Simulation of Thermal Storage Phase Change Material in Buildings

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Abstract—One of the potential and effective ways of storing thermal energy in buildings is the integration of brick with phase change materials (PCMs). This paper presents a two-dimensional model for simulating and analyzing of PCM in order to minimize energy consumption in the buildings. The numerical approach has been used with the real weather data of a selected city of Iran (Tehran). Two kinds of brick integrated PCM are investigated and compared base on outdoor weather conditions and the amount of energy consumption. The results show a significant reduction in maximum entering heat flux to building about 32.8% depending on PCM quantity. The results are analyzed by various temperature contour plots. The contour plots illustrated the time dependent mechanism of entering heat flux for a brick integrated with PCM. Further analysis is developed to investigate the effect of PCM location on the inlet heat flux. The results demonstrated that to achieve maximum performance of PCM it is better to locate PCM near the outdoor.

Keywords—Building, Energy Storage, PCM, Phase Change Material

I. INTRODUCTION

THE energy required for heating and cooling of buildings plays an important role in many countries. In many countries heating/ cooling and air-conditioning systems are used in many commercial and residential buildings.

Due to increase energy demands of these systems, an appropriate insulation of buildings, such as walls, roofs and floors is important in reducing the rate of heat flowing to buildings in summer and winter. Selecting a proper insulation material by considering its thermal properties in each weather conditions should be expected to favor the economics of the buildings. In addition, make a suitable lagging time to heat flux interring the buildings by storing energy is another way to control indoor air quality. The storage of energy can be done in the form of sensible and latent. In sensible heat storage (SHS), energy can be stored only by changing temperature in solid or liquid. SHS system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends on the specific heat of the medium, the temperature change and the amount of storage material [1]. In latent form of energy storage, energy stored by changing the material phase and using of latent heat.

The energy stored in PCM by latent form. Moreover, the thermal conductivity of PCM is usually less than bricks. Therefore, PCMs can play both the above roles as insulation and also storage materials. Due to these advantages the use of PCM in building material is considered in past decade. The characteristics of PCMs make them suitable for use in energy conservation.

Several reported have been discussed the integration of PCM into building fabrics and found it as a potential method of reducing energy consumptions in passively-designed buildings [2-4].

Feldman et al. [5] experiment PCMs in integrated building fabrics and found gypsum wallboard to be compatible with a broad range of PCMs, including fatty acids and esters. A PCM system absorbed into a porous concrete was investigated by Hadjiena et al. [6]. A numerical investigation of heat storage device with fins to absorb the solar radiation is developed by Stritih [7]. Athienitis et al. [8] investigated gypsum board impregnated with PCM for thermal storage in a passive solar test room. They found that the utilization of the PCM gypsum board may reduce the maximum room temperature up to 4°C during the daytime. The thermal performance of a randomly mixed PCMs and a laminated PCM wall system was numerically evaluated by Kim and Darkwa [9]. It was shown that a 20–50% heat flux enhancement was achieved by using laminated systems. In order to achieve thermal storage capacity approximately equal to the heat gains within the space during the daily cycle, a new concept for the concrete panel was developed by Koschenz and Lehmann [10] to incorporate this system in a lightweight building. Velraj et al. [11] presented an active system on PCM based Cool Thermal Energy Storage (CTES) integrated with building air-conditioning system in Tidel Park, Chennai, India. In this system the storage tank is kept separately away from the building. De Grassi [12] used statistical approach to evaluate the thermal behavior of the PCM containing walls. Firstly, it demonstrates the existence of statistically significant linear dependencies among the variables used, and, secondly, highlights the improvements in comfort conditions due to the insertion of PCM inside dry assembled walls.

PCM has also been developed to store energy for air-conditioning applications. The energy is collected and stored in the PCM during the night as a heat sink and used to cool the interior of the building during the hottest hours of the day. This concept is known as free or natural cooling. A mathematical model of a PCM air heat exchanger has been

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made. In order to cool a given space with cold night air, PCM is stored in an air heat exchanger. During the night, the PCM melt and energy is released. During the daytime, air is circulated through the unit, heat is absorbed and the indoor air is cooled [13]. The conclusion in the experimental study of heat transfer in a rectangular PCM thermal storage was that heat storage (melting) is not a problem during thermal storage applications and that the extraction of heat (solidification) can be effectively enhanced using fins [14].

