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Numerical Studies on PCM Phase Change Performance in Bricks for Energy-Efficient Building Application – A Review

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ABSTRACT

Phase change material (PCM) is widely impregnated in energy-efficient building envelopes for heat modulation with the ultimate objective of energy saving. Recently, PCM filled bricks have been tested for the same purpose. Only a handful of research are available which study on the PCM phase change performance as a latent heat storage (LHS). This review intends to give an overview on numerical studies conducted to measure PCM phase change performance in these special bricks developed for energy-efficient buildings. Only organic PCM phase change performance has been tested. The approach used in the numerical studies were enthalpy-porosity method and lattice Boltzmann method. Mainly the studies found that natural convection in the domain provides the biggest influence in determining the PCM phase change performance. PCM filled bricks have been proven to be able to provide heat modulation in energy-efficient buildings. However, more research should be conducted to further understand the phase change phenomena of PCM inside the brick to enable improvement. The design of the brick and selection of PCM is crucial in optimizing the LHS performance. Future research should consider other important elements such as brick development cost, PCM light transparency and PCM environmental impact.

Keywords:
Phase Change Material (PCM) Brick; Energy-Efficient Building

1. Introduction

Over the years, many researches have been conducted to enhance the capability of phase change materials (PCM) as Latent Heat Storage (LHS). LHS systems are used for various applications in the industries – buildings [1], electronics [2] and solar energy harvesting [3]. These applications take advantage of the phase change process that occur during melting or solidification of PCM in LHS systems. During this phase change process, heat is being absorbed (melting) or released

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(solidification). The performance of PCM during its phase change is crucial and ultimately determines the effectiveness of LHS [4].

Buildings in average accounts for 30% of any country's energy consumption [5]. Recently, many studies have been conducted to find new ways to ensure effective energy consumption in buildings by applying unconventional methods. These buildings are widely known as 'Energy-Efficient Buildings'. In addition to that, most of the energy consumption in a building is used to achieve the desired thermal comfort for its occupant. Therefore, one of the possible significant reduction of energy consumption in a building can be achieved by applying cost-efficient cooling techniques. Figure 1 shows the possible options for cooling techniques in buildings [6].

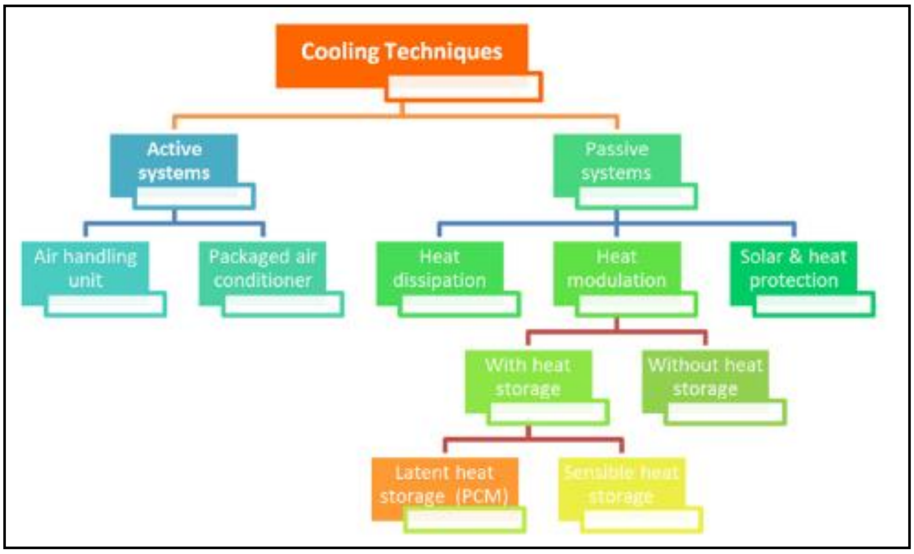

Fig. 1. Cooling techniques in buildings [6]

Energy-Efficient Buildings applies special cooling methods during its daily operations. The buildings are designed to focus on achieving the desired thermal comfort in a building by controlling heat gain and dissipation with minimal energy consumption. This objective can be achieved by applying passive techniques for heat modulation in the building. PCM can be used as LHS to modulate heat in a building.

During the construction process of a building, bricks are being used to construct walls and are an integral part of the structure. Traditionally, bricks are rectangular in shape and made from fired clay. However, nowadays bricks are made from other materials to suit certain special needs. As an example, bricks can be made from PCM in a suitable container to take advantage of its inherent properties –heat storage / removal ability and light penetration. This enable the bricks to function as LHS system to be used for natural heat modulation and natural lighting during daytime which ultimately ensures effective energy consumption in the building. Figure 2 shows how PCM in bricks can be applied to shift a building's daily peak load and saves energy consumption [7].

