Journal of Pure and Applied Science & Technology Copyright © 2011 NLSS, Vol. 3(1), Jan 2013, pp. 44-54

Modeling of PCM Wall of a Building for the Management of Thermal Load

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A theoretical model based on enthalpy formulation and fully implicit finite difference method, has been used for one-dimensional model to predict the time-wise variation of latent heat stored and melt fraction of PCM in the designed model. The objective of this paper is to predict the thermal performance of a latent heat thermal energy storage system roof, a building component which contributes maximum heat load inside the building and comparison of heat load reduction due to addition of PCM wall. Stored heat can easily be utilized for any other application or can be flushed to the ambient.

Keywords: Enthalpy, Latent heat, (PCM) Phase change materials, Heat load.

1. INTRODUCTION

The challenge of energy in the future is clear. It has become necessary to seek effective means of reducing peaks in power consumption and to shift portions of the load from periods of maximum demand. In this context, Thermal Energy Storage (TES) systems can play an important role. Thermal energy storage systems enable greater and more efficient use of these fluctuating energy sources by matching the energy supply with demand. Phase change materials have been considered for thermal storage in buildings since before 1980.

To understand the dynamic behavior of thermal management system, understanding of heat transfer is an important aspect. A number of experimental and theoretical studies have been made on the thermal performance of latent heat thermal energy storage systems for various applications [1-12]. Due to low thermal conductivity of phase change materials (PCM), these systems have an inherent disadvantage of slow heat transfer during the charging and discharging process of the PCM. To enhance the heat transfer, fins in a latent storage system were suggested by Abhat [2] and studied by Smith et al. [1], Humphries [9], Humphries et al. [10] and Henze et al. [11]. Theoretical efforts were also made to study the thermal performance of latent heat storage systems by Laudi et al. [12], Domanski et al. [13], Bansszek et al. [14], Zivkovik et al. [15], Costa et al. [16], Sharma et al. [17] and Sharma et al. [18].

Most of the model developed both for the purpose of numerical technique or parametric study and not for the system in particular for building component. In our mathematical models, we have used enthalpy based formulation for the study of roof having phase change material as thermal management unit, which contributes maximum heat load inside the building. Study has been done for one dimension heat transfer for the variation of absorber plate temperature, heat storage and PCM melt fraction with time.

2. METHODOLOGY

2.1 Numerical Simulation of the System

For the analysis of the system, the following assumptions have been made:

i) Thermo-physical properties of PCM and fin material are independent of temperature. However, they are different for solid & liquid phases of PCM.
ii) The PCM is initially in the solid phase
iii) The PCM is homogenous and isotropic
iv) For one-dimensional simulation, the effects of fins are considered negligible

A material undergoing a phase transformation (solid to liquid or vice versa), conservation of energy can be expressed in terms of temperature and total volumetric enthalpy as

$$\frac{\partial H}{\partial t} + \nabla(uH) = \nabla(K_k(\nabla T)) \tag{1}$$

For constant thermo-physical properties, the above energy conservation equation will reduce to [20]:

$$\frac{\partial H}{\partial t} = \nabla(K_k(\nabla T)) \tag{2}$$

where the total volumetric enthalpy H is the sum of the sensible and latent heats of the PCM, i.e.

$$H(T) = h(T) + \rho_l f(T)\lambda \tag{3}$$

where $$h(T) = \int_{T_m}^{T} \rho_k C_k \, dT \tag{4}$$

In case of isothermal phase change, the liquid fraction of melt is given by

$f = 0$ if $T < T_m$ (solid),
$f = 1$ if $T > T_m$ (liquid), (5)

and, if $0 < f < 1$ the region is called mushy.

2.2 Temperature-Enthalpy Relation

Following equations (3) and (4), the enthalpy of the PCM is

$$H = \int_{T_m}^{T} \rho_s C_s \, dT \qquad T < T_m \text{ (solid)}, \tag{6a}$$

and $$H = \int_{T_m}^{T} \rho_l C_l dt + \rho_l \lambda \qquad T > T_m \text{ (liquid)} \tag{6b}$$

Solving equation (5) for the PCM temperature, one gets

$$T = T_m + \frac{H}{\rho_s C_s} \qquad H < 0 \text{ (solid),}$$

$$T = T_m \qquad 0 \le H \le \rho_L \lambda \text{ (interface),}$$

$$T = T_m + \frac{H - \rho_l \lambda}{\rho_l C_l} \qquad H > \rho_L \lambda \text{ (liquid).}$$

Using equations (3) and (4), an alternative form of equation (1) for one-dimensional heat transfer in the PCM can be obtained as

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\alpha \frac{\partial h}{\partial x} \right) - \rho_l \lambda \frac{\partial f}{\partial t} \tag{7}$$

2.3 Numerical Solution

Equation (7) is solved using a fully implicit finite difference solution method. The finite difference equation for the PCM is obtained on integrating equation (7) over each control volume. Equation (7) has been solved by using TDMA iterations and the liquid fraction update method as proposed by Costa et al (16) and Voller [19].

