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Parametric analysis of influencing factors in Phase Change Material Wallboard (PCMW)

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Abstract:

Incorporating Phase Change Materials (PCMs) into traditional building structures has been considered as an effective way to reduce the mismatch between energy supply and demand and in turn to minimise energy consumption (cooling/heating energy). For building applications, Phase Change Material Wallboards (PCMWs) are of particular interest due to their easy installation to existing buildings for refurbishment. Both interior and exterior PCMWs are investigated in this paper, with a numerical study examining the effects of wallboard thermal properties on its thermal performance. These influencing factors include melting temperature, melting range, latent heat, thermal conductivity and surface heat transfer coefficient. An effective heat capacity model is adopted to consider latent heat with the model validated by an experiment. Inner surface temperature and diurnal energy storage are chosen as the evaluation criteria when comparing the thermal performance between different PCMWs. By analysing the effects of influencing factors on the system thermal performance, this study serves as a useful guide for selection of PCMs in energy-efficient buildings.

Key words: PCMW; latent heat storage; heat transfer; thermal comfort.

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1. Introduction

Foreseeable depletion of fossil fuels and CO_2-induced global warming have driven scientists to research renewable energy technologies and develop highly efficient energy storage systems. The building sector is one of the leading energy consumers in all countries. For example, in 2011 the building sector accounted for nearly 40% of the whole fossil fuel consumption of the U.S.A. [1]. Energy consumption in building applications is still rising due to the increasing demand for better thermal comfort, which is realised by heating, cooling, ventilation and air conditioning devices. To cut energy consumption and CO_2 emission, energy-efficient buildings have gained much attention. Incorporating Phase Change Materials (PCMs) into traditional building structures is considered, not only as an effective way to minimise the energy consumption in buildings, but also as a useful method to reduce the mismatch between energy supply and demand.

The use of PCMs in building applications can generally be divided into three categories: passive solar heating, active heating and night cooling [2]. For most buildings, structures like concrete/brick walls, wallboards, ceilings, floors, windows and shutters are possible places to incorporate PCMs [1-4]. PCMs can also be encapsulated in separate storage systems for active heating or night cooling. In a recent research project of buildings called “MECLIDE”, which was conducted by Alvarez *et al.* [5] from Spain, PCMs were encapsulated in containers which then form parts of the building structure in order to increase the thermal inertia of the building and also to work as an active solution. However, incorporating PCM into traditional building structures is still a frequently used method. Zhang *et al.* [2] investigated these different structures and concluded that Phase Change Material Wallboards (PCMWs) would be an efficient method of incorporation due to their flexibility and easy installation. Pasupathy *et al.* [3] studied the feasibility of using PCMs in building structures including dry walls, concrete blocks, wood-lightweight concrete frame walls and windows. They concluded that latent heat storage technology in building integrated energy systems would be of great importance in the future. Baetens *et al.* [4] reviewed a variety of PCM applications in building envelopes and concluded that incorporating PCMs into concrete structures can store more heat than incorporating PCMs into wallboards, but the former has rather low economic efficiency which has restricted its application. Many scientists have suggested investigating PCM Wallboards (PCMWs) because of their following advantages: flexible installation, easy incorporation, better leakage control and no reduction to the mechanical strength of traditional structures. Zhou *et al.* [1] discussed the thermal performance of PCMWs, covering both experimental aspects and simulation, and also summarisd the latest building applications of PCMs.

PCMWs work well for keeping the room within thermal comfort. Scalat *et al.* [6] built a double-room building with PCMWs on its internal walls and found that the room temperature was kept within the thermal comfort for a long time after turning off the heating or cooling system. Athientis *et al.* [7] set up a direct-gain test room with PCM gypsum boards on its external walls and found that the room air temperature was reduced by 4 K during the daytime. Kuznik and Virgone [8] tested a full scale room with PCMWs for summer, mid-season and winter cases and they found the PCMWs can strongly reduce the overheating effect for all cases. Kuznik *et al.* [9] also monitored a refurbished building with Dupont de Nemours® PCMWs for a whole year and found these PCMWs worked very efficiently when the outside temperature was varying in the melting temperature range of the PCMW. Conducting a study of thermophysical characterisation is a key step to choose the PCMs and supporting materials. Recently, Camila *et al.* [10] developed two devices to characterise effective thermal conductivity and thermal response of real materials at macroscale and found that there were different optimal weight ratios between the PCMs and different supporting materials. Chen *et al.* [11] also developed a new method to measure the thermophysical properties of PCM-concrete brick for engineering use and their method is also suitable for the measurement of PCMWs.

The thermal performance of PCMWs can be measured by different criteria. Two commonly used criteria are: inner surface temperature history and thermal energy storage capacity. Researchers proposed various parameters to evaluate the inner surface temperature history, such as ‘time lag’, ‘decrement factor’ and ‘phase transition keeping time’. These parameters were studied by Zhou *et al.* [12, 13], in which a single shape-stabilised PCMW was modelled under a periodically changing temperature condition and a periodically changing heating flux condition respectively. However, precisely obtaining these parameters can be very difficult since the inner surface temperature function gets distorted by non-linear thermal effects of PCMs [14]. Diurnal energy storage is also useful for the evaluation of the thermal performance. Peippo *et al.* [15] and Neeper [16] used this parameter to optimise the melting temperature of PCMW and obtained very useful results. Koo *et al.* [17] investigated the effects of some influencing factors on interior PCMWs by diurnal energy storage but thermal conductivity was not included.

There is no previous work of parametric thermal analyses evaluating PCMW from both inner surface temperature and diurnal energy storage aspects. This paper investigated the effects of thermal properties of both interior and exterior PCMWs on the system thermal performance. Unlike other existing studies in which the indoor air temperature has been kept constant, this study was conducted under periodically changing conditions (both outdoor and indoor environment), The thermal properties including melting temperature, melting range, latent heat, thermal conductivity and surface heat transfer coefficient, are numerically analysed by both inner surface temperature history and diurnal energy storage in order to give a comprehensive guide to PCMW design.

