Sādhanā Vol. 40, Part 8, December 2015, pp. 2381–2388. © Indian Academy of Sciences

Simulation and experimental study of thermal performance of a building roof with a phase change material (PCM)

A MANNIVANNAN* and M T JAFFARSATHIQ ALI

Department of Mechanical Engineering, Anna University Tirunelveli Region, Tirunelveli 627007, India
e-mail: mani1496@yahoo.com; jafsat91hiq@gmail.com

MS received 22 August 2014; revised 10 November 2014; accepted 18 November 2014

Abstract. Latent heat storage in a phase change material (PCM) is very attractive because of its high-energy storage density and its isothermal behaviour during the phase change process. Low thermal conductivity of the walls and roof reduces the heat gain at a steady state condition. Chloride hexahydrate ($CaCl_2 6H_2O$) as a phase change material (PCM) for a room was proposed in this paper to control the indoor air temperature for a better thermal comfort for human beings. Building concrete roof with vertical cylindrical hole of 0.5×0.5 m and array of 3×3 filled with phase change material (PCM) was considered for analysis. A detailed thermal analysis was carried by both simulation and experimental study. Results showed that this type of PCM room can decrease the indoor air temperature fluctuation by a maximum of 4°C.

Keywords. Building energy conservation; phase change material; concrete roof with PCM.

1. Introduction

In hot climates the thermal insulation materials are commonly used in building roof and walls to reduce the heat flow into indoor space by providing an effective thermal barrier (Esam & Hashem 2011). For single story houses in tropical countries, the heat gain through the roof of houses is unavoidable. Solar radiation incident on a roof may reach to more than 1000 W/m^2 in clear sky conditions and from 20 to 95% of this radiation may be absorbed (Suehrcke *et al* 2008). The latent heat thermal energy storage with a phase change material (PCM) is an effective way of thermal storage system due to its advantages of high energy storage density and its isothermal operating characteristics (i.e., charging/discharging heat at a nearly constant temperature) during the solidification and melting processes (Mithat Akgun *et al* 2007).

Thermal mass of the walls and roof can be increased by incorporating phase change material (PCM) into walls and roof. PCMs are organic or inorganic substances with a melting temperature according to the needs of the applications and high latent heat of fusion, such as paraffin

*For correspondence

and salts. The PCM melts and absorbs part of the heat gain through the melting process during day time and the PCM solidifies and releases the stored heat at night. The net effect is reducing the energy required for cooling during daytime and shifting it to other times. The selection of the PCM is mainly based on the PCM's melting temperature. In addition, low cost, non-toxic, non-flammable, and chemically stable materials are the preferred PCMs. The PCM melting temperature should be within the temperature range of the weather to ensure melting and solidification cycles (Hashem & Esam 2013).

Pasupathy & Velraj (2008) presented the thermal performance of an inorganic eutectic PCM based thermal storage system for thermal management in a residential building. Esam & Hashem (2011) incorporated the PCM into the roof structure with vertical cone frustum holes filled with P CM. The results indicate that the heat flux at the indoor surface of the roof can be reduced up to 39% for a certain type of PCM and geometry of PCM cone frustum holes. John Kosnya *et al* (2012) investigated thermal performance of naturally ventilated solar roof with PCM heat sink and the result showed that about 30% heating and 50% cooling load reductions are possible with experimental roof configuration. Hashem & Esam (2013) determined the experimental test on building roof with cylindrical holes containing PCM the result showed the heat flux at the indoor surface of the roof is reduced between 9 and 17.26%. Huann-Ming Chou *et al* (2013) describes the new design of metal sheet roof with PCM it can effectively reduce the downward thermal flow through the roof into the house. Erlin Meng *et al* (2013) developed a new type of phase change material room which can decrease the indoor air temperature by 4.3°C in summer and 14.2°C in winter.

The various authors reviewed PCM as thermal storage system for thermal management of buildings (Adeel Waqas & Zia Ud Din 2013; Atul Sharma *et al* 2009; Osterman *et al* 2012) and it can be seen that most researchers used paraffin type PCM in the cylindrical holes. In the present work, Chloride hexahydrate ($CaCl_26H_2O$) as a phase change material (PCM) for a room was proposed to control the indoor air temperature for a better thermal comfort for human beings. The simulation and experimental investigation has been presented here with chloride hexahydrate ($CaCl_26H_2O$) as PCM. The simulation were performed using the ANSYS software.

