

Thermal analysis of PCM integrated building blocks for passive cooling application

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Abstract. This experiment deals with the thermal analysis of cement bricks encapsulated with phase change materials (PCM) when subjected to ambient weather conditions such as solar radiation and temperature. Thermal analysis and modelling of building bricks containing PCM has been carried out to exploit the high latent heat of fusion which will help to improve the indoor comfort in buildings. In the model presented in this paper, the PCM is filled in the central cavity of the bricks after encapsulating in an aluminium container. The experimental analysis is carried out by constructing a model and the heat transfer rate is compared with a similar normal brick and the effectiveness of PCM in the building bricks has been valued. The results show that PCM encapsulation in building brick is an effective practice for passive thermal control of buildings.

1. Introduction

Global warming is the most significant threat that that will be faced by mankind in the 21st century along with the energy crisis. About 40% of global energy consumption along with greenhouse gas emissions are accounted by buildings and they play a vital role in global warming [1]. Estimates show that their destructive impact will grow by 1.8% per year through 2050, which indicates that future energy consumption and CO₂ emissions will be worse than today [2]. Therefore, the impact of cooling systems cannot be ignored, as they, along with ventilation and heating systems, account for 60% of the energy consumed in buildings [3]. Passive cooling techniques effectively replace conventional cooling systems and prove as a better alternative. Thermal energy storage (TES) by using latent heat is a competent method to improve the thermal inertia of building envelopes that generally helps to decrease the temperature variations, proceeding to the better quality thermal comfort for the occupants. Phase change materials (PCMs) having high potential for thermal energy storage can be effectively employed for this purpose.

Many past analysis showed that the PCM can be applied on various buildings components [4] such as PCM Trombe walls [5], PCM wallboards [6], PCM shutter [7], Floor heating [8] Ceiling boards [9], PV panel cooling [10] solar drying [11] and walls having Bricks partially filled with PCMs [12]. Various researchers like Alawadhi [13], Castell et al. [14] and Izquierdo-Barrientos et al. [15] conducted numerical and experimental analysis on different types of PCM encapsulated bricks and all the results confirmed the energy saving potential of PCMs in cooling load reduction. The use of PCM encapsulated brick is very much promising in light weight construction.

In this experiment, the heat transfer through a cement brick with and without PCM is studied experimentally and the results are compared with a numerical model. The experiment is conducted in



an artificial environment, where the building bricks are heated by using a light source. The temperatures at similar points are measured to compare the heat transfer.