2. Model description

2.1 Analytical model

Phase Change Material Wallboard (PCMW) can be placed at the internal or external wall, in which PCMW plays different roles and undergoes different heat transfer conditions. The exterior wallboard is used to connect between the outdoor and indoor environment, with its inner surface undergoing combined convective (indoor air) and radiative (indoor heat source) heat transfer, and with its outer surface undergoing conductive heat transfer (to the outdoor environment through the insulation or other construction materials). The interior wallboard is used to achieve the thermal comfort in the room by storing heat in the daytime and releasing it during the nighttime. For interior wallboard, the outer surface can be considered as adiabatic whilst the inner surface undergoes combined convective and radiative heat transfer as in exterior wallboard.

Both the interior and exterior PCMW are illustrated in Figure 1. T_r and T_o are the room and outside air temperatures (K); h_{ex} and h_{in} denote the outside and inside convective heat transfer coefficients [W/(m^{2}K)], respectively; $q_{i,s}$ and $q_{i,h}$ are the solar radiation flux through the window and the radiation from the indoor heat sources (W/m^2), respectively; q_s is the heat flux by solar radiation to the external wall surface (W/m^2); T_m denotes the melting temperature (K) of the PCMW. With the assumptions of constant T_m, unlimited heat storage capacity and neglect of the thermal resistance of the wallboard itself, the optimal melting temperature of the interior and exterior PCMW is given based on the method proposed by Neeper [16]:

$$T_{m,in} = \bar{T}_r + \frac{\int_P \left(q_{i,s} + q_{i,h}\right) d\tau}{h_{in} \cdot P} \tag{1}$$

$$T_{m,ex} = \frac{\frac{1}{h_{in}} \cdot \bar{T}_o + \left(\frac{1}{h_{ex}} + \frac{L_{is}}{k_{is}}\right) \cdot \bar{T}_r + \frac{1}{h_{in}} \cdot \left(\frac{1}{h_{ex}} + \frac{L_{is}}{k_{is}}\right) \cdot \left(\frac{1}{P} \int_P \left(q_s + q_{i,s} + q_{i,h}\right) d\tau\right)}{\frac{1}{h_{in}} + \frac{1}{h_{ex}} + \frac{L_{is}}{k_{is}}} \tag{2}$$

where L_{is} and k_{is} denote the thickness (m) and the thermal conductivity [W/(mK)] of the insulation, respectively. The optimal melting temperature of the interior PCMW depends on the average room air temperature and the total radiation absorbed by the PCMW including $q_{i,s}$ and $q_{i,h}$, whilst the optimal melting temperature of the exterior PCMW depends on the average room air temperature, the average outdoor temperature and the total radiation absorbed by the PCMW. In addition, the optimised melting temperature is also dependent on the following factors: the convective heat transfer coefficients at the inner and external surface, the thickness and the thermal conductivity of the insulation material (or other wall components).

2.2 Numerical model

2.2.1 *Governing equations*

Natural convection during the melting process can affect the heat transfer in PCMW [18]. Jany and Bejan [19] investigated the melting phenomenon with natural convection in an enclosure and presented that the natural convection takes place when:

$$Ra^{1/4} > \frac{H}{L_p} \tag{3}$$

where, H and L_p are the height (m) and thickness (m) of the PCMW. The Rayleigh number can be defined as $Ra = \left[g\beta \left(T_{warm} - T_m \right) H^3 \right] / \upsilon\alpha$, where g is the gravitational acceleration (m/s^2), β is the volumetric thermal expansion coefficient (K^{-1}), T_{warm} is the warm wall temperature (K), υ is the kinematic viscosity (m^2/s) and α is the thermal diffusion (m^2/s). Most PCMWs have small thicknesses (<0.05 m) and large heights (>1 m), so that the value of H/L_p is rather large and consequently natural convection during the melting process can be neglected. The other reason for neglecting the natural convection is that in the real case of PCM wallboard, the core material is always a mix of a PCM and a supporting material, such as a copolymer, in which the mechanical stability of the core material can be maintained while the PCM is in its liquid state. The heat transfer in PCMWs can be simplified into a one-dimensional problem, because the dimension in other directions is much larger than the dimension in the thickness direction.

Some other assumptions made in this study are: (1) the core material of the PCMW is considered to be homogeneous; (2) the PCM has temperature-independent physical and thermal properties, and these properties are considered as constant only except the specific heat of the PCM during the melting and solidification process used in the numerical analyses; (3) the convective heat transfer coefficients of inner surface (h_{in}) and external surface (h_{ex}) are constant; (4) the wallboard has uniform initial temperatures; (5) the exterior surface of the PCMW and the insulation layer have the same temperature at their common boundary.

Based on the above assumptions, the heat transfer of a PCMW can be considered as a one-dimensional heat conduction process. The energy governing equation is given by:

$$\rho_p C_p(T) \frac{\partial T(x,\tau)}{\partial \tau} = k_p \frac{\partial^2 T(x,\tau)}{\partial x^2} \tag{4}$$

where ρ_p and k_p are the density (kg/m^3) and the thermal conductivity [W/(mK)] of the PCMW, T and τ denote temperature (K) and time (s), $C_P(T)$ is the effective specific heat capacity [kJ/(kgK)], given below:

$$C_P(T) = C_{p,s} \qquad T < T_1$$

$$C_P(T) = \frac{H_m}{(T_2 - T_1)} + \frac{C_{P,s} + C_{P,l}}{2} \qquad T_1 < T < T_2 \tag{5}$$

$C_P(T) = C_{p,l} \qquad\qquad T > T_2$

where T_1 and T_2 denote the start and end point (K) of the melting process respectively, H_m is the latent heat (kJ/kg), subscripts s and l stand for the solid and the liquid state respectively.

2.2.2 *Environmental conditions*

The outer surface of an exterior wall can be considered to be exposed to periodically changing outdoor air temperatures and solar radiation. To investigate the effects of influencing parameters on the thermal performance of PCMWs, the situation with the outdoor temperature range crossing the melting temperature is considered. The daily outdoor temperature is assumed to vary sinusoidally between 291 K (18°C) and 305 K (32°C):

$$T_o = 298 + 7 \times \sin\left(2\pi\tau/P\text{-}2\pi/3\right)\ \text{K} \tag{6}$$

where P = 24 hours. The highest outdoor temperature in Eq. (6) appears when τ is at 2pm daily.