2.4 Boundary and Initial Conditions

Equation (7) has been solved for the following initial and boundary conditions.

Initially, the PCM is solid, and its temperature is assumed at a certain temperature below the melting point, viz.

$$h_{init} = \rho_s C_s (T_m - T_{init}) \tag{8}$$

The boundary condition at face x = 0 can be described as

$$h(0,t) = \rho_k C_k \left(T_{Abs} - T_m \right) \tag{9a}$$

i.e. the volumetric enthalpy on the face x = 0 is known at each time and, the face x = L is adiabatic, i.e.

$$\frac{dh}{dx} = 0 \tag{9b}$$

Flow chart used for computational calculation procedure is shown in Figure 1.

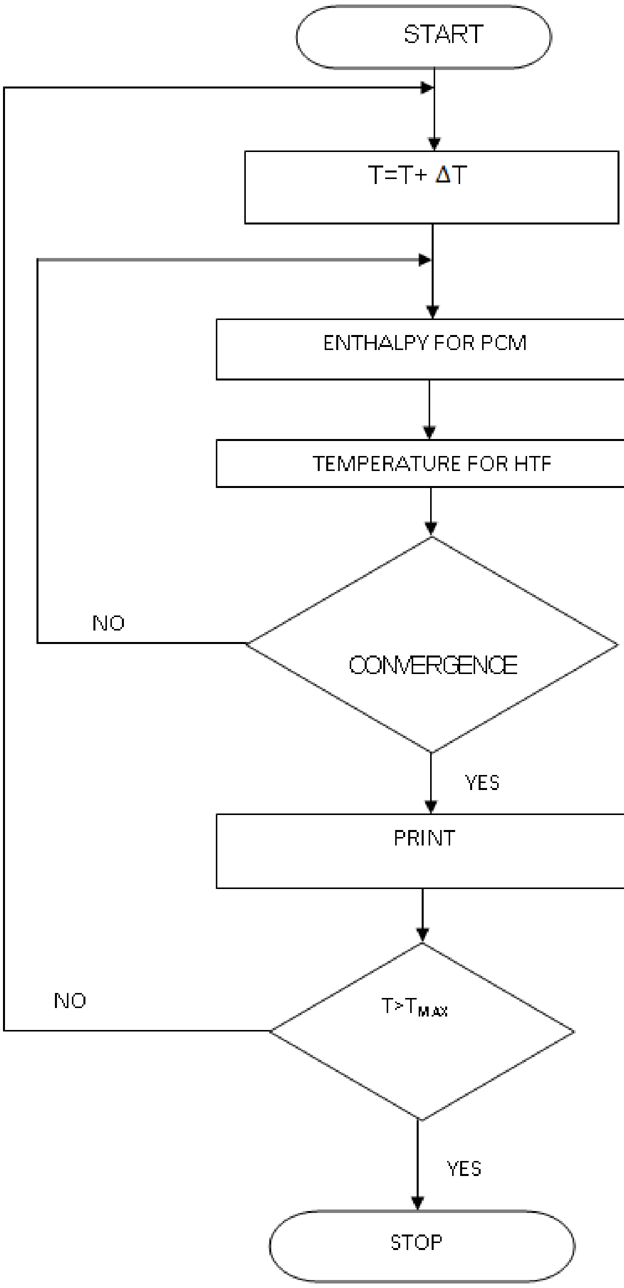

Fig. 1: Flow Chart for Computational Calculations.

3. RESULTS AND DISCUSSION

Schematic view of advance thermal management system integrated with roof is depicted in Figure 2.