2. Methodology

2.1 *Statement of the problem*

Geometry configuration consists of concrete roof slab with dimension of $0.5 \times 0.5 \times 0.08$ m incorporated with nine vertical cylindrical holes of diameter 0.06 m and height 0.04 m. The outdoor surface of the roof is subjected to a time dependent solar radiation and convection boundary conditions. The indoor surface is subjected to a time independent convection boundary condition.

2.2 *Simulation*

In general, the geometry configuration of the roof is three-dimensional spaces. A PRO-E software model of concrete roof without cylindrical holes and PRO-E software model concrete roof with nine cylindrical holes with above mentioned dimension were created. These geometries are imported to ANSYS software, meshed and analysis has been carried out. The type of element for geometry with and without cylindrical holes is solid-tet node 87 (10 node). For geometry without cylindrical holes, number of element is 18432, number of nodes is 21609, maximum cell squish is $2.20268e{-}11$ and maximum aspect ratio is 1.78049. For geometry with cylindrical holes, number of elements is 811259, number of nodes is 738547, maximum cell squish is

Table 1. Thermo physical properties of PCM and concrete.

Material	Melting temperature Tm (°C)	Thermal conductivity k (W/m K)	Specific heat Cp (J/kg K)	Density ρ (kg/m^3)	Latent heat λ (kJ/kg)
Concrete	—	1.25	1000	2300	—
$Cacl_26H_2O$ (Mohammad Rostamizadeh 2012)	29.9	0.53 (liquid) 1.09 (solid)	2200 (liquid) 1400 (solid)	1530 (liquid) 1710 (solid)	187

7.31011e−11 and maximum aspect ratio is 2.68152e+01. The outdoor surface of the roof is subjected to a time dependent solar radiation and convection boundary condition while the indoor surface is subjected to time dependent convection boundary condition. The effect of the natural convection of the liquid PCM and radiation within the PCM are neglected in the simulation.

The selected PCM is calcium chloride hexahydrate ($CaCl_26H_2O$) and its thermo physical properties are shown in table 1. The outdoor surface convection boundary condition h_o = 4.15 W/m^{2}K and solar radiation q_s = 650 W/m^2 and the initial temperature of the domain is 40°C and varying the radiation and temperature using solar ray calculator in ANSYS software. The simulation was kept running until the solution becomes the periodic. The following relations were used to apply the boundary conditions for simulation.

The heat flux at the outdoor surface can be expressed as

$$Q_{os} = h_o\,(T_o - T_{os}) + \propto q_s, \tag{1}$$

where h_o is the outdoor surface convective heat transfer in W/m^{2}K, T_o is the outdoor air temperature in °C, T_{os} is the outdoor surface temperature in °C, $\propto$ is the solar absorptivity, q_s is the solar heat flux in W/m^2. The heat flux at the indoor surface can be expressed as

$$Q_{is} = h_i(T_i - T_{is}), \tag{2}$$

where h_i is the indoor surface convective heat transfer, T_i is the indoor air temperature in °C, T_{is} is the indoor surface temperature in °C. The indoor surface convective heat transfer coefficient can be calculated using the equation below,

$$h_i = \frac{K}{Lc} \times \mathrm{Nu}, \tag{3}$$

where K is the thermal conductivity in W/mK, Lc is the characteristic length of the horizontal slab in m, Nu is the Nusselt number. In order to obtain the indoor surface convection heat transfer however, it is necessary to calculate a value for the Nusselt number.