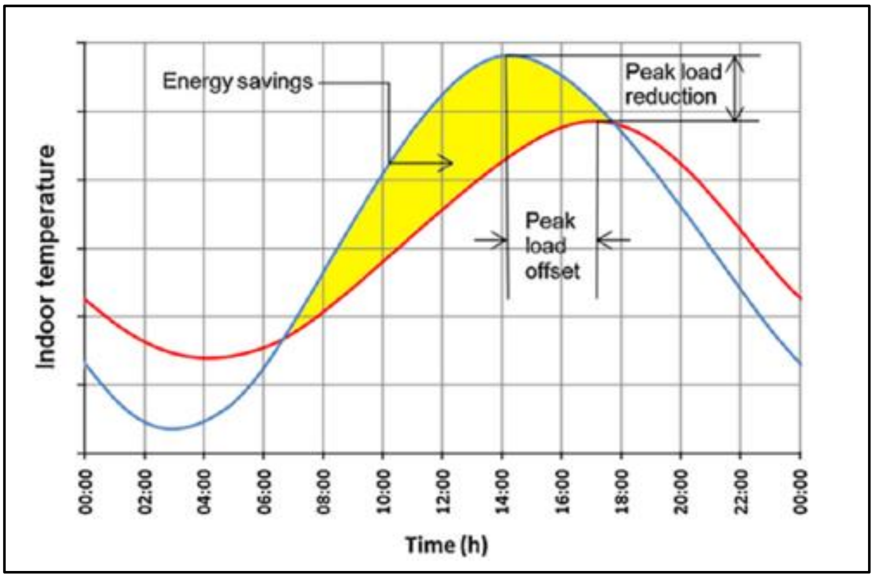

Fig. 2. Potential peak load shifting and energy saving by heat modulation in energy-efficient buildings [7]

This review intends to give an overview on numerical studies conducted to measure PCM phase change performance in these special bricks developed for energy-efficient buildings. Most of researches in this area applied numerical methods for ease of modifying the parameters and cost minimization.

2. PCM Phase Change Performance in Bricks for Energy-Efficient Buildings

There are many ways of applying PCM in buildings [8-10]. It can be integrated into various building envelopes such as glazing, shutters and façade systems. Alternatively, PCM can be impregnated directly into construction materials or used to fill construction bricks as shown in Figure 3. Most researchers have used these methods to apply PCM in buildings as mentioned in other reviews. As far as the author's knowledge, although there are many researches on PCM application for buildings as mentioned, there were only a handful of research focusing on the phase change performance of PCM in bricks. Table 1 summarizes the numerical studies conducted on PCM bricks phase change performance for energy-efficient buildings.

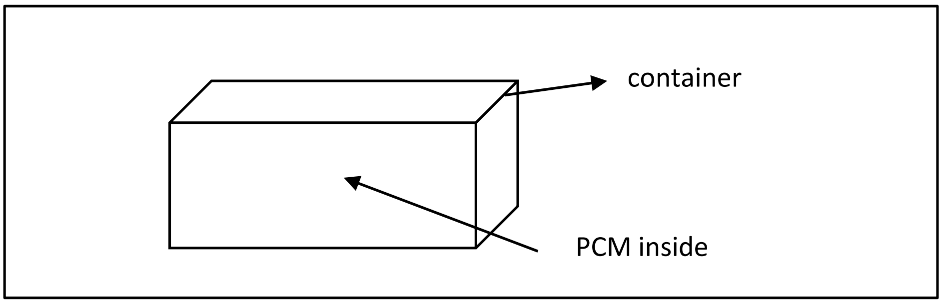

Fig. 3. Example of PCM Brick

Table 1
Numerical Studies on PCM Bricks Phase Change Performance for Energy-Efficient Building Applications

Author	PCM	Brick Size	Numerical Model	Performance Findings
Fuentes et. al. [11]	Fatty acid eutectic mixture (T_m = 21.5°C)	32 x 191 mm	EB - LBM	Natural convection phenomena is crucial to enhance heat transfer in the brick. Brick design configuration and PCM material chosen is important.
Gong et. al. [12]	n-octadecane (T_m = 28.0°C)	30 x 152 mm	EB - LBM	Melting driven by natural convection under high Ra and Pr number demonstrated strong convection phenomenon in the brick.
Souayfane et. al. [13]	Fatty acid eutectic mixture ((T_m = 21.3°C)	32 x 191 mm	EPM - FVM	Model runs relatively faster than LBM. During melting, natural convection enhances average fraction of liquid and position of melting front in the brick.

