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STUDY ON OPTIMUM UTILIZATION OF A PHASE CHANGE MATERIAL FOR COOLING OF A BUILDING

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ABSTRACT

The present work considers a model for understanding the cooling process of a building using phase change material (PCM). The cooling process of the building is represented by a set of mass, momentum and energy conservation equations. These governing equations are discretized based on the control volume method using power law scheme. The obtained linear algebraic equations are solved based on the SIMPLER and TDMA algorithms. In this model, the melting and the solidification of the PCM are represented by the enthalpy update scheme. The simulation predicts the melting and solidification behaviors of the phase change material, temperature of the room in a day. It is found that the recycling of the PCM is not possible for next days. In the present work, aluminum is used as thermal conductivity enhancer (TCE) for complete recycling of the PCM. The simulation finally predicts the optimum amount of the PCM and the aluminum for complete recycling of the PCM.

Keywords: Cooling of a building, Phase Change Material, Thermal Conductivity Enhancer, Thermal Behavior.

1. INTRODUCTION

In the last few decades, a demand for air conditioning has been increased greatly due to the evolving comfort and technological development. It requires a huge consumption of the electrical energy during the day and night time according to the demand by the industrial, commercial and residential activities. It is found that, in hot and cold climate countries, a major part of the total developed power is used for air conditioning and space heating, respectively. But, the continuous use of the fossil fuels to provide this power requirement causes global warming. This global warming and the limited reserves of the fossil fuels addressed a challenge towards the researchers for development of an energy efficient cooling system utilizing the renewable energy sources. Recently, an economically beneficial technology is introduced for heating and cooling of residential and commercial buildings using Phase Change Material (PCM) as a thermal storage device. The PCM stores the heat during peak period and releases the same during off peak period of a day. Hence, the human comfort may be enhanced by encapsulating or embedding a suitable PCM with the walls, ceilings and floor of the buildings.

The present work aims to study the thermal behaviour during cooling of a building roof in case of a hot climate country using a suitable PCM. It is found that the recycling of the PCM is not possible for next days. In the present work, thus, aluminum is used as thermal conductivity enhancer (TCE) for complete recycling of the PCM.

The simulation finally predicts the optimum amount of the PCM and the aluminum for complete recycling of the PCM. It is found that the PCMs are widely used as thermal storage devices in various engineering applications such as in electronic cooling, solar cookers, solar power plants etc. [6]. However, very few works are reported regarding the cooling of the buildings using PCMs and TCE in the literature. In this context, Nayek *et al.* [1] investigated the effectiveness of thermal conductivity enhancers (TCEs) in improving the overall thermal conductance of phase change materials (PCMs) used in cooling of electronics numerically. They showed the performance of heat sinks with various volume fractions of TCE for different configurations with respect to the variation of heat source (or chip) temperature with time; melt fraction and dimensionless temperature difference within the PCM. They found significant effect of the thermal conductivity enhancer on the performance of heat sinks. Fan and Khodadadi [2] investigated a review of experimental/computational studies to enhance the thermal conductivity of phase change materials (PCM) that were conducted over many decades. Their work focused on studies that concern with positioning of fixed and stationary high conductivity inserts/structures. They reported that copper, aluminum, nickel, stainless steel and carbon fiber in various forms were generally utilized as the materials of the thermal conductivity promoters. The reviewed research studies covered a variety of PCM, operating conditions, heat exchange and thermal energy storage arrangements.

