Using Phase Change Materials for Thermal Comfort and Energy Savings in Buildings

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Abstract

During the last two decades, a lot of efforts have been made in order to reduce the energy consumption and utilize the clean energy. One of the effective systems for heating and cooling storage is using phase change materials (PCM) installed in the building to shift the peak load. Phase change materials are one of the latent heat materials having low temperature range and high energy density of melting–solidification compared to the sensible heat storage. In this paper, a model is developed to analyze the thermal performance of a room applying a system with phase change material (PCM) plates in a three layer wall (insulation layer, brick and PCM plate). Using a numerical simulation, indoor air temperature of the room for four days has been illustrated, which is verified by an experimental data. The indoor air temperature line simulated by the present model and the measured data are found to be in good agreement. The effects of thermal conductivity and thickness of PCM on the thermal performance of the room have also been investigated. The results show that this system has a promising prospective for heating and cooling of buildings.

Key words: Latent heat thermal energy storage, Heating & Cooling of building, Phase change material, Numerical analyses

1. Introduction

Considering the rapid development of economy and human society, the issues of energy and environment are receiving more and more attention. In fact, the lack of attention to these matters eventually would lead to full energy and environmental resources deterioration and consequently human destruction will be followed. In this regard, the researchers are trying to improve energy efficiency, use renewable energies and recover waste heat of industrial units. But one of the major consumers of energy is heating and cooling system in buildings which is causing ozone destruction and producing greenhouse gases. For this reason, using new and friendly environment alternatives or applying modern technologies to reduce fuel consumption in this system seems to be necessary.

Recently utilizing latent heat energy storage materials for heating and cooling buildings has been studied and tested for different practical uses by many scientists. The use of these materials in buildings have many benefits that includes reducing the intervals between periods of high and low power consumption, reducing electricity costs, improving thermal comfort levels in winter with solar energy storage in the day and release this energy at night and also reducing the cooling load in summer with cold storage at night and release the energy in the day in order to reduce the room temperature (Zhang et al. 2007).

In 1983, a useful classification of thermal energy storage materials was presented (Abhat 1983), which is demonstrated in Figure 1.

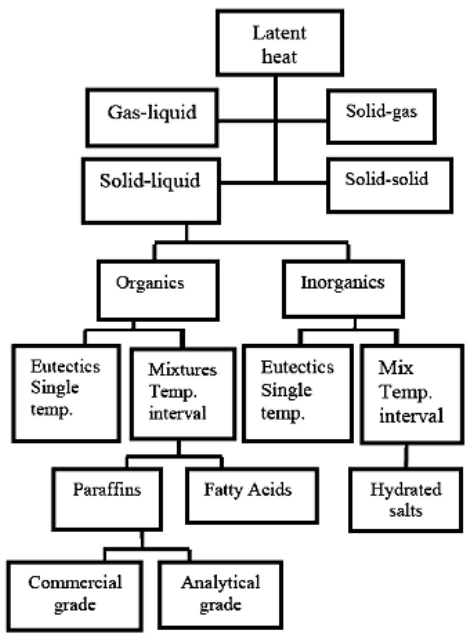

Fig 1: Classification of thermal energy storage materials (Abhat 1983).

A phase change material (PCM) is a substance with high melting heat storage and is classified as latent heat storage units, which starts to melt and absorb energy when surrounding temperature raises and starts freezing and releasing stored energy when environmental temperatures reduces. Comparison between this material and sensible heat storage material shows that phase change materials have storage capacity density of 5 to 10 times more than the sensible heat materials, so storage capacity for the same thermal load in phase change materials is relatively lower. Latent heat storage Materials can be used in a wide range of melting temperatures, but it should be noted that in designing heat storage systems, PCM should supply physical, thermal, kinetic and chemical properties of the desired system (Sharma et al. 2005).

There are three different ways for utilizing phase change materials for cooling and heating buildings: the use of phase change materials in walls of buildings, phase change materials in the ceiling and floor and also applying these materials in separate tanks for hot and cold. The first two methods are passive systems in which increase or decrease in surrounding temperature (around melting temperature of the phase change material) result in automatic storage of cold or heat. But the third method is an active system in which heat or cold stored separately from the building. So the heat and cold would store only in times of need and not used automatically (Ravikumar et al. 2008). In figure 2 forms and effects of phase change materials in buildings is shown.