The direct solar radiation in a day reaches its maximum value when τ is at 12 noon, but calculating the solar radiation absorbed by a vertical wall is complicated since it depends on the location of the city [20]. Here the idealised solar irradiance on the external surface facing south is assumed to obey the Gaussian distribution:

$$I = 400 \times e^{\left(\text{-}0.5\times\left(\frac{\tau\text{-}12}{2}\right)^2\right)}\ \text{W/m}^2 \tag{7}$$

where the maximum solar irradiance at noon is 400 W/m^2.

For both the exterior and interior PCMW, the inner heat gains and the solar radiation through the window are neglected in the simulation work. To achieve good thermal comfort, no matter in summer or in winter, the room air temperature range is assumed to be between 294 K (21°C) and 298 K (25°C) with sinusoidal variation during a 24-hour period:

$$T_r = 296 + 2\sin\left(2\pi\tau/P\text{-}2\pi/3\text{-}2\pi\tau'/P\right)\ \text{K} \tag{8}$$

where τ' is the time delay between the time when the outdoor air temperature achieves the peak value and the time when the indoor air temperature achieves the peak value.

Kuznik *et al.* [21] investigated how time delay (τ') influences the selection of the PCM optimal thickness. The time delays they studied are -4h, -2h, 0, 2h and 4h. They pointed out that the time delay is positive in summer. In the numerical study carried out by David *et al.* [22], a time delay of 3h was used. Since 2h has been used in most previous studies, the time delay in this study is also assumed to be 2 hours, which means the maximum value of the indoor air temperature occurs at 16:00 if the outdoor air temperature reaches its maximum value at 14:00. The idealised outdoor environment including outdoor air temperature, solar irradiance and room air temperature is shown in Figure 2.

2.2.3 *Simulation process*

The purpose of this work is to specify the effects of the influencing parameters on the thermal performance of PCMW. A standard set of parameters should be determined. Based on the technical data of the Energain® thermal mass panel, the standard thermophysical properties are melting temperature of 295 K, melting range of 1 K, density of 885 kg/m^3, thermal conductivity of 0.2 W/(mK), sensible heat and latent heat of 2.4 kJ/(kgK) and 70 kJ/kg respectively. Unlike the commercially produced material, a 1 cm-thickness is used as the base value (standard) here. The insulation material for exterior wall has a density of 35 kg/m^3, thermal conductivity of 0.04 W/(mK), specific heat of 1.2 kJ/(kgK) and thickness of 5 cm.

A combined overall heat transfer coefficient comprising both the convective and radiative heat transfer coefficients for the inner surface of PCMW is used in the simulation. A heat transfer coefficient between 5 W/(m^{2}K) and 12 W/(m^{2}K) for the inner surface is usually adopted in the literature: 5.67 W/(m^{2}K) and 8.3 W/(m^{2}K) used in Ref. [16], 7 W/(m^{2}K) used in Ref. [21], 8 W/(m^{2}K) used in Ref. [15], 8.7 W/(m^{2}K) used in Ref. [14], 9 W/(m^{2}K) used in Ref. [23] and 12 W/(m^{2}K) used in Ref. [17].

For the outer surface of an external wall, Kuznik *et al.* [21] used 25 W/(m^{2}K) and Ahmad *et al.* [23] used 17 W/(m^{2}K), the selection of which varies from case to case. Therefore, the standard overall heat transfer coefficients for outer and inner surface are set to be 17 W/(m^{2}K) and 8 W/(m^{2}K). The standard value of solar absorption coefficient of the external wall is set at 0.6 [24].

COMSOL® is used as the problem solver. A very small mesh sizing is carefully selected and a time step of 120 seconds is used. In order to investigate the effects of all influencing parameters on the system performance, simulations are conducted on different values of each parameter whilst keeping other parameters constant at their standard values. The initial temperatures for all the simulations are 288 K. The data is recorded for the 9*th* simulated day by which time the variation in temperatures are completely periodic and the effect of the initial conditions has diasappeared.

2.3 Validation of solving moving boundary problem

The model is validated by the experiment results of paraffin RT 27 during melting process [25], shown in Figure 3. It shows that the simulation results capture the overall temperature history of the melting process but with small discrepancies. One reason is that some experimental uncertainties exist in the experiment processes. The other reason is that there are several assumptions in the simulation work: constant and time-independent thermophysical properties and natural convective heat transfer not considered in the liquid-state paraffin. In spite of these small discrepancies, the simulation agrees well with the experimental data overall.

The model is also validated with the data from Solomon [26]. He analysed a slab of N-Eicosene paraffin wax with an initial temperature of 294 K (21°C). The thermophysical properties were melting temperature of 309.7 K (36 °C), latent heat of 247 kJ/kg, density of 840 kg/m^3, sensible heat of 2200 J/(kgK) and thermal conductivity of 0.15 W/(mK). The thickness of the slab was 0.15 m. The slab was heated from one side under a constant temperature of 368 K (95°C). In his simulation, the melting range was assumed to be 1 K. Figure 4 shows the comparison between the current simulation and the data in [26], and a very good agreement between them has been achieved.

3. Influencing parameters

3.1 Melting temperature

The interior PCMW is used to store heat from room in the daytime and release it back in the nighttime. Thus the inner surface temperature history is of great interest to determine the thermal performance of the wallboard. Generally speaking, the smoother the inner surface temperature is, the more energy (during cooling or heating) can be saved. Figure 5(a) shows the inner surface temperature history of the interior PCMW with different melting temperatures of melting range of 1 K. It can be seen that the PCMW with a melting temperature of 296 K has the smoothest inner surface temperature history, where the difference between the maximum and minimum temperature during a day is within 1 K. As the room air temperature is controlled within the thermal comfort range, more uniform inner surface temperature history means less extra energy is needed to keep the room within good thermal comfort. The PCMW with a melting temperature of 293 K has the largest difference between the maximum and minimum temperature during a day, because the temperature of 293 K is not within the room temperature range and the latent heat storage/release consequently does not take effect.

Each inner surface temperature history has a plateau around its melting temperature and the plateau gets shorter with the melting temperature away from 296 K. The plateau implies the presence of a phase change process. The longer it is, the longer time the indoor thermal comfort can be kept for, which is beneficial to energy-saving. In this situation, the optimal temperature is 296 K. From Eq.(1), the optimal melting temperature of an interior PCMW equals the average room air temperature when inner heat gains are neglected. The temperature, 296 K, can be obtained through the equation under the standard values, which agrees well with the simulation work.