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Alawadhi and Amon [3] considered PCM and TCE in electronics devices, which avoid overheating. Peippo *et al.* [4] considered a PCM impregnated plasterboard as a storage component in a lightweight passive solar house with good insulation and a large area of south facing glazing. They found that the house saves up to 3GJ in a year or 15% of the annual energy cost. Ravikumar and Srinivasan [5] considered PCM in the withering course region and found nearly uniform roof bottom surface temperature maintained. Recently, Mukherjee *et al.* [6] carried out a numerical simulation on FORTRAN platform for the thermal behavior for building using only PCM. They found that 60% percentage of PCM is liquefied, complete solidification is not possible and room temperature is reached maximum 29 °C. In this paper, a similar kind of work is presented where the cooling of a concrete roof is performed in details numerically using a suitable phase change material and thermal conductivity enhancer. Accordingly, a FORTRAN based numerical code is developed for simulating the present problem where the governing equations are descritized based on the finite volume method [11]. In addition, the present work considers the melting and the solidification behaviours of the PCM. The melting and solidification behaviours are represented in the present model considering the enthalpy update scheme [8]. Since the hydrated salts are attractive materials for use in thermal energy storage due to its high volumetric storage density, relatively high thermal conductivity and moderate costs; Glauber salt (Na_2SO_4–H_2O) which contains 44% $Na_2SO_4$and 56%H_2O is considered in the present work as a PCM which has melting temperature of 32.4ºC close to human comfort temperature (28–30ºC).

2. DESCRIPTION OF PHYSICAL PROBLEM

In the present case, the cooling of a typical room (10m×10m×10m) using a suitable PCM is considered in the summer season as shown in the Fig. 1. In this work, the cooling of a room using PCM and TCE is considered. The roof of the room is made of concrete. The PCM, used as a thermal storage device and TCE, used as increasing the thermal conductivity is kept on the roof. It is assumed that the room is at a constant temperature of 25°C where heat is transported from the roof by natural convection. The PCM absorbs the solar radiation in the day time and PCM and TCE release the absorbed heat in night time. In the present work, a 2-D geometry is considered due to symmetry of the problem Glauber salt (Na_2SO_4–H_2O) is selected as the PCM such that it absorbs heat during melting in the day time and releases heat in the night. Aluminum is selected as the TCE to increase the thermal conductivity of the system. The thermo-physical properties of the concrete, the PCM and the TCE used in the simulation, are given in table-1.

3. MATHAMETICAL MODELING

The present work considers the cooling of a building in the summer season using a PCM and a TCE.

The PCM melts by absorbing the solar radiation in the day time and it solidifies by releasing heat in the night time. In the night time for the complete solidification, a TCE having high thermal conductivity is used. Both the melting and solidification processes involve fluid flow and heat transfer phenomena. These transport phenomena in the PCM are represented by a set of single-phase mass, momentum and energy conservation equations. The concrete material is assigned by very high viscosity and melting point, which ensures that it remains solid and fixed in the domain. The set of governing equations (Brent *et al.* [8]) for both the concrete and PCM regions is given below.

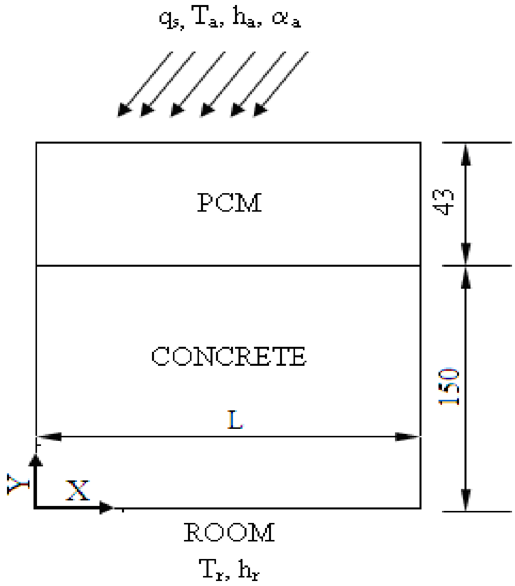

Fig.1. A schematic of the computational domain

Table 1: Thermo-physical properties and system data (Ravikumar and Srinivasan [5])

	Density (kg/m^3)	Thermal Conductivity (W/m-K)	Specific Heat (J/kg-K)	Melting Point (°C)	Latent Heat (J/kg)
Glauber Salt					
Solid	1485	0.544	1420	32.4	254
Liquid	1485	0.544	2100	-	-
Concrete					
	2300	1.28	1130	-	-
Aluminum					
	2700	247	950	660	398

Conservation of mass:

$$\frac{\partial (\rho u_i)}{\partial x_i} = 0 \qquad (1)$$

Conservation of momentum:

The single-phase momentum conservation equation for the *i*th direction is given as

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \nabla.(\mu \nabla u_i) + S_i + \rho g \beta (T - T_{ref}) \qquad (2)$$

In the model, the domain is treated as a porous medium during phase change of the PCM.