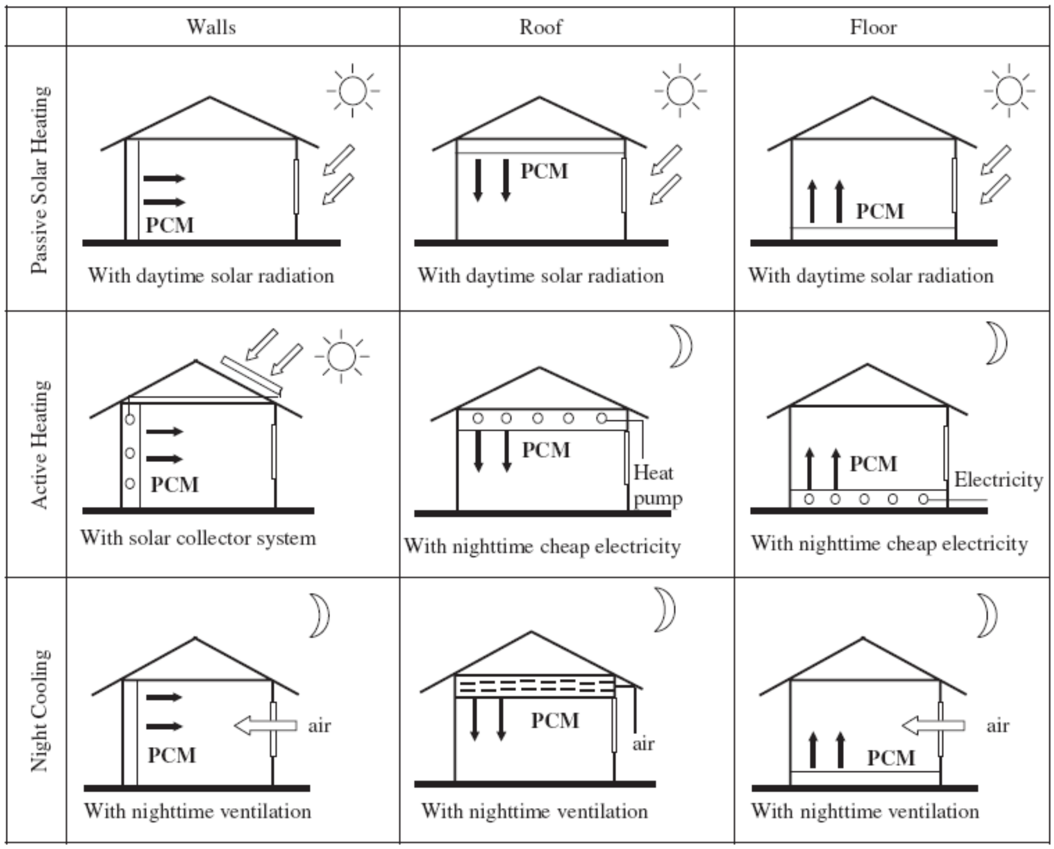

Fig 2: The forms and effects of PCM building envelope (Marco 2005).

In building applications, only PCMs with phase transition temperature at about human comfort temperature (18-28°C) are used. As shown in Figure 3, the difference between indoor temperature and thermal comfort range determines the heating and cooling load, so the use of phase change materials in buildings would reduce the temperature difference between the two and thus reduce the heating and cooling load in the building.

Incorporation of phase change materials in buildings is possible in three ways; direct incorporation, immersion and encapsulation of phase change materials (Hawes et al. 1992). Each of these experimental methods has separately been studied by researchers (Hawes et al. 1993; Feldman et al. 1991; Kaasinen 1992).

One of the numerical studies performed in embedded phase change materials in buildings is the model presented by Kim et al. (2003). This model was solved for a wall and was based on the implicit enthalpy method. This research was investigated more widely by Darkva et al. (2006). Geometry of the problem was extended for the real structural doors and windows. The changes of outdoor temperatures during the day were considered sinus distribution and solar heat flux with Gaussian distribution was hypothesized. Yu et al. (2005) presented a similar model for building floor heating with stabilized phase change materials. In this paper, the formulation of one-dimensional enthalpy model for simulating the performance of phase change materials was used.