Alvadhi [15] evaluated thermal effectiveness of the brick-PCM system by comparing the heat flux at the indoor surface to a wall without the PCM during typical working hours. The model consists of a brick with cylindrical holes filled with PCM. This paramedic study is conducted to assess the effect of different design parameters, such as the PCM's quantity, type, and location in the brick.

In this research, thermal analysis of a two-dimensional model for building brick with rectangular cross-sectional holes containing phase change material is presented. The main objective of the brick-PCM system is reducing the heat flow from outdoor space before it reaches the indoor space during the daytime. This goal is achieved by absorbing the heat gain in the brick using PCM. On the other hand, at night, the stored heat is released to indoor and outdoor spaces. The amount of PCM to obtain the optimization level of PCM in break is important due to trade off between reduction of energy consumption and the economical benefits. The governing equation is applied for Tehran as a case study.

II. Governing Equations

A Schematic view and configuration of a brick containing three holes of PCM is shown in figure 1. The dimension of the brick is 25cm×15cm×15cm. The holes which contain PCM are 6cm×3cm. The outdoor surface of the wall is subjected to outdoor space which has a time dependent temperature. The energy is transferred between the wall and air through force convection and radiation. The indoor surface of the wall is face to indoor conditions which can be applied by ASHRAE comfort conditions [16].

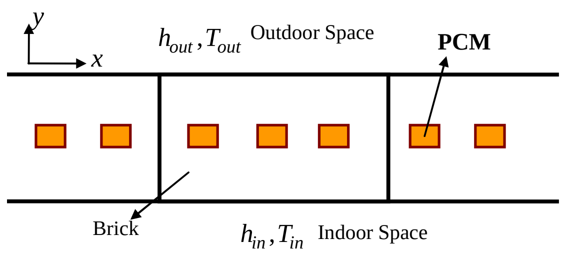

Fig. 1 Schematic view of brick with PCM

In current study the outdoor conditions is for 28 of July of Tehran which is shown in figure 2 is used. The examined PCM is n-octadecane. The thermal properties of each material are shown in table 1 [15]. Compare to figure 1 the selected PCM is beneficial for Tehran climate because its melting temperature value is in the range of temperature variation.

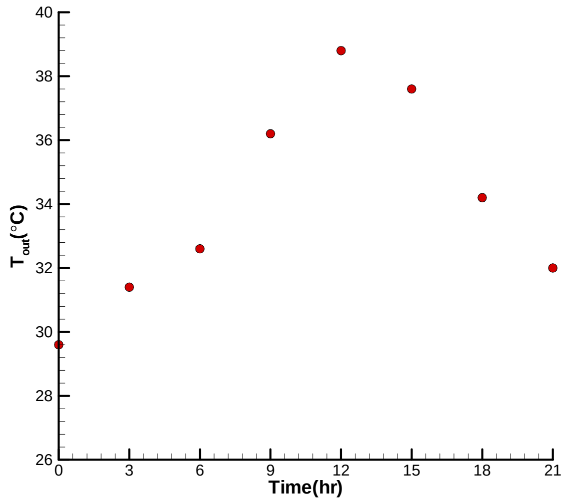

Fig. 2 Outdoor weather temperature for Tehran (28 July)

Table 1 Thermal properties of materials

	n-octadecane	Brick
$T_m(°C)$	27	-----
$k(W/m°C)$	0.358 (solid), 0.148 (liquid)	0.7
$C(kJ/kg°C)$	1.934 (solid), 2.196 (liquid)	0.84
$\rho(kg/m^3)$	865 (solid), 780 (liquid)	1600
$\lambda(kJ/kg)$	243.5	------

The real data for radiation is not available; therefore, the simulation of radiation is base on modified convective heat transfer coefficient. Due to symmetry, only a portion of wall is considered for the rest of the investigation. The computational domain of brick with one PCM is shown in figure 3.