The exterior PCMW is used partly as thermal energy storage, and partly as the thermal resistance of the exterior wall to decrease the heat from the outside environment to the room. The time lag for the exterior wall is defined as the time delay between the peak temperature of the outside environment and the inner surface. Like the interior PCMW, the larger the time lag is, the more energy can be saved. Figure 5(b) presents the effect of the melting temperature on the inner surface temperature history. The temperature 293 K falls outside the range of the room air temperatures and is far away from the average outside temperature, therefore this case has the smallest time lag and the highest peak inner surface temperature. The curve for the PCMW with phase change temperature of 297 K has the largest phase change time and time delay, which are good for energy saving. According to Eq.(2), the optimal melting temperature has been calculated as 296.9 K, which agreed well with the simulation work.

The outside environment in Figure 5(b) is based on summer conditions, so the thermal comfort can be improved by decreasing the highest daily temperature. From this point of view, the case with the melting temperature 299 K should be better than those one with 295 K because the former has a lower peak inner surface temperature than the latter. Moreover, the latter keeps melting for a longer time than the former, therefore the latter is superior to the former in this sense. Lower peak inner surface temperature means smaller temperature variation which is benefited from using PCM, whilst longer melting time means the thermal comfort can be kept for a longer time.

For interior PCMWs, diurnal energy storage is calculated by integrating the heat flux coming into the PCMW through its inner surface during a day. Figure 6(a) shows the effects of melting temperature and its range on the diurnal energy storage of the interior PCMW. For the same melting temperature range, the PCMW with a melting temperature of 296 K has the largest diurnal energy storage. For the PCMW with a melting temperature of 296 K, a narrower temperature range results in higher diurnal energy storage, because the narrower temperature range means the whole melting process of the PCM does not deviate much from the average room temperature. For the single melting temperature, the largest diurnal energy storage occurs at the optimal melting temperature of 296 K, which agrees well with Eq.(1).

Under the same melting range, the diurnal energy storage with melting temperatures of 295 K and 297 K are almost the same, because the differences between them and the optimal melting temperature 296 K (also the average room temperature) are both 1 K . However, the real diurnal energy storage for the PCMW with melting temperature of 297 K should be slightly higher than the one with 295 K, because the one with 297 K has slightly higher sensible heat storage than the one with 295 K. However, such difference should be so small that it cannot be seen in Figure 6(a) since sensible heat is several orders of magnitude smaller than latent heat and also the temperature difference here is only 2 K.

The PCMW with the melting temperature 293 K is fully at its liquid state with melting ranges of 0.2 K, 1 K and 2 K, thus only the sensible heat works for the diurnal energy storage. Latent heat storage is only produced when the melting range increases.

For the situation without inner heat gains being considered, the diurnal energy storage can be optimised by matching the melting temperature to the average room air temperature and narrowing the melting range, as also shown by Koo *et al.* [17]. However, many existing organic PCMs do not have fixed melting temperatures. From Figure 6(a) it can also be seen that, around the optimal melting temperature 296 K, the diurnal energy storage with a 2 K melting range has a more gentle decrease rate compared to the ones with 0.2 K and 1 K melting range when the temperature deviates from the optimal temperature. On this aspect, a melting range of 2 K is acceptable.

It is easy to understand the importance of the diurnal energy storage for an interior PCMW. However, it can also be used to determine the energy saving rate for an exterior PCMW [16]. Larger diurnal energy storage is better for energy saving, because without the latent heat storage, more heat would come into the indoor environment, in which case more cooling energy would be consumed to maintain thermal comfort. Figure 6(b) shows the effect of the melting temperature and its range on the diurnal energy storage of the exterior PCMW. The maximum diurnal energy storage occurs when the melting temperature is 297 K with a melting range of 0.2 K.

This agrees well with Section 3.1 in which the optimal melting temperature was calculated to be 296.9 K. The closer the melting temperature is to 296.9 K, the greater the diurnal energy storage should be. However, as seen from Figure 6(b), when the melting temperature range is above 2 K, diurnal energy storage for 296 K is slightly higher than that for 297 K. At first sight, this looks surprising; but it can be reasonable because the phase change temperature in the former is closer to the average room air temperature than the latter, which has significantly reduced heat loss.

When the PCMW has a melting temperature between the optimal temperature and the average room air temperature, the melting temperature range, if below 4 K, only has a minor effect on the diurnal energy storage. However, the optimal melting temperature of an exterior PCMW depends on the average outside temperature and the average room temperature. The weather changes during a year causing the change of average outside temperature and solar radiation. The design of an exterior PCMW should consider local weather factor. As discussed above, the room air environment has a large effect on diurnal energy storage, so a melting temperature around average room air temperature with a melting range of 2 K – 4 K can be acceptable

3.2 Latent heat

Figure 7 shows the effect of latent heat on the inner surface temperature history. For interior PCMW, the time lag is defined as the time difference between the peak room temperature and the peak inner surface temperature. A larger time lag is preferred to maintain the thermal comfort in the room, which can significantly reduce energy consumption for heating or cooling. The increase of the latent heat results in the increase of the time lag and more gentle temperature variation during the whole day. In this aspect, an interior PCMW with a higher latent heat is preferred. Compared to interior PCMW, the influence of the latent heat on the inner surface temperature is much smaller for exterior PCMW. Larger latent heat can increase the time lag and the lowest inner surface temperature. However, the highest inner surface temperature cannot be reduced significantly.

The effects of latent heat on the diurnal energy storage of the PCMW are shown in Figure 8. Regardless of latent heat, the maximum diurnal energy storage always occurs when the melting temperature of the PCMW equals to the average room temperature. Generally speaking, the diurnal energy storage increases with the increase of the latent heat. There is a large increase of the diurnal energy storage when the latent heat changes from 30 kJ/kg to 50 kJ/kg, with the increase being about 60 kJ/m^2 for interior PCMW and 130 kJ/kg for exterior PCMW, respectively.