The source term S_i (Brent *at el.*, [8]) in the Eq. (2) is used for the purpose, which offers additional frictional resistance towards the fluid flow and given as

$$S_i = Au_i \tag{2a}$$

where A is defined as

$$A = -\frac{C(1-f_l)^2}{f_l^3 + b} \tag{2b}$$

In equation (2a, b), f_l is the liquid fraction of the PCM. The C is a morphological constant whose value is sufficiently large (~1.6×10^6). The term 'b' is a computational constant introduced to avoid division by zero. The additional frictional resistance is zero in the liquid phase ($f_l = 1$) and it varies smoothly from zero to a very large value at the solid phase $(f_l = 0)$.

Conservation of energy:

The single-phase energy equation is given as

$$\frac{\partial(\rho c_p T)}{\partial t} + \frac{\partial(\rho c_p u_i T)}{\partial x_i} = \nabla.(k\nabla T) + S_h \tag{3}$$

where S_h a source term is represents the absorption of the latent heat during melting or evolution of the latent heat during solidification by the PCM. The corresponding latent heat source term S_h is given as

$$S_h = -\frac{\partial}{\partial t}(\rho\,\Delta H) \tag{3a}$$

where

$$\Delta H = 0 \qquad T < T_{melt} \tag{3b}$$

$$= L \qquad T > T_{melt} \tag{3c}$$

The enthalpy value (ΔH) is updated in every iteration based on the enthalpy update scheme (Brent *et al.*, [8]) as

$$[\Delta H_P]^{n+1} = [\Delta H_P]^n + \frac{a_P}{a_P^0}\lambda\left[\{H_p\}^n - cF^{-1}\{\Delta H_p\}^n\right] \tag{3d}$$

where ΔH_P is the latent heat content at Pth node point of the computational cell, n is the iteration number, $a_P^o = \rho\,\Delta V/\Delta t$, a_p is the coefficient of T_p in the discretized energy equation (Patankar, [11]), λ is the relaxation factor, c is the specific heat and F^{-1} is the inverse latent heat function. In the present work, the PCM is considered as a pure substance; hence F^{-1} is equal to T_{melt} . Based on the latent heat content (ΔH), the fraction of liquid at any cell is calculated as

$$f_l = \frac{\Delta H}{L_a} \tag{3e}$$

Boundary conditions:

The set of governing Eqs (1-3) is simulated effectively with appropriate boundary conditions. The boundary conditions are given as

Top face:

The top surface of the PCM is subjected to both solar radiation and convection. The top surface is represented by an equivalent surface temperature given as

$$T_{ts} = T_a + \frac{\alpha_a q_s}{h_a} \tag{4a}$$

Ravikumar and Srinivasan [5] found a variation of solar radiation and ambient temperature in the Coimbatore city, Tamilnadu, India during June. In the present work, the similar profiles for the solar radiation and ambient temperature are considered. The net variation of the top surface of the domain is shown in Fig.6

$$\frac{\partial u_1}{\partial x_1} = 0 \text{ and } u_2 = 0 \tag{4b}$$

Bottom face:

Some of the absorbed radiation heat is convected into the room. Accordingly, a convection boundary condition is considered at the bottom surface of the roof.

$$-k\frac{\partial T}{\partial x} = h_r(T_{rs} - T_r) \tag{5a}$$

$$u_i = 0 \tag{5b}$$

Left and right faces:

The boundary conditions for both left and right surfaces are

$$\frac{\partial T}{\partial x_1} = 0 \tag{6a}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{6b}$$

4. NUMERICAL MODELING

In the present study, the set of the governing equations are discretized based on a semi-implicit finite volume method using power law scheme (Patankar, [11]). The discretized linear equations are solved using the SIMPLER algorithm and tri-diagonal matrix solver. The convergence is declared when $|(\phi-\phi_{old}) / \phi_{max}| < 10^{-5}$ where ϕ stands for the solved variables at a grid point at the current iteration level, ϕ_{old} represents the corresponding value at the previous iteration level and ϕ_{max} is the maximum value of the variable at the current iteration level in the entire domain. The work conducts a comprehensive grid-independence study. It is found that a 102 × 82 uniform grid is suitable for present simulation and a time step of 0.1s offers a better convergence.