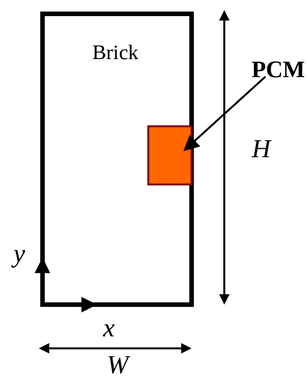

Fig. 3 Computational domain of brick with one PCM

The following assumption is considered

- The thermal properties of the brick is constant
- The thermal properties of PCM is constant in each phase (solid and liquid)
- Thermal expansion of brick and PCM are neglected
- The effect of natural convection in liquid PCM is not taking into account due to insignificant temperature difference between initial and boundary conditions [15]

With the above assumption two-dimensional heat conduction equation can be applied for both brick and PCM respectively.

For brick

$$(\rho C)_b \frac{\partial T_b}{\partial t} = \frac{\partial}{\partial x}(k_b \frac{\partial T_b}{\partial x}) + \frac{\partial}{\partial y}(k_b \frac{\partial T_b}{\partial y}) \quad (1)$$

For PCM

$$(\rho C)_{PCM} \frac{\partial T_{PCM}}{\partial t} = \frac{\partial}{\partial x}(k_{PCM} \frac{\partial T_{PCM}}{\partial x}) + \frac{\partial}{\partial y}(k_{PCM} \frac{\partial T_{PCM}}{\partial y}) \quad (2)$$

The effect of latent heat is not mentioned in the equations 1 and 2. With additional consideration by making the specific heat of the PCM as a function of time, the latent heat effect can be simulated. The specific heat in each temperature range is defined by Eq. 3, 5 and 5 [15]

For $T < T_m$

$$(\rho C)_{PCM} = (\rho C)_{solid} \quad (3)$$

For $T_m \le T \le T_m + \Delta T$

$$(\rho C)_{PCM} = \frac{(\rho C)_{solid} + (\rho C)_{liquid}}{2} + \frac{\rho_{solid} + \rho_{liquid}}{2}\left(\frac{\lambda}{\Delta T}\right) \quad (4)$$

For $T \ge T_m + \Delta T$

$$(\rho C)_{PCM} = (\rho C)_{liquid} \quad (5)$$

In the above mention equation C is specific heat, T_m is melting temperature and ρ is density. ΔT is the phase change transition temperature which is $1^{\circ}C$ [15]. The indoor temperature is $T_{in} = 23.5^{\circ}C$. The simulation should be run until periodic boundary condition is obtained. With considering Fig. 2 the boundary conditions in each side is defined.

At y=0

$$-k_b \frac{\partial T_b}{\partial y} = h_{in}(T_{in} - T_{si}) \quad (6)$$

Where T_{si} is indoor surface temperature of brick and h_{in} is indoor convection heat transfer coefficient.

At y=H

$$-k_b \frac{\partial T_b}{\partial y} = h_{out,m}(T_{out} - T_{so}) \quad (7)$$

Where T_{so} is the outlet surface temperature of brick and $h_{out,m}$ is the modified convection/radiation heat transfer.

At the contact surface of PCM and brick

$$k_{PCM} \frac{\partial T_{PCM}}{\partial n} = -k_b \frac{\partial T_b}{\partial n} \quad (8)$$

Where *n* is the coordinate normal to contact surface.

At *x=0* and *x=W*

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = \left.\frac{\partial T}{\partial x}\right|_{x=W} = 0 \quad (9)$$

The Eq. 9 shows the symmetry condition.

III. NUMERICAL METHOD

The governing equations 1 and 2 with considering boundary conditions are solved by finite volume method [17]. The equations are integrated through rectangular meshes. Firstly, the equations are discritized. In order to investigate mesh independent results, several mesh generations has been compared. The results show less than 1% different between 14365 and 19076 meshes. The convergences of the equation set are check in each time step. The residual of the equation for convergences is assumed 10^{-6}.

IV. RESULTS AND DISCUSSION

One of the important factors which have influence on both economic and thermal efficiency of integrated brick is PCM quantity. The effect of PCM quantity on the inlet heat flux by time variation is shown in figure 4. by comparing figure 2 and 4 it can be found that generally there is a delay time between peak temperature among a day and peak inlet heat flux. On the other hand, PCM will reduce the peak heat flux. The value of maximum heat flux for current case study with brick only, 1 PCM and 2 PCM are 13.6, 10.94 and 9.14 W/m^2 respectively. It is obvious that PCMs reduced significantly the amount of maximum heat flux. With only 1 PCM, 19.55% and 2 PCM, 32.8% reduction can be found. These reductions decrease the rate of energy consumption in cooling or air-conditioning unit.

