beyond 1st diurnal cycle. Consequently, latent heat property of only SHPD and n-Eicosane can be utilized in the given condition. Out of these two, n-Eicosane gives minimum peak temperature of inner concrete with minimum temperature fluctuation throughout the cycle. Therefore, n-Eicosane is determined as the most suitable PCM of the five PCM studied for the given ambient conditions.

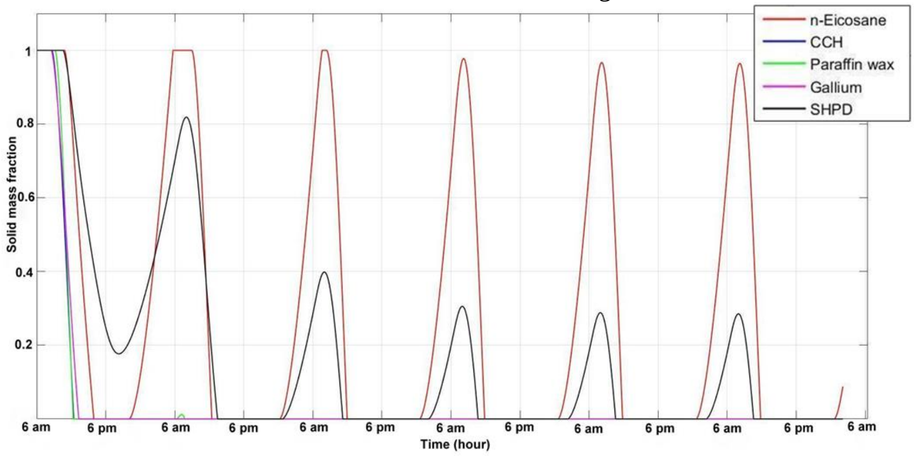

Figure 5: Variation of solid phase mass fraction with time

4. Conclusion

For the given geographic conditions of Jodhpur following conclusions are made from the study:

1. n-Eicosane gives a peak temperature of inner concrete 308.2 K and peak PCM temperature of 316.3 K. After the thermal performances of all the five PCMs become repetitive from the fourth diurnal cycle, n-Eicosane gives the minimum peak temperature of inner concrete with minimum temperature fluctuation throughout the cycle. This makes n-Eicosane the most suitable PCM out of the five PCMs discussed in the study for the given ambient condition and configuration.
2. For CCH peak temperature of inner concrete is 309.3 K (Peak PCM temperature is 317.3 K), for Paraffin wax peak temperature of inner concrete is 308.9 K (Peak PCM temperature is 317.2 K) and for Gallium peak temperature of inner concrete is 310.1 K (Peak PCM temperature is 317.3 K) after these PCM's thermal performance become repetitive from fourth cycle. These three PCMs have low melting points, small latent heating duration and result in high temperature fluctuation. Moreover, these three PCMs cannot completely solidify at the end of the first 24-hour cycle. So their performances deteriorate in the following cycles where the duration of latent heating is further reduced and duration of sensible heating is further increased. From the fourth cycle, these three PCMs start operating in the superheated liquid region and they cannot come back to solid phase during the night hours. Thus the objective of using PCM is lost. Therefore these three PCMs are not suitable for the given geographic condition.
3. SHPD gives long duration of latent heating at a lower temperature in the first two cycles. Its performance slightly deteriorates from fourth cycle onwards when its behavior becomes repetitive. However, the situation is not as unacceptable as in the cases of CCH, Paraffin Wax and Gallium because SHPD can return to solid phase during the night hours like n-Eicosane thereby reducing temperature fluctuation inside the room. The peak inner concrete temperature is 308.8 K while the peak temperature of the PCM is 316.7K. SHPD can be used as an alternative of n-Eicosane with a slightly reduced thermal performance for the given ambient conditions.

References:

[1] K. Peippo, P. Kauranen, P.D. Lund, A multicomponent PCM wall optimized for passive solar heating, Energy Buildings 17 (1991) 259–270.

[2] D.A. Neeper, Thermal dynamics of wall board with latent heat storage, Solar Energy 68 (2000) 393–403.

[3] Y. Zhang, G. Zhou, K. Lin, Q. Zhang, H. Di, Application of latent heat thermal energy storage in buildings, Building Environment 42 (2007) 2197–2209.

[4] A. Khudhair, M. Farid, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, Energy Conservation Management 45 (2004) 263–275.

[5] N. Zhu, Z. Ma, S. Wang, Dynamics characteristics and energy performance of building using phase change material: a review, Energy Conservation Management 50 (2009) 3169–3181.

[6] L.F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, A.I. Fernández, Materials used as PCM in thermal energy storage in buildings: a review, Renewable Sustainable Energy Reviews 15 (2011) 1675–1695.

[7] H. J. Alqallaf & E. M. Alawadhi, Concrete roof with cylindrical holes containing PCM to reduce the heat gain. Energy and Buildings 61 (2013) 73–80.

[8] K.A.R. Ismail, J.R. Henriquez, Thermally effective windows with moving phase change material curtains, Applied Thermal Engineering 21 (2001) 1909–1923.

[9] R. Barzin, John J.J. Chen, B. R. Young, M. M. Farid, Application of PCM underfloor heating in combination with PCM wallboards for space heating using price based control system. Applied Energy 148 (2015) 39–48.

[10] K. Lin, Y. Zhang, X. Xu, H. Di, R. Yang, P. Qin, Experimental study of under-floor electric heating system with shape-stabilized PCM plates, Energy Buildings 37 (2005) 215–220.

[11] G. Hed, Use of phase change material for change of thermal inertia, in; Proceedings of the 6th Expert Meeting and Workshop of Annex 17, Advanced Thermal Energy Storage through Phase Change Materials and Chemical Reactions – Feasibility Studies and demonstration Projects in Arvika, Sweden, 2004.

[12] A. Waqas & S. Kumar, Phase Change Material (PCM)-Based Solar Air Heating System For Residential Space Heating In Winter, International Journal of Green Energy, 10:4, (2013) 402-426.

[13] A. Waqas & S. Kumar, Utilization of Latent Heat Storage Unit for Comfort Ventilation of Buildings in Hot and Dry Climates, International Journal of Green Energy, 8:1, (2011) 1-24.

[14] A. Pasupathy, L. Athanasius, R. Velraj, R.V. Seeniraj. Experimental investigation and numerical simulation analysis on the thermal performance of a building roof incorporating phase change material (PCM) for thermal management. Applied Thermal Engineering 28 (2008) 556–565.

[15] SP: 41 (S&T) -1987 - handbook on functional requirements of buildings, Bureau of Indian Standards, New Delhi, 1987.

[16] Ministry of New and Renewable Energy. Solar energy, chapter 4 (Thermal Performance of Buildings).