For interior PCMW, as shown in Figure 8(a), the increase of diurnal energy storage becomes very limited beyond 50 kJ/kg, because the PCM inside the wallboard may not complete a whole thermal cycle when latent heat is too large. The latent heat has a large effect on the diurnal energy storage if the PCM can finish the phase change in one thermal cycle. However, if the latent heat is so large that one thermal cycle cannot be completed, the diurnal energy storage of an interior PCMW would barely be affected by the latent heat. From this point of view, an interior PCMW should be designed in the way that as much PCM as possible should finish phase change within a thermal cycle, which can be optimised according to the PCMW properties and environmental conditions.

For exterior PCMW, the lowest curve in the Figure 8(b) is for the latent heat of 30 kJ/kg. The PCM inside this wallboard can totally melt and solidify in a thermal cycle. Once phase change has occurred, only the sensible heat storage exists. For the melting temperature of 293 K, the PCM is always in its liquid state and latent heat storage does not take effect, therefore the diurnal energy storage is not affected by the latent heat.

From 295 K to 298 K, the increase in diurnal energy storage is the most significant when the latent heat is between 30 kJ/kg and50 kJ/kg. When changing the latent heat from 50 kJ/kg to 70 kJ/kg, the increase in diurnal energy storage is slightly higher at 296 K than that at 297 K. When the latent heat is above 70 kJ/kg, the increase in diurnal energy storage is also higher at 296 K than that at 297 K. The reason is that the PCMW of 297K cannot finish phase change in one thermal cycle when the latent heat increases up to 70 kJ/kg.

If the PCM can fully melt or solidify in one thermal cycle, the diurnal energy storage of exterior PCMW is much higher than that of interior PCMW, when the melting temperatures are closer to their optimal melting temperatures.

3.3 Thermal conductivity

As seen from Figure 9, thermal conductivity does not have so strong an influence on the inner surface temperature as melting temperature and latent heat do. For different thermal conductivities, the difference in time lag is rather small, especially for exterior PCMW. The inner surface temperature history when the thermal conductivity is 0.1 W/(mK) has the largest increase rate compared to others; however, when the thermal conductivity is above 0.4 W/(mK), the obtained curves are almost the same as each other, meaning that the increase of the thermal conductivity cannot save further energy.

Figure 10 shows the effect of the thermal conductivity on diurnal energy storage, from which similar results can be seen. When the thermal conductivity is above 0.4 W/(mK), the diurnal energy storage is barely be affected by increasing the thermal conductivity of the PCMW. However, when below 0.4 W/(mK), the enhancement by increasing thermal conductivity is significant. For example, the diurnal energy storage can reach an enhancement of 20% when the thermal conductivity is increased from 0.1 W/(mK) to 0.4 W/(mK) for interior PCMW.

For a normal exterior wall without latent heat storage, it is true that lower thermal conductivity is better for energy saving since the thermal resistance of the exterior wall is increased. However, for a PCMW, a lower thermal conductivity is not necessarily better in the sense of energy saving, because a higher thermal conductivity improves the thermal performance of the latent heat storage so that more energy can be saved.

It can be seen from Figure 10(b) that when the melting temperature is below 294 K or above 298 K, a lower thermal conductivity is preferred. However, when the melting temperature is between 295 K and 297 K, the diurnal energy storage increases along with the increase of thermal conductivity, because the higher thermal conductivity can enhance the heat absorption from the room. In addition, the heat released into the room can be increased when the room air temperature is lower than the wallboard temperature. Zhang *et al.* [14] concluded from their theoretical study that the energy-saving effect of the external walls was improved when decreasing thermal conductivity, because the insulation (or other wall structures) was not considered in their model, resulting in more heat released into the outside environment than into the room. In their study, the thermal resistance from the outside environment was lower than that from the indoor environment since the insulation was not considered; the temperature difference between the PCMW and the outside environment was larger than the difference between the PCMW and the indoor air, which has driven more heat to be transferred to the outside environment rather than the indoor environment. However, Zhang *et al.* [14] also pointed out that when considering the insulation it is useful to increase the thermal conductivity of PCMW up to 0.4 W/(mK) for higher diurnal energy storage. It can be seen that in this point their study agreed very well with the current work.

As concluded from previous paragraphs, the performance of PCMWs can be much improved if the thermal conductivity of PCMs can be enhanced to 0.4 W/(mK). Existing PCMs used in building applications are mostly organic materials because they do not have super-cooling and phase segregation phenomena. However, they have rather low thermal conductivities, most of which are below 0.2 W/(mK) [27], which can jeopardise thermal energy storage. Despite the fact that some inorganic PCMs can have a thermal conductivity as high as 0.5 W/(mK), they do have very serious problems, such as super-cooling which decrease the effective storage capacity [28], and phase segregation which changes the chemical composition of the core material [29]. Another problem for organic PCMs like paraffin waxes and alkanes [30] is their flammability, which can raise safety issues in building applications. The technology of enhancing heat transfer of PCMs is therefore worthy of much further research.

3.4 Effect of surface heat transfer coefficients

Figure 11 and Figure 12 show the effects of surface heat transfer coefficients on the thermal storage of interior and exterior PCMW, respectively. The inner surface heat transfer coefficient has a larger effect on both interior and exterior PCMW. The diurnal energy storage increases with the increase of internal heat transfer coefficients, because a higher heat transfer coefficient can result in more heat entering the PCMW from the room. Compared to the inner surface heat transfer coefficient, the external surface heat transfer coefficient has a much weaker effect, because of the existence of the insulation which greatly increases the thermal resistance from the outside environment to the PCMW. Despite showing a weak effect in this study, the external surface heat transfer coefficient can have much stronger influence for a lightweight building where a structure of very good thermal insulation is usually adopted to reduce the influence of the outside environment.

The inner and outer convective heat transfer coefficients usually have values of 2.5 W/(m^2K) and 16 W/(m^2K) respectively, according to the ISO15099 [31]. When designing a PCMW, the overall heat transfer coefficients should be calculated carefully, considering the local situation, radiation, location of the wallboard, occupants and other influencing factors. How to select correct, accurate and realistic heat transfer coefficients is of great importance for the PCMW design.