The empirical correlations for the average Nusselt number (Nu) are found using the following equation

$$10^4 - 10^7 = \mathrm{Nu} = 0.54\,(Ra_L)^{1/4} \tag{4}$$

$$10^7 - 10^{11} = \mathrm{Nu} = 0.15\,(Ra_L)^{1/3}. \tag{5}$$

2.3 *Experimental investigation*

An experimental set-up consisting of the two rooms of size 0.5 × 0.5 × 0.76 m with a concrete roof of 0.5 × 0.5 × 0.08 m incorporated with nine vertical cylindrical holes of diameter 0.06

m, height 0.04 m and another one with a concrete roof of 0.5 × 0.5 × 0.08 m without holes. Figure 1a shows experimental test room with a concrete roof incorporated with nine vertical cylindrical holes. Figure 1b shows experimental test model of concrete roof with holes filled with PCM material. The upper surface of the concrete roof is covered with thin layer of glass to protect the PCM from being contaminated in the rainy season. Experiments were conducted on room with concrete roof without hole and with holes filled with PCM on the same day. Thermocouples were placed to record outdoor, indoor and PCM temperatures.

Figure 1. (**a**) Experimental test room with a concrete roof incorporated with nine vertical cylindrical holes. (**b**) Experimental test model of concrete roof with holes filled with PCM.

3. Results and discussion

3.1 *Temperature contours*

The concrete roofs with PCM and without PCM were simulated in ANSYS software. The outdoor surface of the roof is subjected to time dependent radiation and convection boundary condition and indoor surface of the roof is convection boundary condition and initial temperature of concrete and PCM is 28°C, and the simulation was kept running until the periodic condition is established, taking about one day. At 9 am the maximum temperature 29°C is in the top of the roof and indoor surface temperature is 27°C. Figure 2 represents a sample temperature contour of slab without PCM at 12 pm. At 12 pm the maximum temperature in the top of the roof raised to 37°C and indoor surface temperature increased to 33°C. At 1 pm the maximum indoor temperature of 36°C is noted, due the heat flux from outdoor to indoor.

Figure 3 shows a sample temperature contour of concrete with PCM at 12 pm. At 9 am the maximum temperature 29°C is at outdoor concrete portion and the minimum temperature 25°C is at PCM portion. From figure 3, it can be noticed that indoor temperature is 31°C, outdoor temperature is increased to 39°C and PCM portion temperature increased to 31°C due to increase in solar irradiation. In this case, the maximum indoor temperature 32°C is noticed at 1 pm and at the same time PCM portion temperature increased to 52°C. The increase in PCM temperature is due to PCM absorbed the surrounding heat and reduced the indoor temperature. The indoor temperature at 1 pm is 4°C less when compared to concrete roof without PCM.

3.2 *Variation of heat flux with respect to time*

The variation indoor heat flux with respect to time for with and without PCM is shown in figure 4. The simulation and experimental results are in close agreement. The indoor surface heat flux with PCM is reduced when compared to without PCM and maximum heat flux reduction occurred

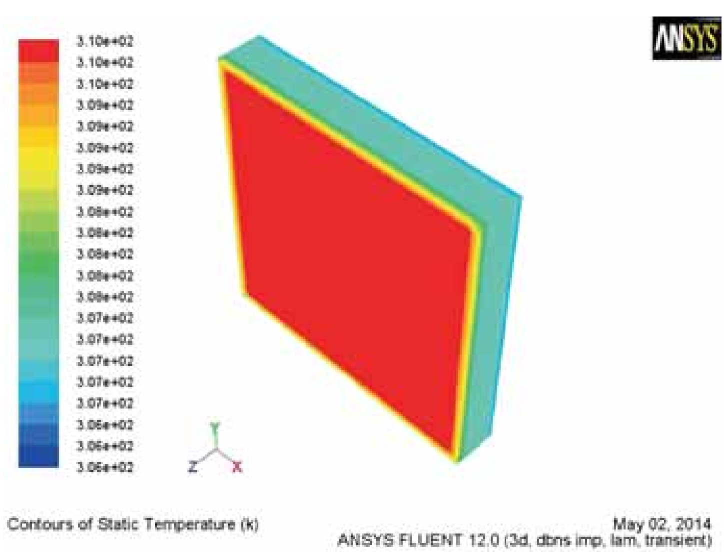

Figure 2. Temperature contour without PCM at 12 pm.