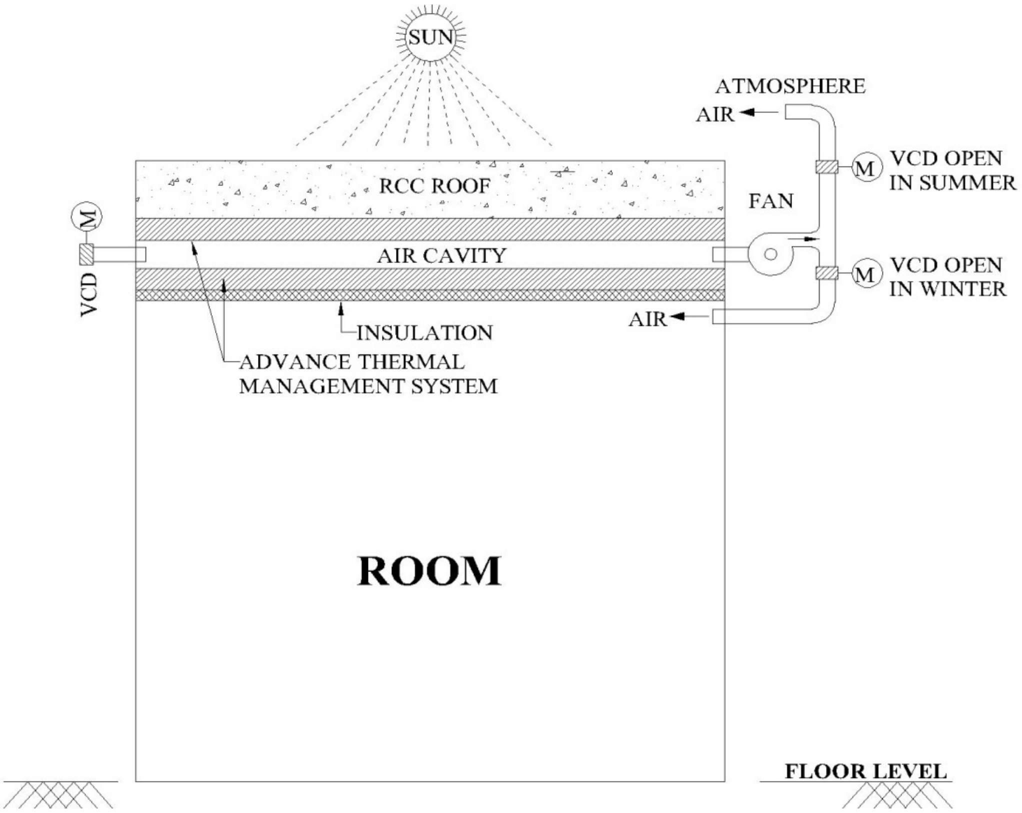

Fig. 2: Schematic view of Roof with Thermal Management System.

One-dimensional discretization of their equation (7) is shown in Figure 3.

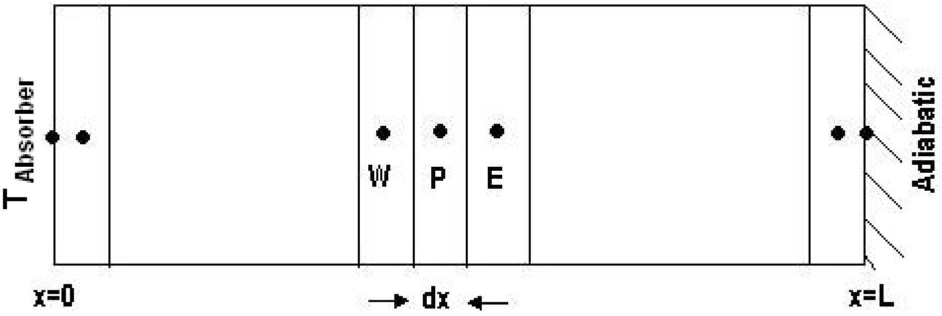

Fig. 3: One-dimensional domain.

For one-dimensional calculations, 32 space steps of 3.1 mm and the time step of 2 minutes has been used. These steps were obtained by optimizing for space and time domain being selected. The thermo-physical properties of paraffin used in calculations are given in Table 1.

Table 1: Thermo-Physical properties of n-octadecane.

Properties	**Value**
Melting point	27.7°C
Latent heat	243.5 $kJkg^{-1}$
Density (liquid)	777 kgm^{-3}
Thermal conductivity (liquid at 313 K)	0.148 W/m K
Thermal conductivity (solid at 298 K)	0.358 W/m K
Thermal Diffusivity (liquid at 313 K)	8.64×10^{-8} m^2/s
Thermal Diffusivity (solid at 298 K)	2.14×10^{-7} m^2/s
Kinematic viscosity (liquid at 313 K)	4.013×10^{-6} m^2/s
Thermal expansion coefficient	9.0×10^{-4} K^{-1}

The initial temperature of PCM was assumed 5°C less than the melting point of the PCM. To see the effect of absorber temperature on the melting rate, calculations have been made with 5°C, 10°C, 15°C and 20°C higher temperature of the absorber temperature than the melting temperature for melt fraction, heat stored and PCM temperature. This absorbing surface temperature is indicated as Tm+ 5°C, Tm+10 °C, Tm+15 °C and Tm+20°C. The latent heat energy stored by the system for different input temperature of absorber surface is depicted in Figure 4.