Note:
EB – LBM Enthalpy Based Lattice-Boltzmann Method
EPM – FVM Enthalpy-Porosity Method coupled with Finite Volume Method
Tm Melting temperature

Several types of organic PCMs mainly paraffins and fatty acids have been considered for application as bricks for energy-efficient buildings. Inorganic PCMs have not been tested for similar application. Fuentes et. al [11] and Souayfane et. al [13] studied the phase change performance of fatty acid mixture in bricks. The bricks used were at identical size with significant aspect ratio. Both authors agreed that natural convection phenomena during phase change process must be enhanced to ultimately ensure good PCM performance for heat modulation by the brick. Gong et. al [12] studied how a paraffin based PCM performs in a slightly smaller brick configuration. The study found that melting driven by natural convection under high dimensionless Rayleigh and Prandtl number demonstrates strong convection phenomenon in the brick.

3. Numerical Models for PCM Phase Change Process in Bricks

The equations to simulate PCM solidification and melting in bricks are represented by natural convection coupled with phase change. The physics of the problem is similar to simulating a two-dimensional phase change process in a rectangular cavity filled with PCM shown in Figure 4 [12].

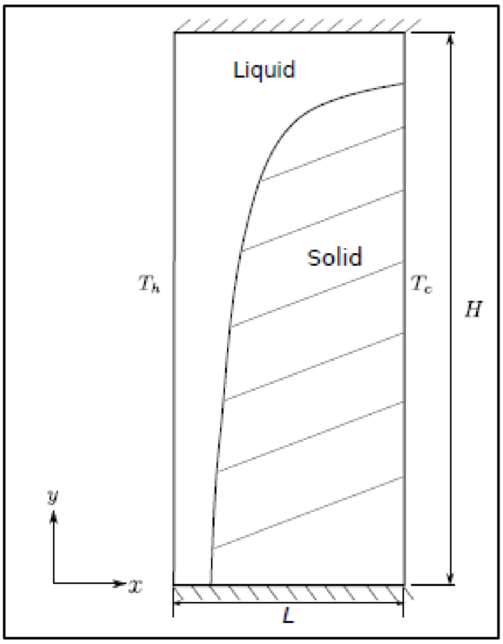

Fig. 4. Physics of the problem [12]

The PCM is incompressible and behaves as a Newtonian fluid. The continuity, momentum and energy conservation equations for 2-dimension are written as follows:

Continuity Equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

X-momentum Equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho}\left[-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+Source\ term\ /external\ force\right]$$

Y-momentum Equation:

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=\frac{1}{\rho}\left[-\frac{\partial P}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+Source\ term\ /external\ force\right]$$

Energy Equation:

$$\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=\frac{k}{(\rho C_p)}\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right)\pm Source\ term\ /external\ force$$

Source term/external force are added to suit the problem to be solved. Three regions will be present throughout the numerical work: a solid region, a liquid region, and a mushy region. The 2 main approach used for numerical studies were Enthalpy-Porosity Method (EPM) and Lattice-Boltzmann Method (LBM).

3.1 Enthalpy-Porosity Method (EPM)

This approach can be coupled with any numerical techniques available such as Finite Volume Method (FVM) or Finite Element Method (FEM). In this method, the basic conservation equations have to be solved throughout a single calculation domain. Details on the theory of the method is available [14-15].

In a system going through a phase change via heat transfer, the total enthalpy is indicated as:

$$H = h + \Delta H$$

where it is the sum of sensible enthalpy, h and latent heat, ΔH. The latent heat component is temperature dependent and the phase change process should occur within a temperature range:

$$\Delta H = \varepsilon(T) = \left\{ \begin{matrix} L\ for\ T > T_L \\ L(1-\varepsilon)\ for\ T_L > T > T_S \\ 0\ for\ T < T_S \end{matrix} \right\}$$

where a parameter known as liquid fraction, ε is introduced to indicate the fraction of liquid in all cells and T_L and T_S is the melting and freezing temperature respectively while L is the latent heat of fusion. The liquid fraction is defined as follows:

$$\varepsilon = \frac{\Delta H}{L}$$

For linear phase change:

$\varepsilon = 0$ if $T < T_S$ $\varepsilon = 1$ if $T > T_L$

For TS < T < TL, liquid fraction, ε is

$$\varepsilon = \frac{T - T_S}{T_L - T_S}$$

This parameter is calculated for each cell in the domain at each iteration, based on an enthalpy balance. The mushy zone is a region in which the liquid fraction lies between 0 and 1. The mushy zone is modelled as a pseudo porous medium in which the porosity increases from 0 to 1 or decreases from 1 to 0 as the domain liquefies or solidifies. Porosity decreases to zero in the solid region and therefore the velocity in the region will also drop to zero as indicated in the next source term.