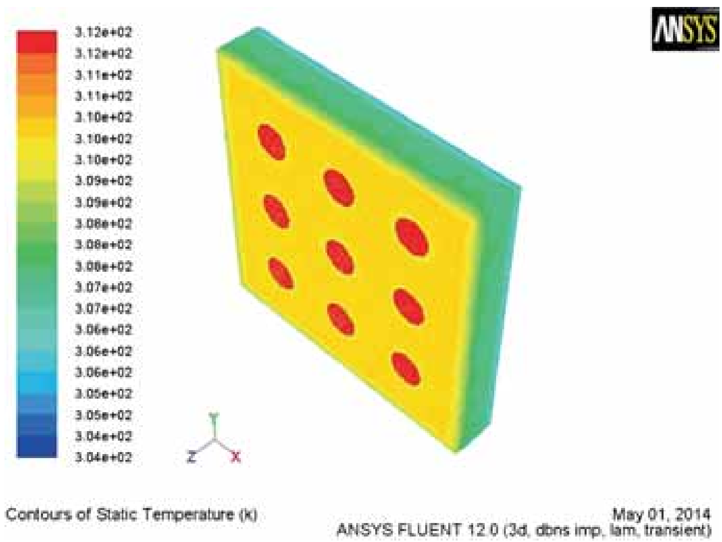

Figure 3. Temperature contour with PCM at 12 pm.

between 13 and 15 h. The reason may be due to the thermal mass of the solid concrete roof is less than the solid or liquid PCM and the net effect of melting and solidification cycle of the PCM. Maximum heat flux reduction is about 51% at 13 h.

3.3 *Variation of temperature with respect to time*

Figure 5 represents the variation in temperature at various points with respect to time obtained in simulation and experiments. The deviation in results between simulation and experiments is in the order of 3 to 8%. The outdoor temperature increases as time progresses and the maximum temperature noticed is 45°C. The variations in the indoor temperature were noted with

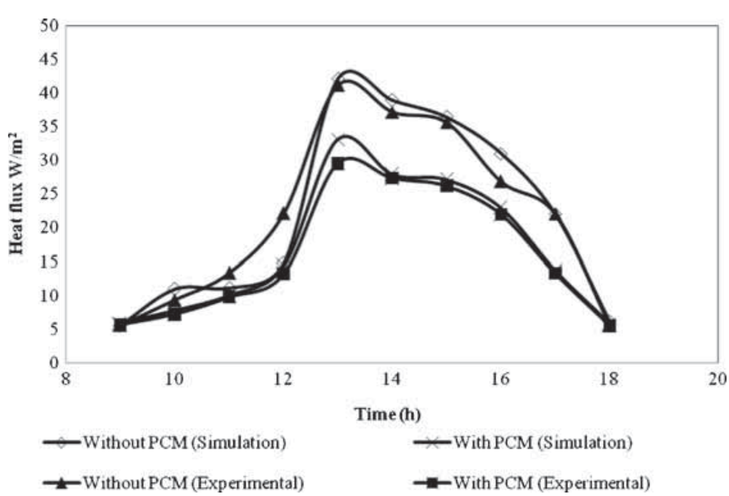

Figure 4. Variations of heat flux with respect to time.

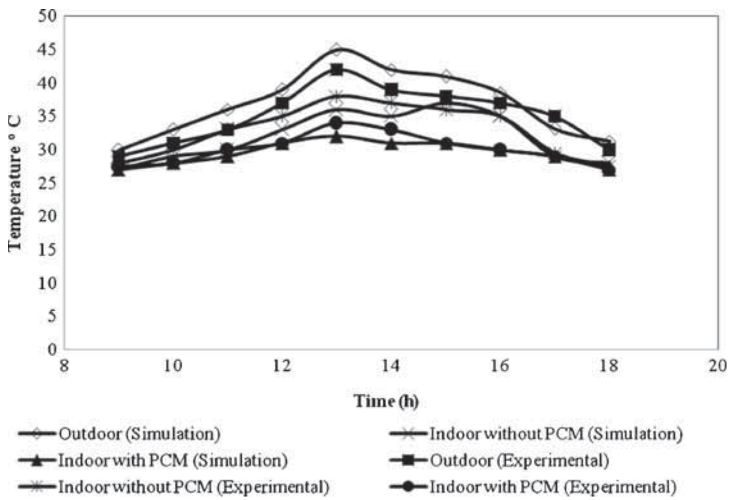

Figure 5. Variations of temperatures at indoor and outdoor with respect to time.

the presence of PCM and without PCM on the same day to understand the effect of PCM. It was noticed that after 9 am, (all the time) the temperature of indoor with PCM is less when compared to roof without PCM. The maximum indoor temperature noticed with PCM was 34°C and that of without PCM is 38°C. Concrete roof with PCM gives a maximum reduction in indoor temperature of about 4°C. As the indoor temperature goes higher than 29.9°C (melting temperature of PCM), the PCM melts by absorbs heat from surrounding and hence indoor heat reduces.