4. Conclusion

This paper presents a parametric study of all influencing factors on the thermal performance of PCMWs. Both interior and exterior PCMWs are investigated numerically under periodically changing environments, with solar radiation also being considered. Thermal properties, such as melting temperature, melting range, latent heat, thermal conductivity and surface heat transfer coefficients, are optimised qualitatively in two design criteria: inner surface temperature history and diurnal thermal storage. The useful results are shown as follows:

(1) The optimal melting temperature of an interior PCMW equals the average room air temperature without considering the heat gains inside the room; the optimal melting temperature of an exterior PCMW depends on both the outside and the inside environment, but mainly on the inside environment because of the existence of the insulation. The high thermal resistance of the insulation reduces the influence of the outside environment. However, the influence of the external environment is more significant for lightweight buildings of low thermal mass. If insulation is not used, a melting temperature range of 2 K – 4 K is acceptable for both interior and exterior PCMWs.

(2) A large latent heat has a positive influence on the diurnal energy storage, but under the condition that all the PCM completes a whole melting-freezing thermal cycle during a day. In addition, an excellent encapsulation method should be developed to avoid leakage problems. A cost-benefit analysis should also be considered to determine fiscal payback and ensure the economic viability of implementin PCM wallboards. In this simulation, a PCM with latent heat of at least 50 kJ/kg is needed at an affordable cost.

(3) The influence of the wallboard's thermal conductivity is not as strong as that of other thermal parameters such as PCM melting temperature and latent heat. However, it is useful to enhance the thermal conductivity to 0.4 W/(mK) for both interior and exterior PCMWs.

(4) The surface heat transfer coefficients (both inner and outside) can significantly affect the thermal performance of PCMW. Choosing suitable parameters is of great importance to optimise performance.

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References:

[1] Zhou D, Zhao CY, Tian Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. Applied Energy 2012; 92: 593-605.

[2] Zhang YP, Zhou GB, Lin KP, Zhang QL, Di HF. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. Building and Environment 2007; 42: 2197-2209.

[3] Pasupathy A, Velraj R, Seeniraj RV. Phase change material- based building architechture for thermal management in residential and commercial establishments. Renewable and Sustainable Energy Reviews 2008; 12: 39-64.

[4] Baetens R, Jelle BP, Gustavsen A. Phase change materials for building applications: A state-of-the art review. Energy and Buildings 2010; 42: 1361-1368.

[5] Alvarez S, Cabeza LF, Ruiz-Pardo Alvaro, Castell A, Tenorio JA. Building integration of PCM for natural cooling of buildings. Applied Energy 2013, 109: 514-522.

[6] Scalat S, Banu D, Hawes D, Paris J, Haghighata F, Feldman D. Full scale thermal testing of latent heat storage in wallboard. Solar Energy Materials and Solar Cells 1996; 44: 49-61.

[7] Athienitis AK, Liu C, Hawes D, Banu D, Feldman D. Investigation of the thermal performance of a passive solar test-room with wall latent heat storage. Building and Environment 1997; 2 (5): 3405-410.

[8] Kuznik F, Virgone J. Experimental assessment of a phase change material for wall building use. Applied Energy 2009; 86(10):2038-2046.

[9] Kuznik F, Virgone J, Johannes K. In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. Renewable Energy 2011; 36: 1458-1462.

[10] Barreneche C, Navarro ME, Fernandez AI, Cabeza LF. Improvement of the thermal inertia of building materials incorporating PCM. Evaluation in the macroscale. Applied Energy 2013, 109: 428-432.

[11] Cheng R, Pomianowski M, Wang X, Heiselberg P, Zhang YP. A new method to determine thermophysical properties of PCM-concrete brick. Applied Energy 2013, 112: 988-998.

[12] Zhou GB, Yang YP, Wang X, Cheng JM. Thermal characteristics of shape-stabilized phase change material wallboard with periodical outside temperature waves. Applied Energy 2010; 87:2666-2672.

[13] Zhou GB, Yang YP, Xu H. Performance of shape-stabilized phase change material wallboard with periodical outside heat flux waves. Applied Energy 2011; 88(6): 2113-2121

[14] Zhang YP, Lin KP, Jiang Y, Zhou GB. Thermal storage and nonlinear heat trasnfer characteristics of PCM wallboard. Energy and Buildings 2008; 40: 1771-1779.

[15] Peippo K, Kauranen P, Lund PD. A multicomponent PCM wall optimized for passive solar heating. Energy and Buildings 1991; 17: 259-270.

[16] Neeper DA. Thermal dynamics of wallboard with latent heat storage. Solar Energy 2000; 68 (5): 393-403.

[17] Koo J, So H, Hong SW, Hong H. Effects of wallboard design parameters on the thermal storage in buildings. Energy and Buildings 2011; 43:1947-1951

[18] Tian Y, Zhao CY. Natural convection investigations in porous phase change materials. Nanoscience and Nanotechnology Letters 2011; 3(6): 769–772.

[19] Jany P, Bejan A. Scaling theory of melting with natural convection in an enclosure. International Journal of Heat and Mass Transfer 1988; 31 (6): 1221-1235.

[20] Slama RB. Incidental solar radiation according to the solar collector slope-horizontal measurements conversion on an inclined panel laws. The Open Renewable Energy Journal 2009; 2: 52-58.

[21] Kuznik F, Virgone J, Noel J. Optimization of a phase change material wallboard for building use. Applied Thermal Engineering 2008; 28: 1291-1298.

[22] David D, Kuznik F, Roux JJ. Numerical study of the influence of the convective heat transfer on the dynamical behaviour of a phase change material wall. Applied Thermal Engineering 2011, 31: 3117-3124.

[23] Ahmad M, Bontemps A, Sallée H, Quenard D. Thermal testing and numerical simulation of a prototype cell using light wallboards coupling vacuum isolation panels and phase change material. Energy and Buildings 2006; 38: 673-681.

[24] Yao J, Yan CW. Effects of solar absorption coefficient of external wall on building energy consumption. World Academy of Science, Engineering and Technology 2011, 52.

[25] Zhou D, Zhao CY. Experimental investigations on heat transfer in phase change materials (PCMs) embedded in porous materials. Applied Thermal Engineering 2011; 31 (5): 970-977.

[26] Solomon AD. An easily computable solution to a two-phase Stefan problem. Solar Energy 1979; 23 (6): 525-528.

[27] Tian Y, Zhao CY. A numerical investigation of heat transfer in phase change materials (PCMs) embedded in porous metals. Energy 2011;36:5539–5546.