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Calculation of average room temperature:

It is found that the temperature of the room changes continuously during the day. The room temperature depends on the heat transfer rate to the room during the day, which is calculated as

$$\frac{d(\rho_a L C_p T_r)}{dt} = q_r \tag{7a}$$

Where q_r is heat flux to the room and calculated as

$$q_r = h_r (T_{rs} - T_r) \tag{7b}$$

5. RESULTS AND DISCUSSION

The present numerical model is validated against a benchmark problem solved by Brent et al. [8]. The work deals with melting of a pure gallium in a side heated rectangular cavity. The comparison between the present prediction and the prediction by Brent et al. [8] is shown in Fig. 2. A good agreement is found. Henceforth, the present numerical code is extended for analysis of the present problem.

In the Mukherjee *et al*. [6] model, it is found that the PCM is melted up to 60% of the total PCM mass in the day time and in the night about 80% of the total melted PCM is solidified. In this model, an effort is made for the optimum use of PCM with complete recycling using a suitable TCE. Initially, the thermal behavior of the room is predicted without PCM and then, the behavior is compared with that considering the PCM and TCE.

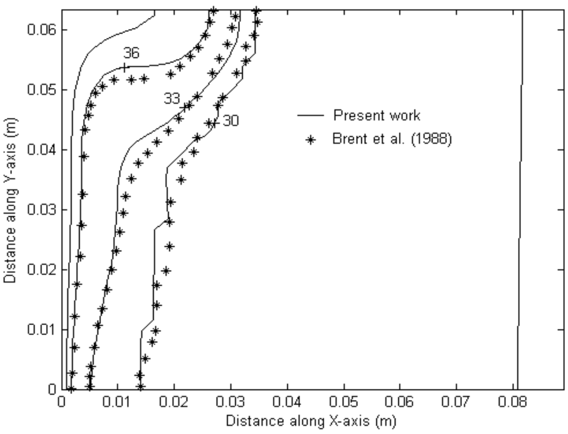

Fig.2. Temperature field at 6min for 2-D melting of gallium

5.1 Cooling of Building using only PCM.

Glauber Salt $(Na_2SO_4 - H_2O)$ as PCM of 43mm height is used to cool the building above the concrete of height 150mm. In the day time, PCM absorbs the radiant heat from the surrounding and melts and in night it releases the heat to solidify. In solidification, conduction is dominated and in melting natural convection is dominating but in comparison this two natural convection give more heat transfer. Due to this fact melting is faster than solidification and PCM melts completely but not solidifies totally.

This phenomenon is clear from the figure 3, where PCM melts around at 6 pm completely but not solidity completely. So, complete recycling of PCM is required. The maximum room temperature found here is around 31.5 ℃ (see Figure 4).

5.2 Cooling of building using PCM with TCE

In this case, the PCM with aluminum as TCE is considered. TCE increases the thermal conductivity of the system. As PCM melts completely during day time, TCE is not required to add in this process but in solidification case the PCM does not totally solidified as shown in figure 3. So, TCE is added after melting process which leads to an increase in the thermal conductivity of the system. In figure 5, it is shown that at 6 pm PCM melts completely after that TCE is added and as a result PCM is completely solidified in 24 hours. In this case, it is seen that the room temperature is reached maximum around 31.7 ℃ which is good for the human comfort.

