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PCM Building Material under Cyclic Melting and Freezing Processes

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Abstract

One of the interesting applications for Phase Change Materials (PCMs) is in buildings by incorporating them in conventional construction. By including PCM into wall construction, the heat transfer through the wall can be seasonably controlled with the absorption and the release of the latent heat. The choice of phase change temperatures is a key parameter in the design of PCM building materials. This temperature has been studied previously by different researchers. The present work aims to study the thermal behavior of microencapsulated phase change materials incorporated in building material under cyclic convection boundary conditions. The effect of some physical parameters on the thermal behavior of wallboard is also discussed.

Keywords: Phase change material (PCM), Building construction, Heat transfer, periodic boundary conditions.

Introduction

One of the interesting applications for Phase Change Materials (PCMs) is in buildings by incorporating them in conventional construction [1-7]. By including PCM into wall construction, the through-wall heat transfer can be seasonably controlled with the absorption and release of latent heat [8-9]. The choice of phase change temperatures is a key parameter in the design of PCM building materials since they decide the storage system capacity, size and application range. This temperature has been studied previously by different researchers [10-12]. Peippo et al. [13] affirmed that the melting temperature of the PCM that maximizes the heat absorbed during the diurnal period should be between 1 and 3°C higher than the indoor temperature. Neeper [14] judged that the transition temperature of the PCM should be close to the indoor temperature to minimize the thermal load of the building. The melting temperature of 22°C, which is 2°C higher than the indoor comfort temperature, is adopted by Heim and Clarke [15]. Finally, Zhang et al. [6], in their interesting review, affirmed that the melting temperature of the PCM should be near the indoor temperature. Considering these results, a main conclusion would be that the optimal value of the melting temperature depends on the average room temperature, which varies from building to building and from season to season.

The present work aims to study the thermal behavior of microencapsulated phase change materials incorporated in building material under cyclic convection boundary conditions. The validity of the numerical study is ascertained by comparing our results with previously published results. The effect of some physical parameters on the thermal behavior of wallboard is also discussed.

1. Physical model [16]

The physical model presented in Kousksou et al. [16] for a single charge/discharge of such a microencapsulated PCM incorporated in building material is used to analyze the behavior of the PCM building material under cyclic melting and freezing processes. The main assumptions of the model are:

- The PCM is pure, homogeneous and isotropic.
- Melting and solidification processes occur at the same and constant temperature.
- The PCM field is supposed to be spherically symmetric.

- The thermophysical properties of the PCM and of the building material are temperature independent,
- Supercooling during freezing is neglected.
- Heat transfer is caused by heat conduction and is one-dimensional.

Based on these assumptions, the energy balance equations for the building material and the PCM read as:

- ***Building material***

$$(1-\varepsilon)(\rho\, c)_B \frac{\partial T_B}{\partial t} = \frac{\partial}{\partial x}\left((1-\varepsilon)\, k_B \frac{\partial T_B}{\partial x}\right) + U\, a\, (T_{PCM} - T_B) \qquad \textbf{(1)}$$

Where ρ_B the density of the building material, c_B the specific heat capacity of the building material, U the overall constant heat transfer coefficient, ε the volume fraction of the PCM in the building material, T_B the temperature of the building material, T_{PCM} the PCM temperature and a is the superficial capsule area per unit volume which is classically expressed as a function of the volume fraction of the PCM in the building material ε and of the capsule diameter d, namely:

$$a = \frac{6\varepsilon}{d} \qquad \textbf{(2)}$$

- ***Phase Change Material (PCM)***

During sensible heat storage (PCM is completely solid or liquid)

$$\varepsilon(\rho\, c)_{PCM} \frac{\partial T_{PCM}}{\partial t} = \frac{\partial}{\partial x}\left(\varepsilon\, k_{PCM} \frac{\partial T_{PCM}}{\partial x}\right) + Ua\,(T_B - T_{PCM}) \qquad \textbf{(3)}$$

During the latent-heat storage (melting or freezing)

$$\frac{\partial f}{\partial t} = \frac{aU}{\varepsilon \rho_{PCM} H_m}(T_B - T_m) + \frac{k_{PCM}}{\rho_{PCM} H_m}\frac{\partial^2 T_{PCM}}{\partial x^2} \qquad \textbf{(4)}$$

Where k_{PCM} the thermal conductivity of the PCM, ρ_{PCM} the PCM density, c_{PCM} the specific heat capacity of the PCM, f the liquid fraction of PCM, T_m the melting temperature of the PCM and H_m is the latent heat of the PCM.