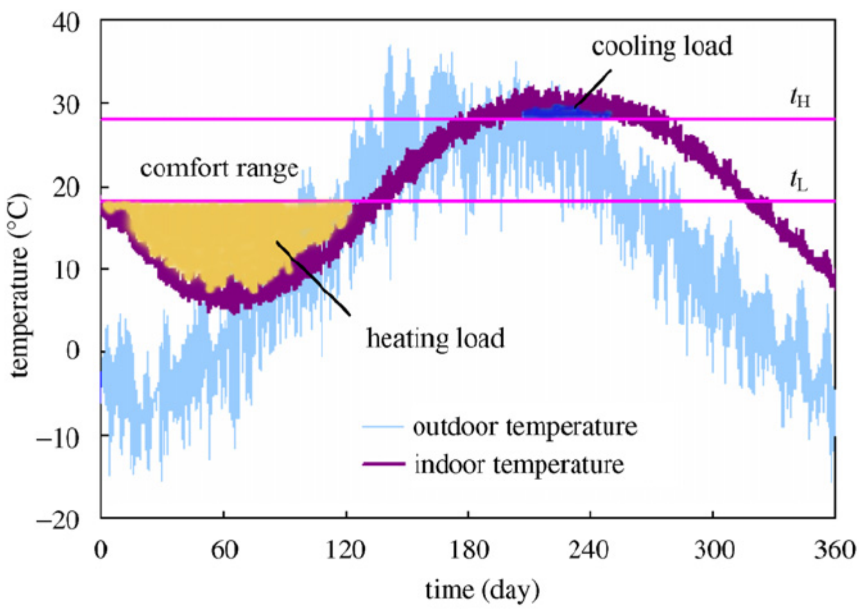

Fig 3: The indoor/outdoor air temperature and heating/cooling load (Zhang et al. 2006).

The purpose of the present paper is to study the effects of phase change materials at the thermal peaks of buildings by presenting a simple model. Numerical analysis of finite difference was used and the results were compared with similar experimental data.

2.Data and Material

A three layer wall is considered which consists of (1) insulation layer (2) brick and (3) a mixture of gypsum and PCM. The scheme of the wall is shown in Figure 4.

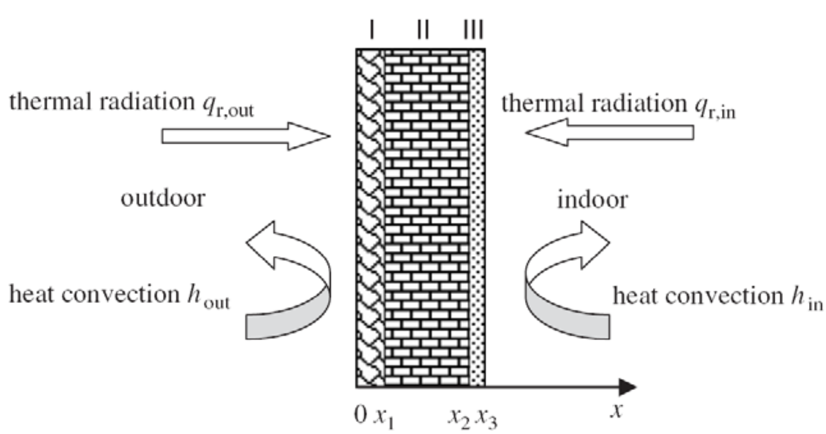

Fig 4: Schematic of wall's heat transfer (I, insulation layer; II, brick; III, PCM plate).

The assumptions which has been used in this model are as follows:

1. One-dimentional temperature variation.
2. Ambient temperature and solar radiation outside the building are functions of time during the day.
3. Constant physical properties of materials is considered.
4. Heat transfer coefficients inside and outside the building are fixed.
5. Natural convection heat transfer of PCM during the phase change and the effect of subcooling during the solidification stage have been ignored.
6. Radiation heat transfer within the room is ignored.

Governing Equation will be as follows:

$$k_n \frac{\partial^2 T}{\partial x^2} = \rho_n c_n \frac{\partial T}{\partial t} \tag{1}$$

where T is the temperature (°C) in position x (m) and time t (hr). K is constant thermal conductivity ($Wm^{-1}°C^{-1}$), ρ is density (kgm^{-3}) and C is specific heat ($Jkg^{-1}°C^{-1}$).
Boundary conditions of this problem can be written as follows:

$$h_{out}(T_{out} - T_1) + q_{out} = -k_1 \frac{\partial T_1}{\partial x} \quad , \quad x = 0 \tag{2}$$

$$T_1 = T_2 \quad , \quad x = x_1 \tag{3}$$

$$k_1 \frac{\partial T_1}{\partial x} = k_2 \frac{\partial T_2}{\partial x} \quad , \quad x = x_1 \tag{4}$$