4. Conclusions

Through simulation and experimental studies on the thermal performances of the room, the following conclusions can be drawn.

- This type of PCM room can decrease the indoor air temperature maximum by 4°C.
- The maximum reduction in indoor surface heat flux is about 51%.
- Chloride hexahydrate ($CaCl_26H_2O$) can be used as a phase change material (PCM) to provide the thermal comfort.
- The developed model could be helpful for the simulation when PCM is used in buildings with different wall structures, wall materials, PCM holes shapes and dimensions.

The similar analysis may be considered by changing the parameters like influence of reinforcements, geometry, nano-particle size and volume concentration as scope for future research.

Nomenclature

T_o Outdoor air temperature (°C)
T_{os} Outdoor surface temperature (°C)
Ra_L Rayleigh Number

$\propto$	Solar absorptivity
Lc	Characteristic length (m)
K	Thermal conductivity (W/mK)
Nu	Nusselt number
h_i	Indoor surface convection coefficient (W/m^2K)
h_o	Outdoor surface convective heat transfer (W/m^2K)
q_s	Solar heat flux (W/m^2)
Q_{os}	Outer surface heat flux (W/m^2)
Q_{is}	Inner surface heat flux (W/m^2)
hi	Indoor convection coefficient (W/m^2K)
T_i	Indoor air temperature (°C)
T_{is}	Indoor surface temperature (°C)

References

Adeel Waqas and Zia Ud Din 2013 Phase change material (PCM) storage for free cooling of buildings- A review. *Renewable and Sustainable Energy Rev.* 18: 607–625

Atul Sharma, Tyagi V V, Chen C R and Buddhi D 2009 Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Rev.* 13: 318–345

Erlin Meng, Hang Yu, Guangyi Zhan and Yang He 2013 Experimental and numerical study of the thermal performance of a new type of phase change material room. *Energy Convers. Manage.* 74: 386–394

Esam M Alawadhi and Hashem J Alqallaf 2011 Building roof with conical holes containing PCM to reduce the cooling load: Numerical study. *Energy Convers. Manage.* 52: 2958–2964

Hashem J Alqallaf and Esam M Alawadhi 2013 Concrete roof with cylindrical holes containing PCM to reduce the heat gain. *Energy and Build.* 61: 73–80

Huann-Ming Chou, Chang-Ren Chen and Vu-LanNguyen 2013 A new design of metal-sheet cool roof using PCM. *Energy and Build* 57: 42–50

John Kosnya, Kaushik Biswas, William Miller and Scott Kriner 2012 Field thermal performance of naturally ventilated solar roof with PCM heat sink. *Sol Energy* 86: 2504–2514

Mithat Akgun, Orhan Aydın and Kamil Kaygusuz 2007 Experimental study on melting/solidification characteristics of a paraffin as PCM. *Energy Convers. Manage.* 48: 669–678

Mohammad Rostamizadeha, Mehrdad Khanlarkhani and Mojtaba Sadrameli S 2012 Simulation of energy storage system with phase change material (PCM). *Energy and Build.* 49: 419–422

Osterman E, Tyagi V V, Butala V, Rahim N A and Stritih U 2012 Review of PCM based cooling technologies for buildings. *Energy and Build.* 49: 37–49

Pasupathy A and Velraj R 2008 Effect of double layer phase change material in building roof for year round thermal management. *Energy and Build.* 40: 193–203

Suehrcke H, Peterson E L and Selby N 2008 Effect of roof solar reflectance on the building heat gain in a hot climate. *Energy and Build.* 40: 2224–2235