2. Mathematical model and boundary conditions

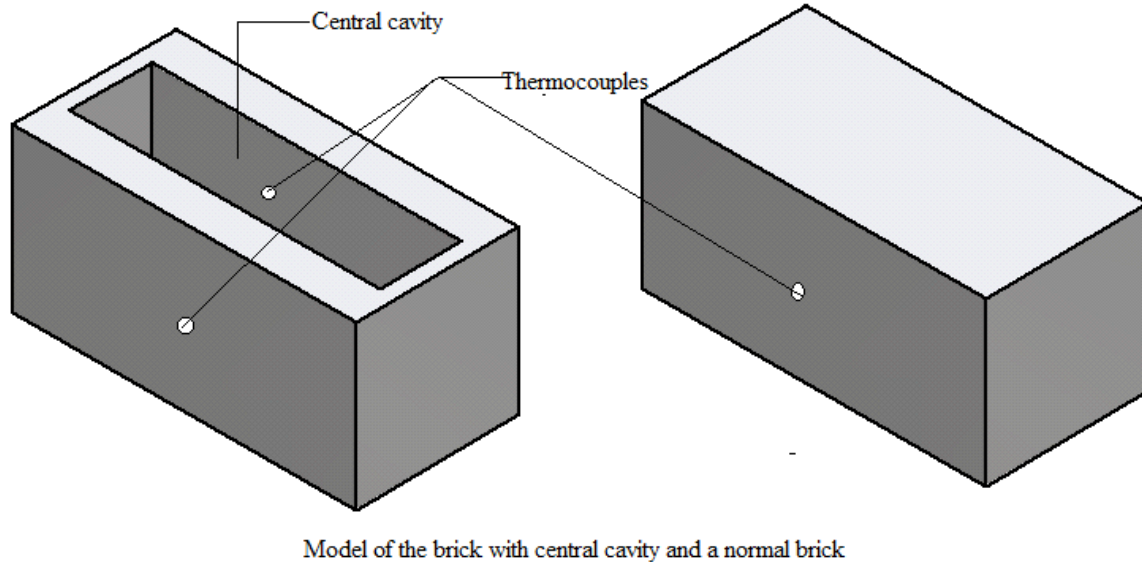


Figure 1. Model of the bricks used for experiment along with the thermocouple positions

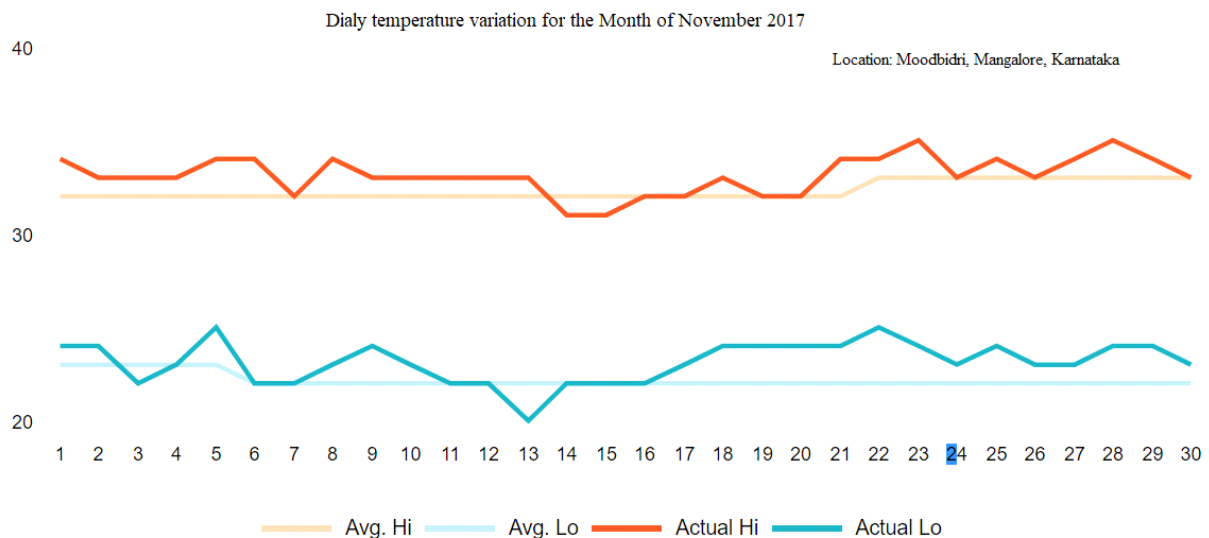


Figure 2. Daily climatic temperature variation for the month of November 2017 at Moodbidri, Mangalore [18]

Figure. 1 gives the schematic representation of the building bricks used for the experiment. The dimensions of the brick are 0.40 m X 0.20 m X 0.15 m with a cavity at the middle. The dimensions of the central cavity are 0.35 m X 0.15 m X 0.10 m and a thin aluminium box containing PCM is inserted in the cavity. The exposed brick surface to the sun at the outside are open to the solar radiation and forced convection boundary conditions and while inside bricks of the wall are subjected to heat transfer by natural convection. The inner and outer surfaces of the building bricks are lay open to radiative heat loss to the atmosphere and the initial temperature of the whole brick is anticipated to be at 26 °C. The heat transfer coefficient at the outer and inner wall is taken to be 20 W/m² K and 10

W/m² K respectively [13]. The phase change material used for the study is HS 26, a commercial PCM that melts at 26°C. Figure. 2 show the daily climatic temperature variation of the location for the month of November 2017. The properties of PCM used in the present study are given in Table 1.