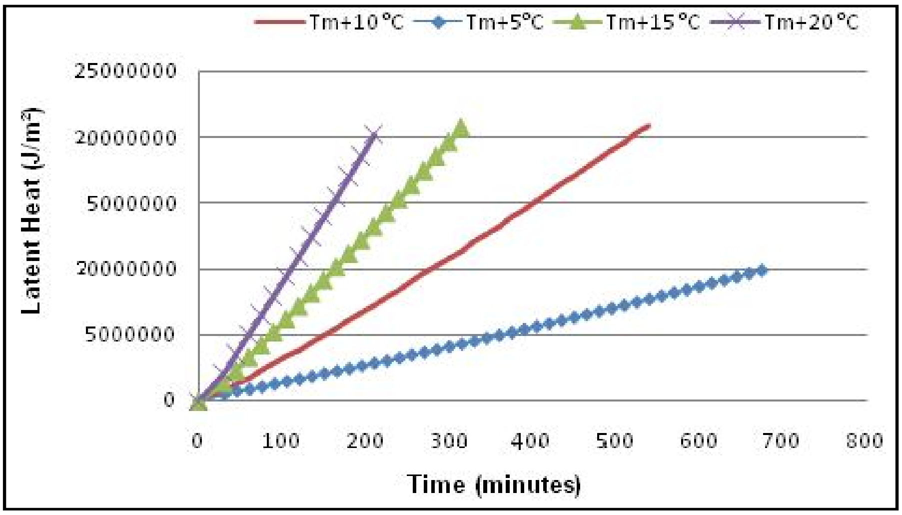

Fig. 4: Time wise variation of heat stored in TMS at different absorbing surface temperature.

From the figure, it can also be seen that as the temperature difference between the absorber and the melting point of the PCM increases the higher amount of heat is stored in less time and the same is also tabulated in Table 2.

Table 2: Time taken, Latent Heat Stored and Melt Fraction with different absorber surface Temperature.

Absorber Surface Temperature (°C)	Time (Minute)	Heat Stored (kJ/m^2)	Fraction of Melt (%)
Tm+5	660	9.85x10^6	47
Tm+10	525	2.07x10^7	100
Tm+15	315	2.07x10^7	100
Tm+20	210	2.07x10^7	100

Variation of melt fraction of PCM with time is plotted in Figure 5 for different surface temperature. It can be seen from the figure that the time taken for melting of PCM decrease as the exposed surface temperature increase from 5 °C to 20 °C higher than the melting point. The time taken for 100% melting decreases from 660 minutes to 210 minutes as the surface temperature increases from 5 °C to 20 °C higher than the melting point. Time taken for complete melting for various temperature differences is shown in Table 3.

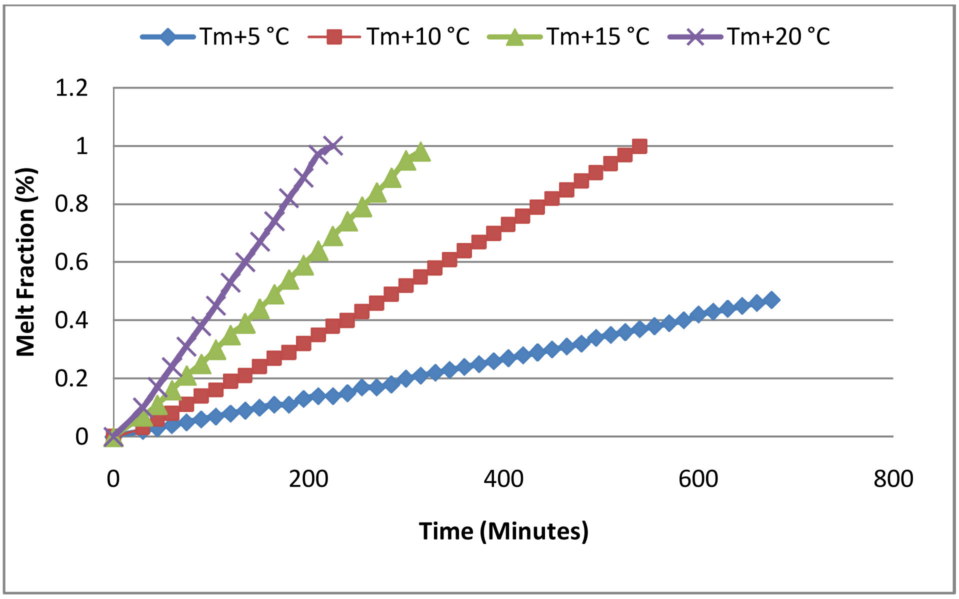

Fig. 5: Variation of melt fraction of PCM with time at different absorbing surface temperatures.