$$T_2 = T_3 \quad , \quad x = x_2 \tag{5}$$

$$k_2 \frac{\partial T_2}{\partial x} = k_3 \frac{\partial T_3}{\partial x} \quad , \quad x = x_2 \tag{6}$$

$$h_{in}(T_{in} - T_3) = -k_3 \frac{\partial T_3}{\partial x} \quad , \quad x = x_3 \tag{7}$$

where h_{out} is exterior heat transfer coefficient ($Wm^{-2}°C^{-1}$), h_{in} is coefficient of heat transfer inside the building, q_{out} is exterior solar radiation (Wm^{-2}), T_{out} is outside temperature (°C) and T_{in} is indoor temperature (°C).
Temperature distribution in the room was studied by numerical analysis of finite difference implicit method. In order to evaluate the accuracy of the results, they were compared with an experimental data in similar conditions (Zhou wt al. 2008). The required parameters for the analysis are shown in Table 1, and for variation of outside air temperature and solar radiation during the day, an experimental distribution shown in Figure 5 is used. After verifying the model, the effects of some parameters in the system such as constant thermal conductivity of phase change material and thickness of the PCM plate have been studied.

Materials	Insulation Layer	Brick	PCM Plate
Density (kgm-3)	30	1400	850
Specific Heat Capacity (Jkg-1°C-1)	1380	1050	1000
Constant Thermal Conductivity (Wm-1°C-1)	0.042	0.58	0.2

Table 1. Thermodynamic and thermal properties of materials used in the wall

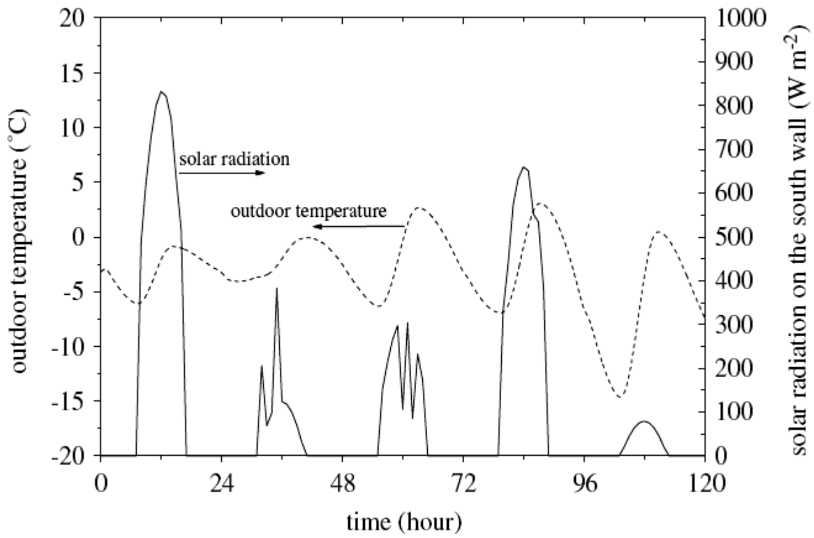

Fig 5: Hourly variation of outdoor temperature and solar radiation on the wall (Zhou wt al. 2008).

3. Results and Analysis

Numerical analysis of this paper was used to achieve indoor air temperature distribution and was compared with an experimental data (Zhou wt al. 2008). This comparison is shown in Figure 6 accordingly.

According to the acceptable agreement between the model and the experimental data and in order to maximize the advantages of using the wall with phase change materials in thermal storage of buildings, the effects of thermal conductivity of phase change material and thickness of PCM and plaster wall in Figures 7 and 8 have been studied.