Table 1. Properties of PCM used in the experimental study

Property	Value
Melting Temperature (°C)	25.0
Freezing Temperature (°C)	24.0
Latent Heat (kJ/kg)	185
Density - Liquid (kg/m ³) @ 30°C	1510
Density - Solid (kg/m ³) @ 15°C	1800
Specific Heat - Liquid (kJ/kgK)	2.3
Specific Heat - Solid (kJ/kgK)	NA
Thermal Conductivity - Liquid (W/mK) @ 30°C	0.55
Thermal Conductivity - Solid (W/mK) @ 15°C	1.05
Type of Base Material	Inorganic
Congruent Melting property	Yes
Flammability	No
Thermal Stability (Cycles)	~2000
Maximum Operating Temperature (°C)	80
Flash Point (°C)	NA

The heat transfer through the wall of a building is three-dimensional in nature, but, by comparing to its thickness width of the wall is much larger and therefore, the walls' ends effect has a negligible effect on the heat transfer in the wall. Therefore for the analysis purpose we consider only two dimensional heat transfer. The brick properties are temperature independent, but they are unique for the PCM selected for the application. For simplification, the value of the coefficient of thermal expansion of PCM and that of brick is considered to be negligible. Major assumptions considered for the current study are as follows:

- The radiation falling on the exposed surface of brick is equally distributed.
- After melting, the PCM is Newtonian and incompressible.
- The bricks properties are temperature independent.
- The two dimensional heat flow is assumed.
- After melting, the liquid PCM flows in a laminar manner, and the radiation and three-dimensional convection effects are negligible.
- For the liquid phase of PCM, two-dimensional convection and conduction heat transfer is assumed.

3. Mathematical formulation

The mathematical equations are formed for different parts like front, back and inside of the brick.

3.1 For exposed and inside surface of the Brick;

On the exposed brick surface of the building, we can consider convective heat transfer, short and long wave radiation, that can be mathematically expressed as;

$$-k_{Brick} \frac{\partial T}{\partial x} = h_o(T_{amb} - T_{Brick}) + \varepsilon_{Brick}\sigma(T_{amb}^4 - T_{Brick}^4) + \alpha_{Brick}E(t) \quad \text{----- (1)}$$

Where, k_{Brick} = Brick thermal conductivity, h_o = forced convective heat transfer coefficient = 20 W/m² K [13] T_{amb} = Atmospheric temperature, T_{Brick} = front wall temperature of brick, ε_{Brick} = Emissivity of brick = 0.8, σ = Stefan-Boltzmann constant = 5.67×10^{-8} Wm²K⁻⁴, α_{Brick} = A

absorptivity of building bricks = 0.65 [14], E is the incident solar radiation. The heat transfer from the face of building bricks inside the room is given by the expression:

$$-k_{Brick} \frac{\partial T}{\partial x} = h_i(T_{indoor} - T_{Brick}) + \varepsilon_{Brick}\sigma(T_{indoor}^4 - T_{Brick}^4) \quad (2)$$

Where h_i = Natural convective heat transfer coefficient and T_{indoor} = the room temperature.

3.2 For the central portion of the brick:

Heat transfer is governed by pure conduction mode. The heat transfer diffusion equation is used for the brick and PCM domain. The Navier-Stokes equations used for incompressible fluid gives the velocity field u in Eq. (3) and can be expressed as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \cdot \nabla T = -\nabla \cdot (-k \nabla T) \quad (3)$$

Where ρ = Density, C_p = Specific heat and k = Thermal conductivity.

We assume that, after melting the PCM velocity is zero. Therefore the equation (3) is modified as

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = 0 \quad (4)$$

This equation represents pure conduction inside the central cavity, where PCM is filled.