2. Results and discussion

In this work, the outside surface of the PCM wallboard is subjected to three cyclic boundary conditions: temperature ramp on both lateral sides of the sample, sinusoidal outside temperature and sinusoidal outside heat flux on one lateral side of the sample.

3.1. Thermal characteristics of phase change material wallboard with temperature ramp on both lateral sides

To compare our results with experiments data offered by [17], we have tested the cement mortar with 20% of PCM. The PCM building material is placed in a rectangular mould with the interior dimension of 25×25×4 cm^3 [17]. The PCM has a melting point provided by manufacturer equal to +26 °C. The thermophysical properties of cement mortar and PCM are presented in the following tables:

Table 1: Physical Properties of Mortar

Density	1400 $kg.m^{-3}$
Thermal conductivity	0.65 $W.m^{-1}.°C^{-1}$
Specific heat capacity	925 $J.kg^{-1}°C^{-1}$

Table 2: Physical Properties of PCM

Density (solid/liquid)	995 $kg.m^{-3}$
Thermal conductivity (solid)	0.2 $W.m^{-1}.°C^{-1}$
Thermal conductivity (liquid)	0.13 $W.m^{-1}.°C^{-1}$
Specific heat capacity (solid)	1700 $J.kg^{-1}°C^{-1}$
Specific heat capacity (liquid)	2153 $J.kg^{-1}°C^{-1}$
Latent heat of fusion	16674 $J.kg^{-1}$
Melting temperature	26 °C

The mean micro-encapsulated PCM diameter is supposed to be $100\,\mu m$ [17]. Each side of the phase change material wallboard is exposed to a time dependent linear surface temperature ($T_{B,out}$ and $T_{B,int}$) which is comprised between 11 and 40°C (see Figure 1). The thermal cycle with temperature linear variation allowed us to easily detect any deviation of the temperatures inside the construction material with respect to a linear variation.

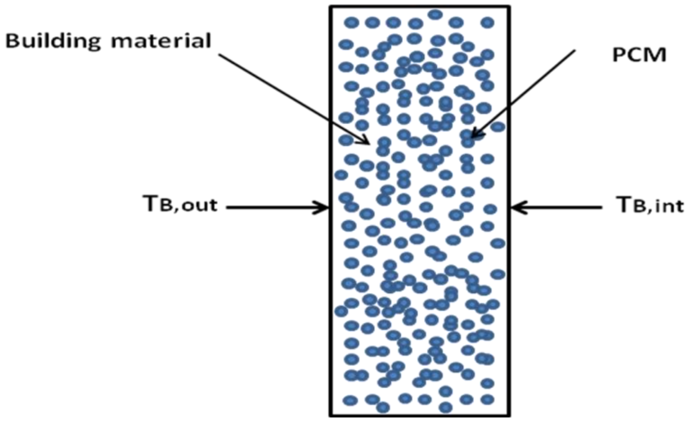

Figure 1: Building material with microencapsulated PCM

Comparison between experimental and numerical heat fluxes on the left side of the sample (Figure 2) during the melting and solidification processes shows a good agreement. A slight difference between the experimental and numerical curves can be observed at the beginning of the melting process. These differences can be partially justified by the fact that in the numerical simulation, the PCM mortar is considered to be pure, isotropic and homogeneous material with constant characteristics for liquid and solid phases which may not entirely true. If the temperature dependent material properties are known, the numerical methods will give more precise results for the PCM temperature. Thus the material properties of the PCM should be well known in order to obtain sufficiently accurate results with the numerical methods. These differences can also be justified by the presence of the impurities in the studied PCM. It is interesting to note that these results are also similar to those reported by Hasse et al. [18] under similar conditions.