Table 3: Variation of different Nodes Temperature, Melt Fraction with Time for different absorbing surface Temperature.

Time (Minutes)	Melt Fraction (%)		Node No. 1 Temp (°C)		Node No. 16 Temp (°C)		Node No. 32 Temp (°C)	
	Tm+5	Tm+20	Tm+5	Tm+20	Tm+5	Tm+20	Tm+5	Tm+20
0	0	0	32.7	47.7	22.7	22.7	22.7	22.7
30	2	10	32.7	47.7	23.1	23.4	23.0	23.0
105	7	45	32.7	47.7	24.6	27.6	23.4	24.1
210	14	100	32.7	47.7	26.0	37.4	24.9	27.7
315	21	-	32.7	47.7	26.8	-	25.9	-
420	28	-	32.7	47.7	27.4	-	26.8	-
525	35	-	32.7	47.7	27.7	-	27.4	-

To see the variation of temperature at different nodes inside the PCM for temperature difference of 5 °C, 10 °C, 15 °C and 20 °C at different given times are shown in Figure 6. Obviously, the temperature as the melt fraction of PCM increases with time the temperature of the last node PCM roof facing towards room increases.

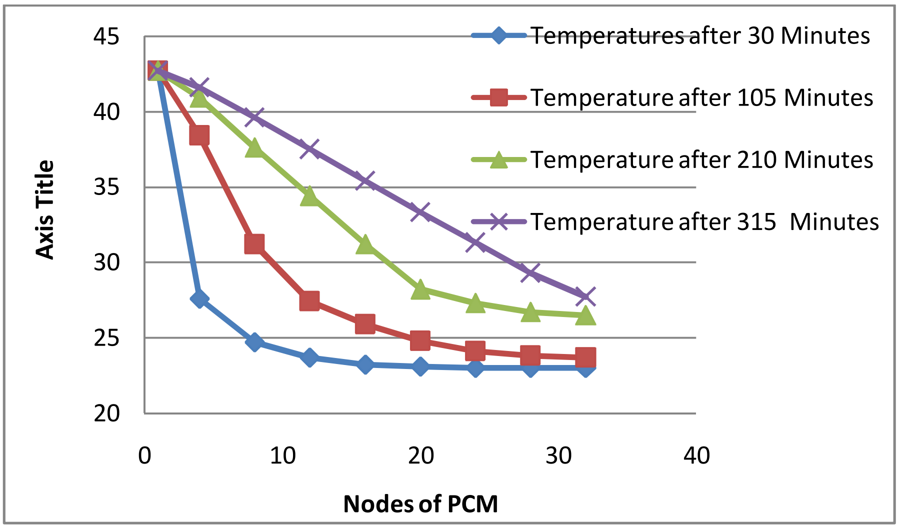

Fig. 6: Time wise variation in Temperatures at various nodes at Tm+15 °C Temperature of absorbing surface.

To compare the heat load entering through roof with and without PCM, calculations have been made for a configuration given in Table 4. Based on it heat load penetrating is tabulated in Table 5 and one can easily see that use of PCM has reduced 80% heat load, Hence, the reduction in the size of Air conditioning equipment.

Table 4: Thermo-physical properties of fire clay bricks and Load calculation parameters.

Parameter	Fire clay brick
Density	1600 kg/m^3
Thermal Conductivity	0.675 W/m K
U value of roof	0.235 W/m^2 K
Outdoor temperature	43.5 °C
Indoor temperature	24.0 °C
Outdoor Relative Humidity	19%
Indoor Relative Humidity	50%
Coil bypass factor	0.1

Table 5: Heat load penetrating through standard roof and PCM roof.

Roof Configuration	Heat Load (W/m^2)
Standard roof of 150 mm	68.6
150 mm roof with 93 mm PCM	13.5

4. CONCLUSION

A theoretical model based on enthalpy formulation and fully implicit finite difference method, has been developed for one-dimensional model to predict the time-wise variation of latent heat stored and melt fraction of PCM in the designed model. Variation of temperature with time for each node in one-dimension model was also obtained. From the results obtained authors can conclude that due to the use of PCM in advance thermal management system contributes:

i) Storing of solar energy incident on the roof prevents the entering of heat inside the living space during peak temperature hours

ii) Creates a time lag in the heat entering inside the building

iii) Reduction in temperature variations.

iv) Stored heat can easily be utilized for any other application or can be flushed to the ambient.

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