Since the internal heat generation is negligible during the heating and cooling of the bricks, we can consider a temperature dependent function $B(T)$ for the modeling of heat transfer inside the PCM domain.

$$B(T) = \begin{cases} 0 & T < (T_m - \Delta T) \\ (T - T_m + \Delta T)/2\Delta T & (T_m - \Delta T) \leq (T_m + \Delta T) \\ 1 & T > (T_m + \Delta T) \end{cases} \quad (5)$$

T_m is melting temperature and ΔT is the transition temperature. The value of function $B(T)$ varies linearly between 0 and 1 for solid and liquid states of PCM [15].

The density, thermal conductivity and heat capacity of PCM varies with temperature. It can be modeled by using the relations;

$$\rho(T)_{PCM} = \rho_s + (\rho_l - \rho_s)B(T) \quad (6)$$

$$k(T)_{PCM} = k_s + (k_l - k_s)B(T) \quad (7)$$

$$C_{PCM}(T) = C_{ps} + (C_{pl} - C_{ps})B(T) + \lambda D(T) \quad (8)$$

$$D(T) = e^{\left(\frac{-(T - T_m)^2}{\Delta T^2} \right) / \sqrt{\pi \Delta T^2}}$$

Where $D(T) = e^{\left(\frac{-(T - T_m)^2}{\Delta T^2} \right) / \sqrt{\pi \Delta T^2}}$

λ = Latent heat of fusion for selected PCM and $D(T)$ is the delta function, which shows zero value except in the transition zone.

3.3 Momentum transfer

For the solid brick, the momentum transfer equation is not considered. It is considered only for the melted PCM and which is assumed to be a Newtonian fluid. The momentum transfer and energy conservation equations were solved simultaneously by using heat transfer diffusion equation. For modelling the fluid flow in melted PCM, the mass and momentum transfer equations are modified as follows.

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla) \vec{u} - \mu \nabla^2 \vec{u} = -\nabla P + \vec{F}_b + \vec{F}_a \quad (9)$$

Where, $\vec{F}_b$ is the buoyancy force per unit volume and is given by the Boussinesq approximation as explained by Ebrahimi and Dadvand [17]

$$\vec{F}_b = -\rho_l(1 - \beta(T - T_m))\vec{g} \quad (10)$$

β = Coefficient of thermal expansion for PCM and g = gravitational constant. The value of $\vec{F}_a$ can be calculated by using the equation;

$$\vec{F}_a = -A(T) \cdot \vec{u} \quad (11)$$

Where for a porous medium, $A(T)$ is found from the Carman - Koseny equation.

4. Experimental Setup

The experimental setup is used to compare the heat transfer rate of bricks with and without PCM. The figure 3 shows the setup used for the experiment. This contains two cement bricks, one with PCM filled in the central cavity and other one normal brick without PCM. As mentioned above, the dimensions of the brick are 0.40 m X 0.20 m X 0.15 m with a central vertical cavity of 0.35 m X 0.15 m made up of thin aluminium box containing PCM.

The container filled with PCM and properly sealed to prevent leakages is inserted to the central cavity of the brick. Pre calibrated K Type thermocouples are fixed in the brick at outside wall, middle portion and inside wall to measure the temperature variations. A light source is used to provide heating effect as shown in figure 3. All the thermocouples are connected to a data logger to record the temperature at one hour interval.