[28] Tian Y, Zhao CY. A review of solar collectors and thermal energy storage in solar thermal applications. Applied Energy 2013;104:538–553

[28] Tian Y, Zhao CY. Heat transfer analysis for phase change materials (PCMs). Proceedings of 11th International Conference on Energy Storage (Effstock 2009). Publisher: Richard Stockton College of New Jersey, 2009.

[29] Tian Y, Zhao CY. A thermal and exergetic analysis of Metal Foam-enhanced Cascaded thermal Energy storage (MF-CTES). International Journal of Heat and Mass Transfer 2013;1-2:86–96.

[30] Tian Y, Zhao CY. Thermal analysis in phase change materials (PCMs) embedded with metal foams. Proceedings of 14th International Heat Transfer Conference (IHTC14) 2010;7:425–434

[31] International Standards Document, ISO 15099: 2003. Thermal performance of windows, doors and shading devices – Detailed calculations. 1st Ed., 15/15/2003. Available online at <ftp://law.resource.org/et/ibr/et.iso.15099.2003.pdf> [accessed on 07.11.2013].

Figure Captions

Figure 1	The interior PCMW (a) and exterior PCMW (b)
Figure 2	Illustration of idealised outdoor environment and room air temperature variation
Figure 3	Comparison between the current simulation results and the experimental data in [25]
Figure 4	Comparison between the current simulation result and the data in [26]
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Figure 6	Effects of the melting temperature and its range on the diurnal energy storage of (a) interior PCMW and (b) exterior PCMW
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Figure 10	Effect of thermal conductivity on diurnal energy storage: (a) interior PCMW; (b) exterior PCMW
Figure 11	Effect of heat transfer coefficient on thermal storage of interior PCMW
Figure 12	Effect of heat transfer coefficient on thermal storage of exterior PCMW: (a) inner surface; (b) external surface

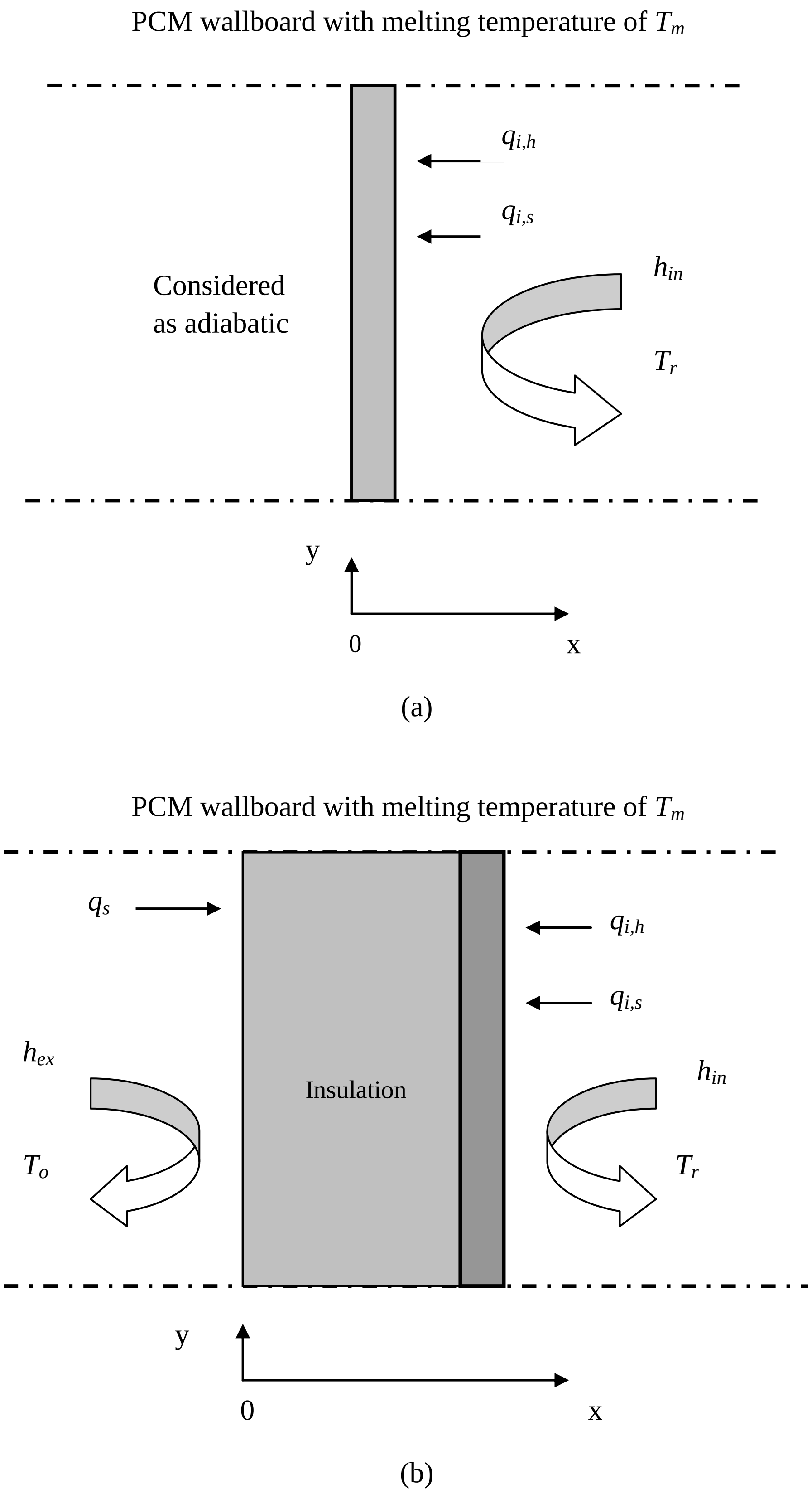


Figure 1 The interior PCMW (a) and exterior PCMW (b).