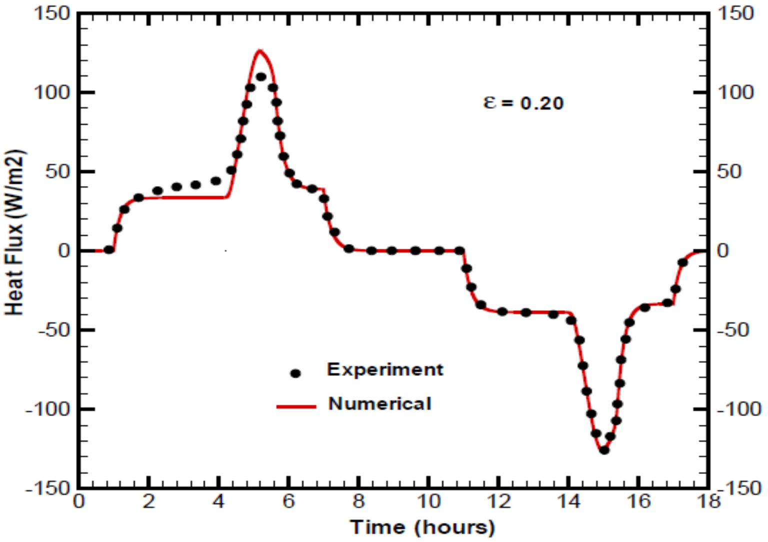

Figure 2: Numerical and experimental heat flux during heating and cooling processes at the front side of the sample.

The numerical heat flux versus $T_{B,out}$ for various value of the volume fraction ε of PCM inside the building material are plotted in Figure 3. As can be seen the kinetic of the phase change process depends on the value of ε . The increase in the percentage of the PCM in the sample leads to an increase in the time required for the phase transition process. We can also note that the peak temperatures range becomes broader and its shifts to greater temperatures with increasing the volume fraction of the PCM in the mortar. Figure 3 compares also the behavior of the building material with and without PCM. We note that the building material without PCM stores only the sensible heat. The comparison between these curves (mortar and mortar with PCM) illustrates the large ability of PCM to absorb and release the heat and achieving the objective of time shifting.

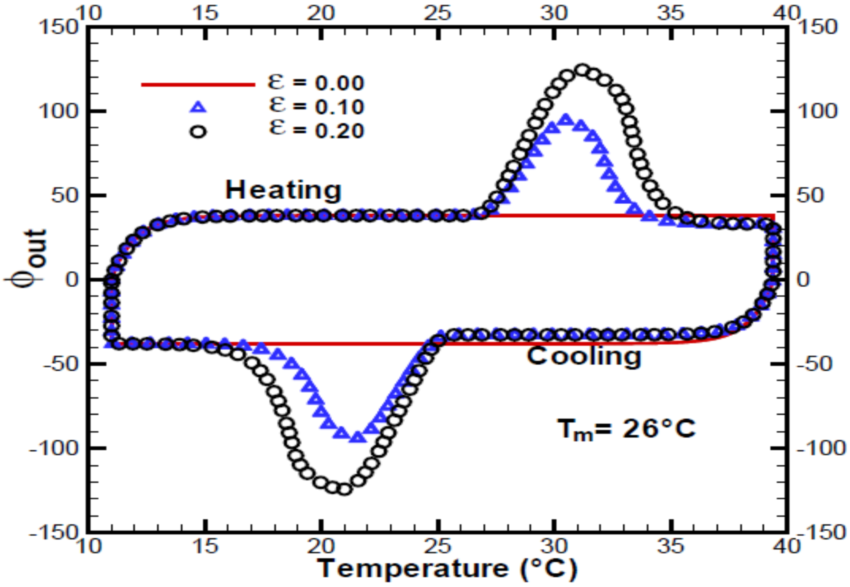

Figure 3: Numerical heat flux ϕ_{out} versus $T_{B,out}$ during heating and cooling for various ε

3.2. Thermal characteristics of phase change material wallboard with sinusoidal outside temperature variation

This section aims to investigate the thermal performance of the mortar shape-stabilized phase change material (MSSPCM) wallboard under sinusoidal variation of the outside temperature and compare it with the traditional building materials. Using the above-described model simulations were carried with the following conditions:

The outside temperature T_{out} represents the daily variation of the atmosphere temperature:

$$T_{out}(°C) = 18 + 7\sin(wt) \quad \textbf{(5)}$$

The inside temperature is fixed at $T_{\text{int}} = 20°C$

The exterior surfaces are exposed to the outside and inside temperature and the corresponding boundary conditions are (see Figure 1):

$$h_{out}(T_{out} - T_{B,out}) = -K \left.\frac{\partial T}{\partial x}\right|_{x=0} \quad \textbf{(6)}$$

$$h_{\text{in}}(T_{\text{int}} - T_{B,\text{int}}) = K \left.\frac{\partial T}{\partial x}\right|_{x=L} \quad \textbf{(7)}$$

h_{out} and h_{in} are respectively the outside and inside convective heat transfer coefficients, and k is the thermal conductivity of the PCM building material given by the following expression:

$$K = \varepsilon K_{PCM} + (1-\varepsilon)K_B \quad \textbf{(8)}$$

At $t = 0$ the initial conditions are $T_{B(x,0)} = T_{PCM(x,0)} = T_{\text{int}}$

Two parameters "time lag" φ and "decrement factor" df were used to analyze the thermal behavior of conventional building materials under periodic convection boundary conditions [20-23]. φ describes the time delayed when the heat wave reaches the low level from the outside to the inner surface of wallboard and df can be defined as the ratio of the wallboard inner heat wave amplitude ($A_{w,in}$) to the outside heat wave amplitude ($A_{w,out}$), i.e. $\frac{A_{w,in}}{A_{w,out}}$. The same parameters were also used by Zhou et al. [21-22].

Figure 4 presents the variation of the numerical inner surface temperature versus time for different building materials. The thermophysical properties of the studied materials are listed in Table 3. The inner surface temperature for both EPS (Expanded polystyrene) and RefM (Reference mortar) conserves the sinusoidal form of the outside temperature with only the amplitude decreased. However, for MSSPCM, a flat segment around the melting temperature within the inner surface temperature is observed and the temperature amplitude is significantly decreased. The flat time ψ corresponds to the time that the wallboard inner surface temperature remains constant at or near the melting temperature (see Figure 4). As indicated in Figure 4, the EPS gives the smallest time lag due to its highest thermal diffusivity and the Ref M produces the highest decrement factor due to its highest thermal conductivity.

Table 3: Physical Properties

Parameters	MSSPCM	Ref M	EPS
T_m (°C)	18 – 20 – 22	--	--
H_m (kJ/kg)	0 – 20 – 40 – 80 – 160	--	--
C_p (J/kg.K)	1500	1000	1400
k (W/m.K)	0.2 – 0.4 – 0.8	0.61	0.04
ρ (kg/m^3)	1250	1400	55
h_{in} (W/m^2.K)	5.4 – 8.7 – 15.4		
h_{out} (W/m^2.K)	8.7 – 18.6 – 25.4		
L (mm)	20		