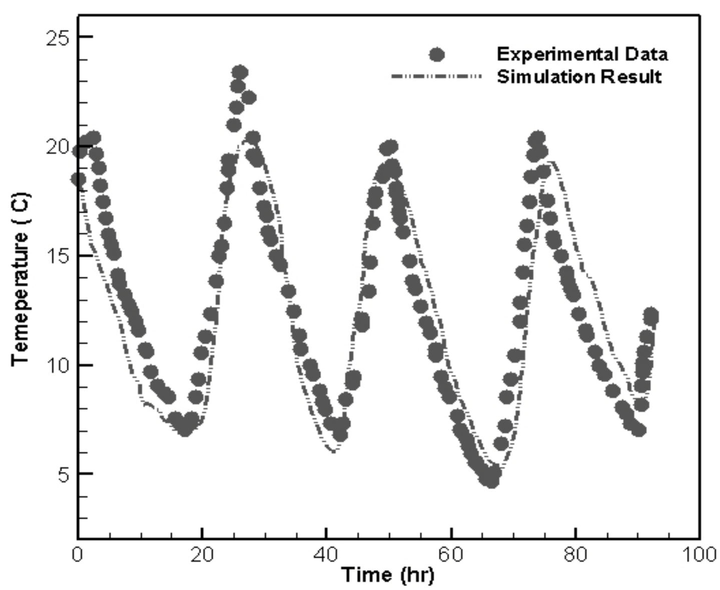

Fig 6: Experimental data (Zhou wt al. 2008) and numerical analysis of temperature distribution inside the building.

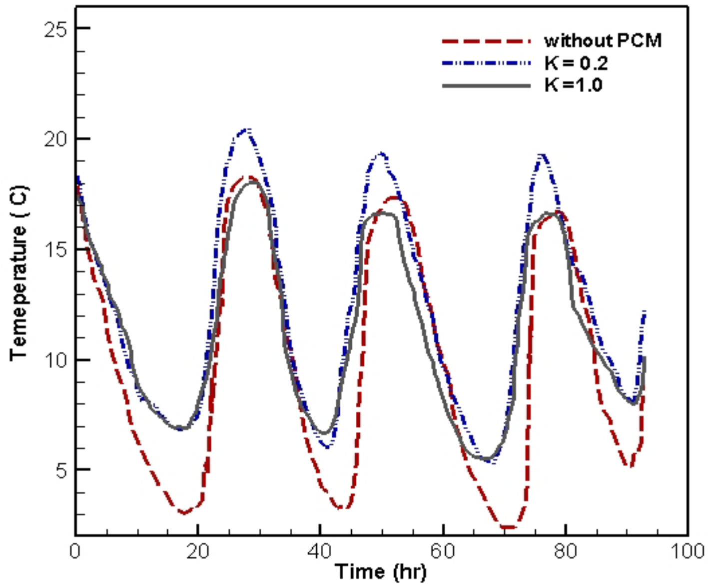

Fig 7: Effect of constant thermal conductivity of PCM on the temperature distribution inside the building

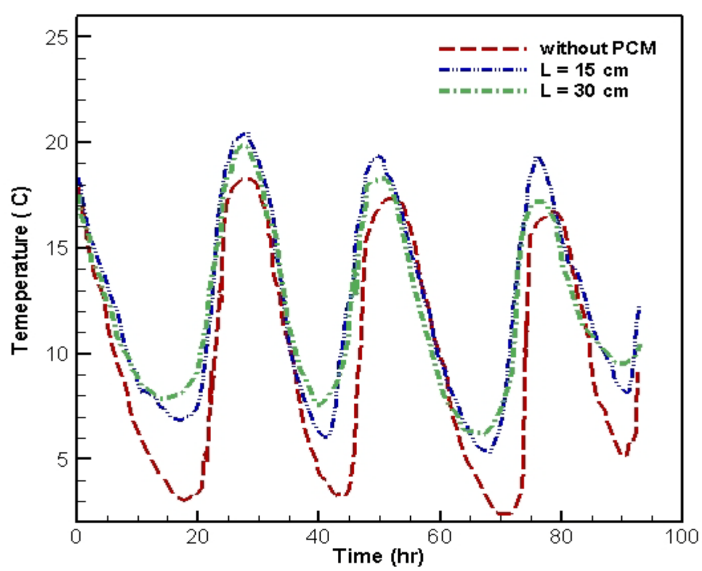

Fig 8: Effect of thickness of PCM and plaster wall on the temperature distribution inside the building

Comparison of temperature distribution in Figures 7 and 8 indicate the fact that with increasing thermal conductivity of phase change material and the wall thickness of this material, less temperature fluctuations and thus less wasted energy will be resulted.

5. Conclusions

In this paper a model is presented in order to evaluate the system using phase change materials in buildings. This model is compared with an experimental data and satisfactory agreement is observed. The effects of some parameters like thermal conductivity of phase change material and thickness of PCM and plaster wall were investigated and as expected the positive effect of increasing these two parameters on the system observed. The results of the numerical analysis indicate that this system has a good performance for increasing the energy efficiency in buildings. By choosing the proper phase change material with phase change temperature and heat capacity regarding to the condition of the system, using this system in other buildings with different heating loads is applicable.

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