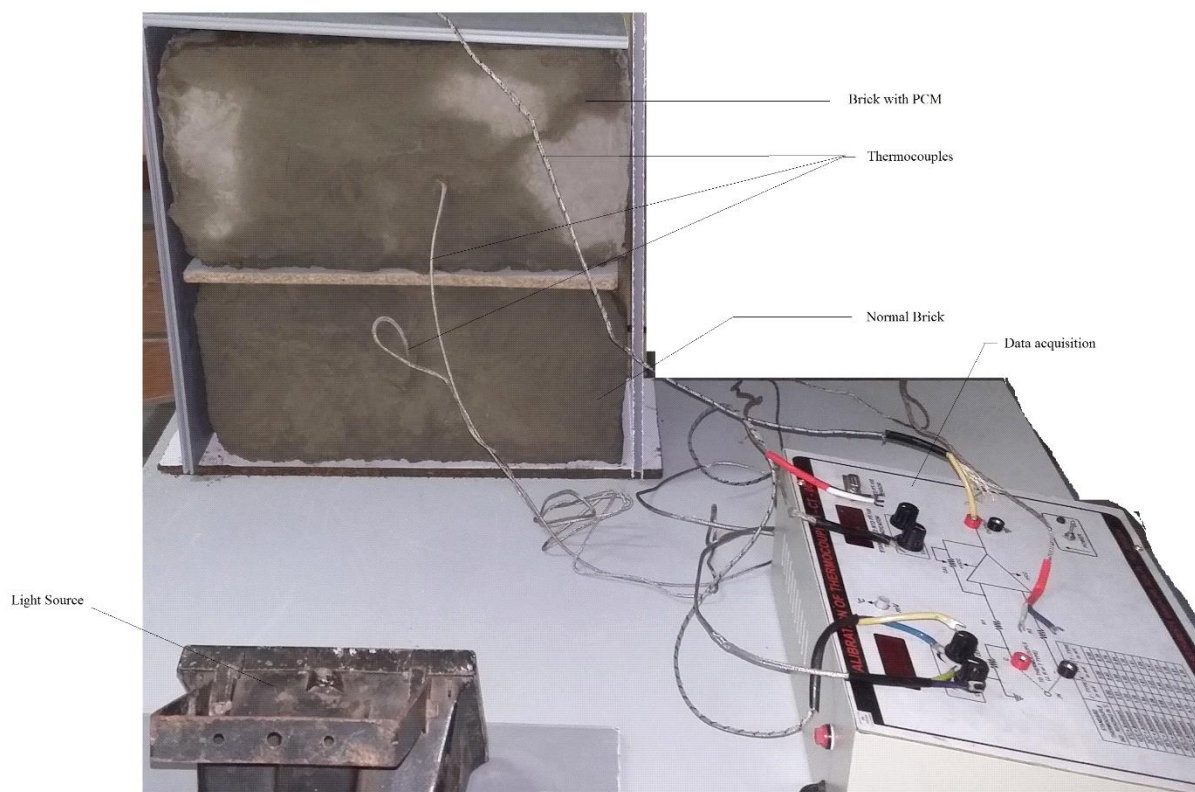


Figure 3. Experimental setup

The surface of the cement brick is made smooth to absorb maximum thermal energy. A similar size brick without PCM is also arranged in the experimental setup to compare the heat transfer rates and evaluate the effect of PCM. The normal brick is also connected with three thermocouples to measure the temperatures at outside surface, middle of the brick and inside surface. The bricks and the light are arranged in such a manner that, the light falls only the outside face of the bricks. All the other faces are covered with insulating material.

5. Results and Discussion

The experimental results shows considerable reduction in heat transfer by the application of PCM in the brick. Figure 4 shows the variation of inside surface temperature of the brick with and without

PCM encapsulation. A maximum variation of 5 °C is obtained by the application of PCM. As the ambient temperature increases, the inside room temperature is kept nearly in a comfort zone if the brick is PCM encapsulated as shown in Figure 5.

While considering the cooling load, 11.88% of reduction is recorded on average basis during the experimental analysis. This amount is very much important while considering the high rise buildings, where major heat infiltration is through exposed wall.