3.1.1 Source term S_x and S_y in x and y-momentum equation

$$S_x u = -C\frac{(1-\varepsilon)^2}{\varepsilon^3 + b}u \qquad S_y v = -C\frac{(1-\varepsilon)^2}{\varepsilon^3 + b}v$$

The condition that all velocities in solid regions are zero is accounted for by defining the source term S_x and S_y. The velocity value is gradually reduced from a finite value in liquid to zero in full solid for solidification process and vice versa for melting over the control volume that are changing phase. The cell is assumed to behave as a porous cell with porosity, ε = liquid fraction. Value of C depends on the morphology of the porous media while b is a small computational constant to avoid division by zero.

3.1.2 Source term Sb in y-momentum equation

$$S_b = (\rho\beta)_{nf}\, g\left(h - h_{ref}\right)$$

Since *the phenomena is natural convection in the liquid region, buoyancy is represented by Boussinesq Approximation.*

3.1.3 Source term S_h in energy equation

$$S_h = \frac{\partial[\rho\Delta H]}{\partial t} + \frac{\partial[\rho\Delta H]}{\partial x} + \frac{\partial[\rho\Delta H]}{\partial y}$$

The latent heat source term is the rate of change of volumetric latent heat. This source term must be accompanied by positive sign for melting and a negative sign for solidification.

3.2 Enthalpy-Based Lattice Boltzmann Method (EB-LBM)

This method uses enthalpy approach to model phase change while LBM is used to solve the equations. LBM predicts the evolution of particles displacement due to collision and streaming in mesoscale point of view which is represented by distribution functions. Particles behavior are pre-averaged or only particle distributions that live on the lattice nodes are traced, rather than all the individual particles. Distribution functions are used to calculate the macroscopic variables by taking moment to the distribution function. Therefore, lattice Boltzmann method links mesoscale variables with macroscale variables like the previously discussed method. This method satisfies the macroscopic equations or conservation equations stated earlier in this section.

The Boltzmann equation discretized in space and time is given as follows:

$$f_i(x + c_i\Delta t, t + \Delta t) - f_i(x, t) = -\frac{f_i - {f_i}^{eq}}{\tau_f} + F_i$$
$$g_i(x + c_i\Delta t, t + \Delta t) - g_i(x, t) = -\frac{g_i - {g_i}^{eq}}{\tau_g}$$

where distribution function f is used to calculate density and velocity fields while distribution function g is used to calculate temperature field thus the term Double Distribution Function (DDF). The right side of equation is collision term represented by Bhatnagar-Gross-Krook (BGK) approximation. F is the external force field and τ is the relaxation time for each equation. The equilibrium distribution functions are defined so that they satisfy macroscopic equation (Navier-Stokes equations) through Chapman-Enskog expansion:

$${f_i}^{eq} = \omega_i\rho(1 + 3(c_i.u)/c^2 + 4.5(c_i.u)^2/c^4 - 1.5u^2/c^2)$$
$${g_i}^{eq} = \omega_i\rho(1 + 3c_i.u + 4.5(c_i.u)^2 - 1.5u^2)$$

The values of weight ω_i is decided as per the chosen lattice model. As example, some researchers used D2Q9 model (refer Figure 5) for their models therefore $\omega_1 = \frac{4}{9}, \omega_{2,3,4,5} = \frac{1}{9}, \omega_{6,7,8,9} = \frac{1}{36}$

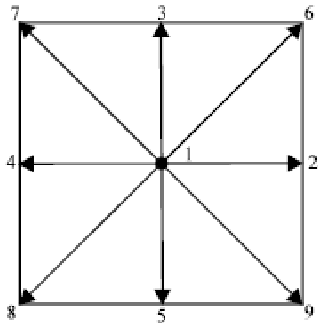

Fig. 5. D2Q9 LBM Model

Macroscopic variables such as density, velocity and temperature are calculated by taking moment to the distribution functions:

$$\rho(x,t) = \sum_i f_i(x,t) \ , \rho u(x,t) = \sum_i c_i f_i(x,t) \ , \rho T(x,t) = \sum_i c_i g_i(x,t)$$

The time relaxation and effective viscosity are as follows:

$$\upsilon = \frac{1}{3}\left(\tau_\upsilon - \frac{1}{2}\right)$$

To solve phase change problem, the similar principle applied for enthalpy formulation is applied at mesoscale level. Details on the theory of this method is available [16-17].

4. Conclusions

PCM filled bricks have been proven to be able to provide heat modulation in energy-efficient buildings. However, more research should be conducted to further understand the phase change phenomena of PCM inside the brick to enable improvement. The design of the brick and selection of PCM is crucial in optimizing the LHS performance. Future research should consider other important elements such as brick development cost, PCM light transparency and PCM environmental impact.

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