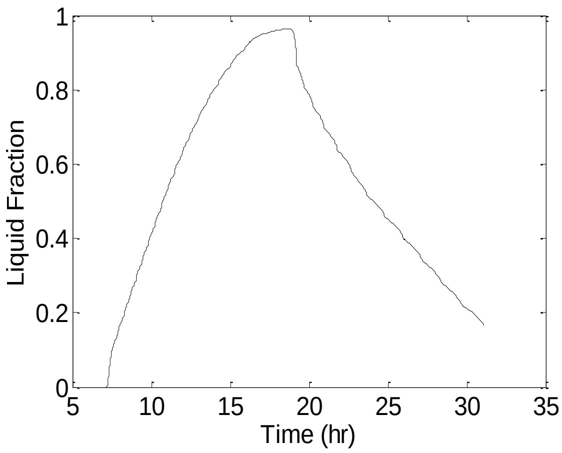

Fig.3. Variation of Melt Fraction of the PCM with time

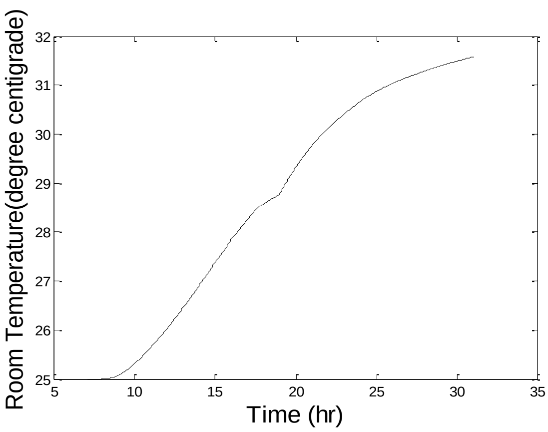

Fig.4. Variation of room temperature with time

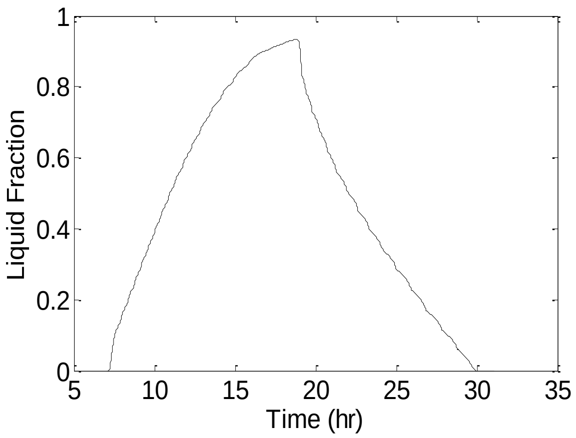

Fig.5. Variation of Melt Fraction of the PCM with time

5. CONCLUSION

In the present work, the optimum use of PCM to cool the building using TCE is studied numerically. In this model, the melting and the solidification of the PCM are represented by the enthalpy update scheme. The simulation predicts the melting and solidification behaviors of the phase change material, temperature of the room in a day. It is found that the recycling of the PCM is not possible for next days. Aluminum is used as thermal conductivity enhancer (TCE) for complete recycling of the PCM. The simulation predicts the optimum amount of the PCM and the aluminum for complete recycling of the PCM. This work also predicts the variation of temperature, melt fraction of PCM. It is found that minimum room temperature is maintained by using PCM and TCE and complete recycling of PCM is achieved.

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NOMENCLATURE

Symbol	***Meaning***	***Unit***
C	Morphological constant	
c_p	Specific heat	J/kg.K
f_l	Liquid fraction of PCM	
g	Gravitational acceleration	m / s^2
h	Heat transfer coeff.	W/ m^2 .K
ΔH	Enthalpy content	J/kg
k	Thermal conductivity	W/m.K
P	Pressure	Pa
t	Time	s
T	Temperature	°C
u_i	Velocity in i*th* direction	m/s
Greek symbol	***Meaning***	***Unit***
ρ	Density	Kg/ m^3
μ	Viscosity	Pa-s
λ	Relaxation factor	
Subscripts	***Meaning***	
a	Atmospheric	
l	Liquid	
melt	Melting	
r	Room	
ref	Reference	

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