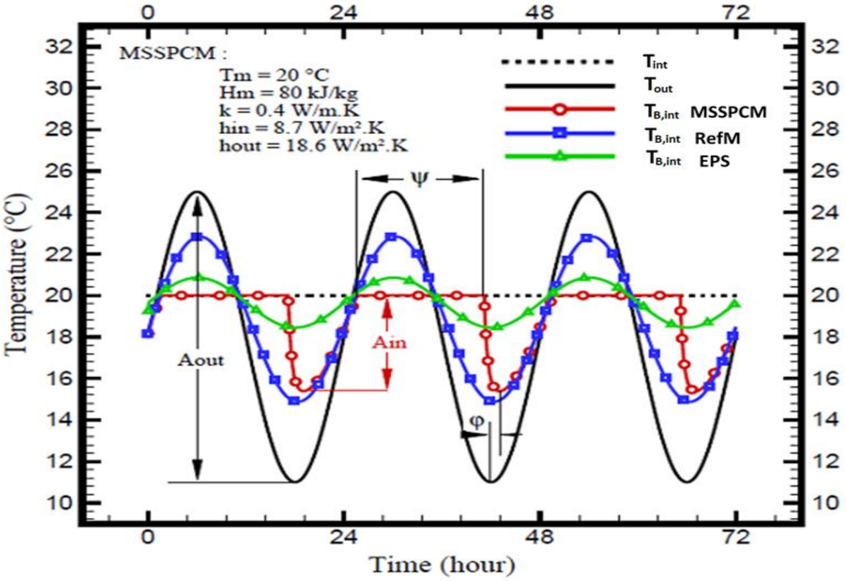

Figure 4: Inner surface temperature variation with time during melting and solidification processes for MSSPCM, Ref M and EPS

3.3. Thermal characteristics of phase change material wallboard with sinusoidal outside heat flux variation

The purpose of this section is to describe the thermal performance of the MSSPCM wallboard under periodic variation of the outside heat flux. Using the above-described model simulations were carried with the following boundary conditions:

$$\phi_{out} = -K \left.\frac{\partial T}{\partial x}\right|_{x=0} \tag{9}$$

$$\phi_{int} = h_{\text{int}}(T_{in} - T_{B,\text{int}}) = K \left.\frac{\partial T}{\partial x}\right|_{x=L} \tag{10}$$

Where: ϕ_{out} is the outside heat flux.

The variation of the inside surface heat flux versus time for different building materials is presented in Figure5. For both EPS and Ref M, the inner surface heat flux curve retains the sinusoidal form with slight time delayed and amplitude decreased. Tow horizontal segments corresponding to the phase change processes within the inner surface heat flux curve of MSSPCM are observed. During the melting and the freezing processes the heat flux vanishes and the heat propagation through the building material is blocked. It is also found that the EPS has the smallest time lag and the highest decrement factor. The phase change processes inside the MSSPCM produces largest time lag and lowest decrement factor.

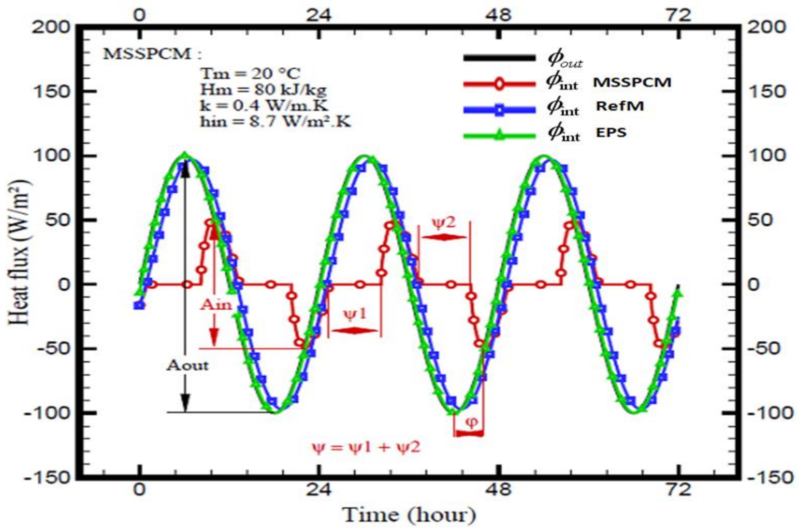

Figure 5: Inner surface heat flux variation with time during melting and solidification processes for MSSPCM, Ref M and EPS.

Conclusion

Thermal behavior of PCM building wall under periodic boundary conditions were investigated numerically and compared with the conventional building materials. It is found that for different periodic boundary conditions, thermal wave amplitude is considerably decreased and wave phase is delayed due to the latent heat thermal storage. The effect of some physical parameters on the thermal behavior of wallboard is also discussed. The results show that the MSSPCM is better than the Ref M and EPS for both variation of inner surface temperature and heat flux, because the phase change processes inside the MSSPCM produces the largest time lag and the lowest decrement factor.

The numerical results obtained with the proposed model proved to be in good agreement with those provided by the literature.

Considering the results obtained in the present study, it seems now relevant to consider the use of the present model to address the question of the integration of such phase change materials into building materials.

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