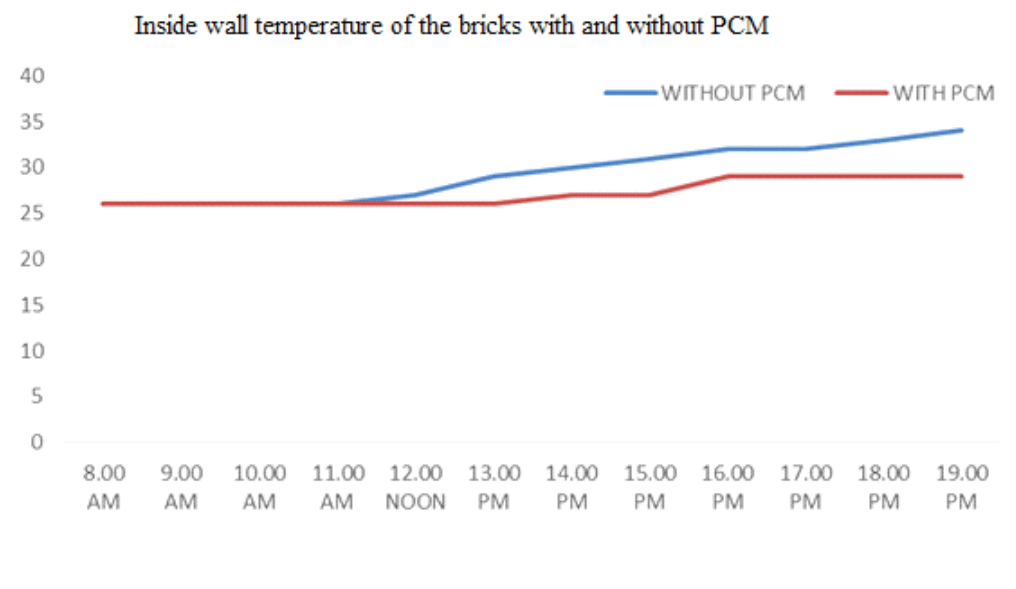


Figure 4. Comparison of Inside wall temperature with and without PCM

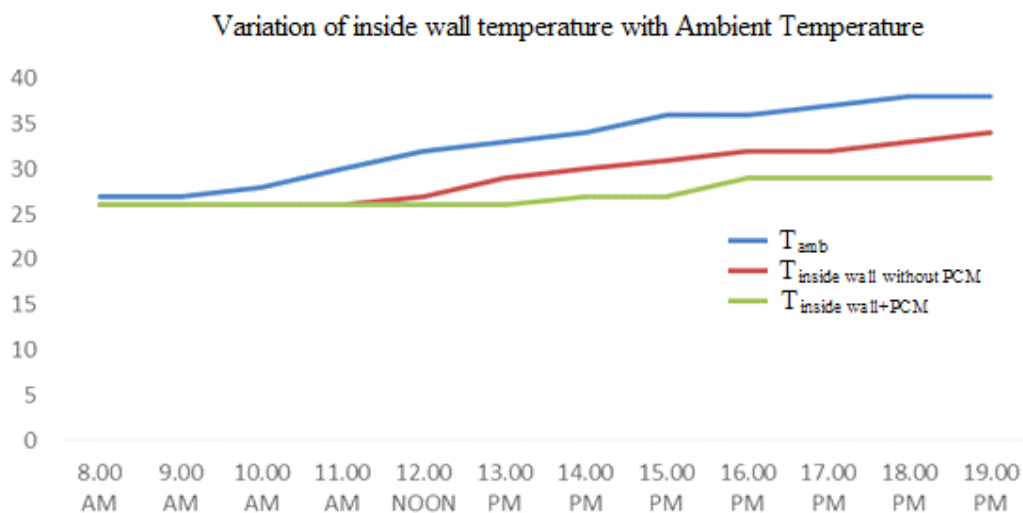


Figure 5. Comparison of inside temperature with ambient condition

6. Conclusions

The use of phase change materials in Thermal Energy storage (TES) is well known. By incorporating the PCM in building envelope improves thermal comfort of the inside room and also it increases the energy efficiency of the building. If the thermal mass of the building wall is low, the PCM

encapsulation will help to reduce the temperature fluctuations. In this analysis it is proved that, by applying a PCM in the middle of the brick, the inside wall temperature is nearly reduced by 5°C.

This method is very effective in case of high rise buildings, where a considerable amount of cooling load is entered through wall. This method also helps to shifts the peak temperature time. But during the cooling cycle of the PCM, there is a chance to release the heat into the interior space. This can be avoided by offsetting the PCM application distance towards the exterior side.

7. References

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