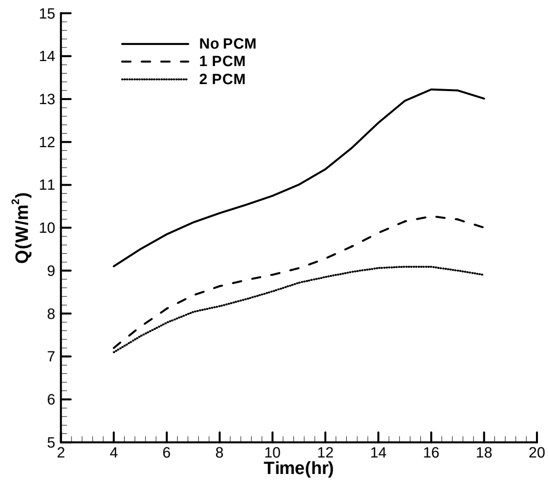

Fig. 4 Effect of PCM number on inlet heat flux

The temperature contour in various times can help us to evaluate the inter heat flux mechanism during a day.

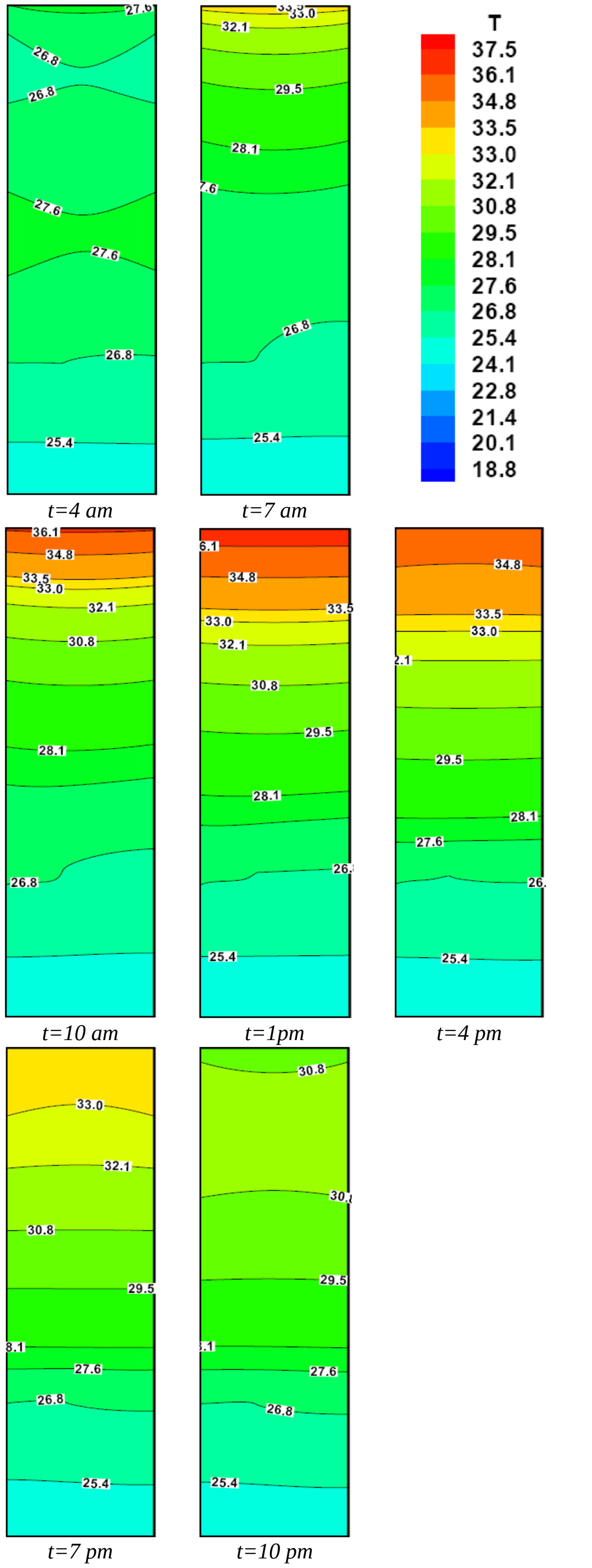

Fig. 5 Temperature contour in various hours for brick with 2 PCM

The temperature contour in various times of a day for a brick containing 2 PCM is shown in figure 5.

As shown in figure 5 at 4 am there is a small difference between inner and outer brick temperature; therefore, lower heat flux flows through the wall and inter the room. Up to 4 pm the temperature difference between two sides of the brick gets increased. Finally at around 4 pm the maximum inlet heat flux is obtained. By analyzing constant temperature lines in figure 5, the effects of PCM material is obvious. For instance, in 7 am there is a break point in constant temperature line $26.8\,^{\circ}C$. This break point is a result of localized PCM which banned the interring heat flux to the room. After 4 pm, due to decrease in outdoor temperature, the energy stored in PCM released to the air.

One of the important factors that affect the thermal efficiency of the integrated brick is the location of PCM holes in brick. Previous result of figure 4 and 5 are obtained base on symmetry assumption of PCM location. The PCM can either be located near indoor or outdoor. The effect of outdoor heat flux on the PCM is changed depending on its location. For further investigation, the above procedure is developed for two other location of PCM. One of them located near outdoor and the other located near indoor. The locations of PCM for this investigation are shown schematically in figure 6.

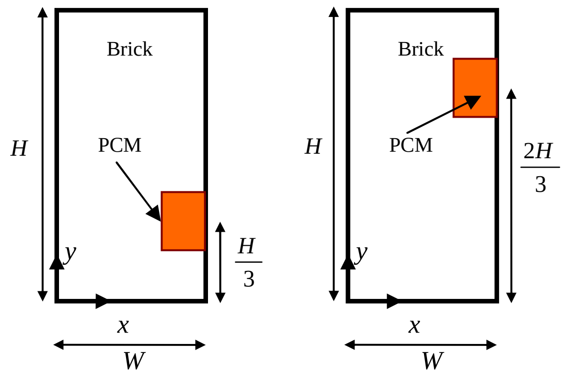

Fig. 6 Schematic of computational domain of brick with one PCM in asymmetry condition

The analysis for figure 6 is shown in figure 7 to investigate the effect of PCM location. It can be seen to achieve the maximum performance of PCM it must be located near outdoor. When the PCM locates near the outdoor, the effect of outdoor heat flux flows to the room is increased. On the other hand, PCM temperature rise and its phase change occur sooner. Finally, it's more beneficial to locate PCM holes near outdoor to prevent heat flux entering the room.

V. CONCLUSION

The effect of using PCM in integrated brick was investigated numerically. The result of brick only is compared with integrated brick. It is shown that by utilizing PCM in brick the maximum inlet heat flux may reduce about 32.8% depending on PCM quantity. The other factor that has influence on thermal efficiency of the integrated brick is PCM location. The investigation shows that to obtain the maximum performance the PCM should be located near outdoor.

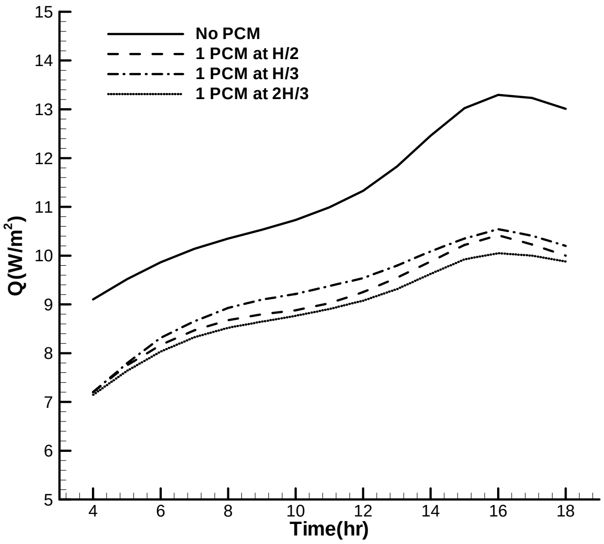

Fig. 7 Effect of PCM location on inlet heat flux

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