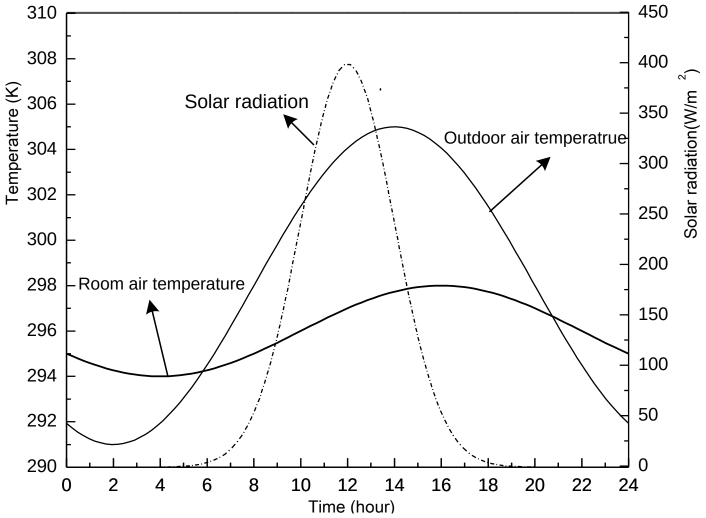


Figure 2 Illustration of idealised outdoor environment and room air temperature variation.

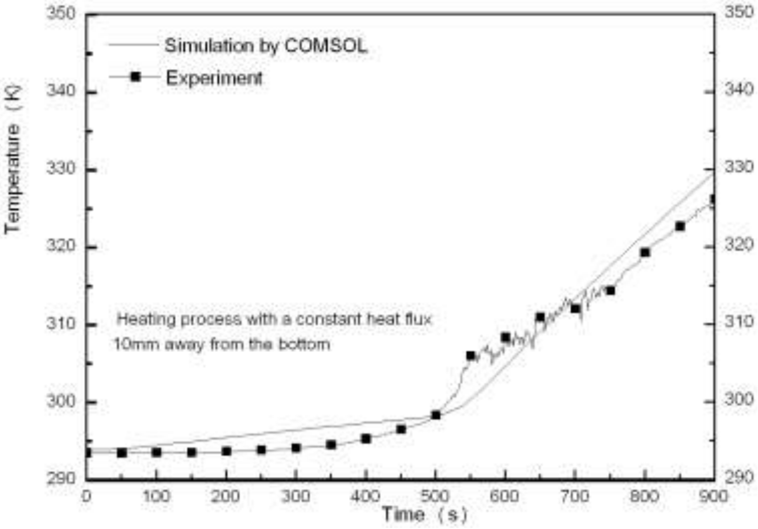


Figure 3 Comparison between the current simulation results and the experimental data in [25]

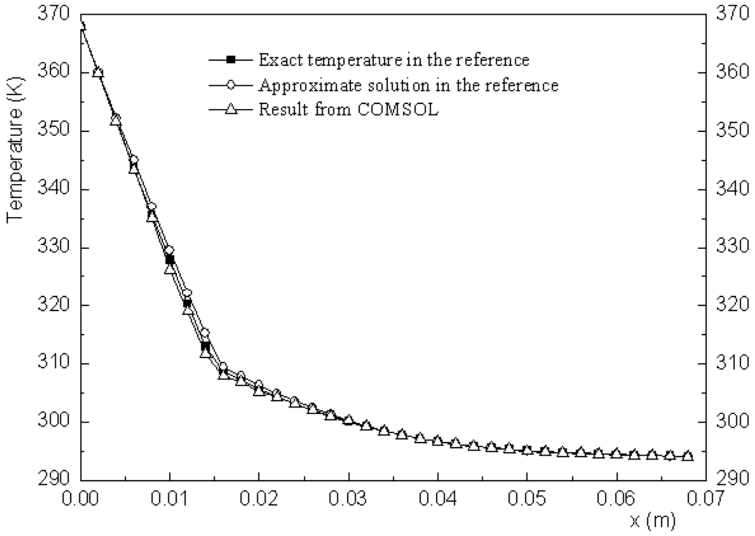
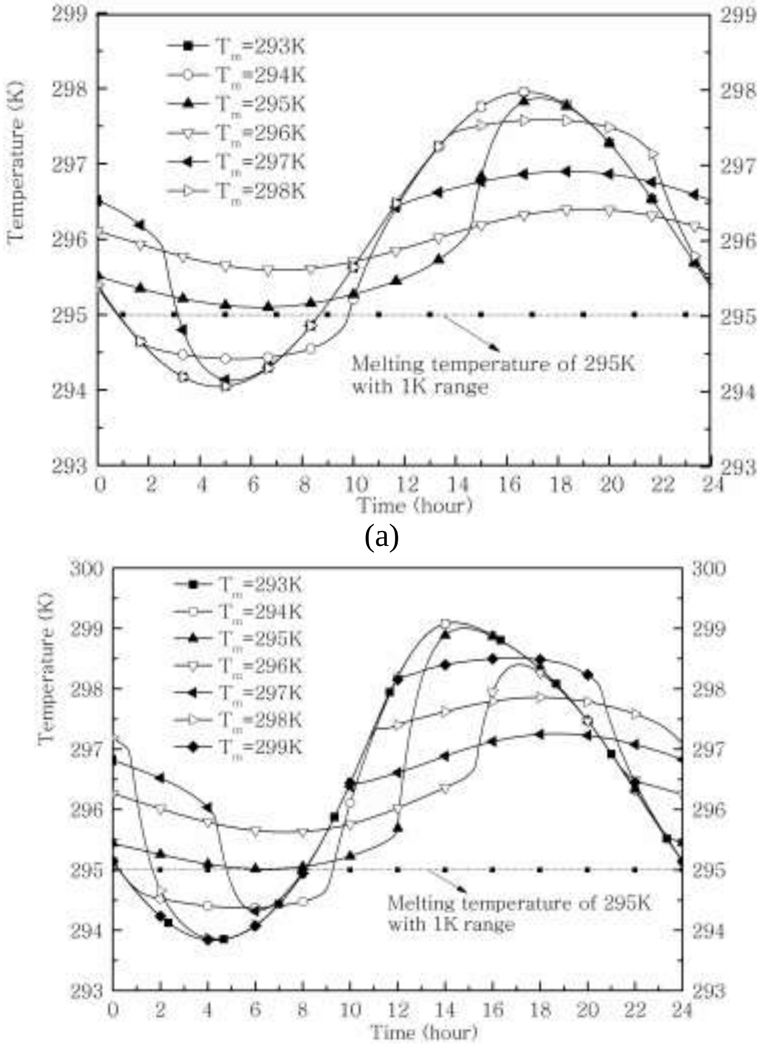


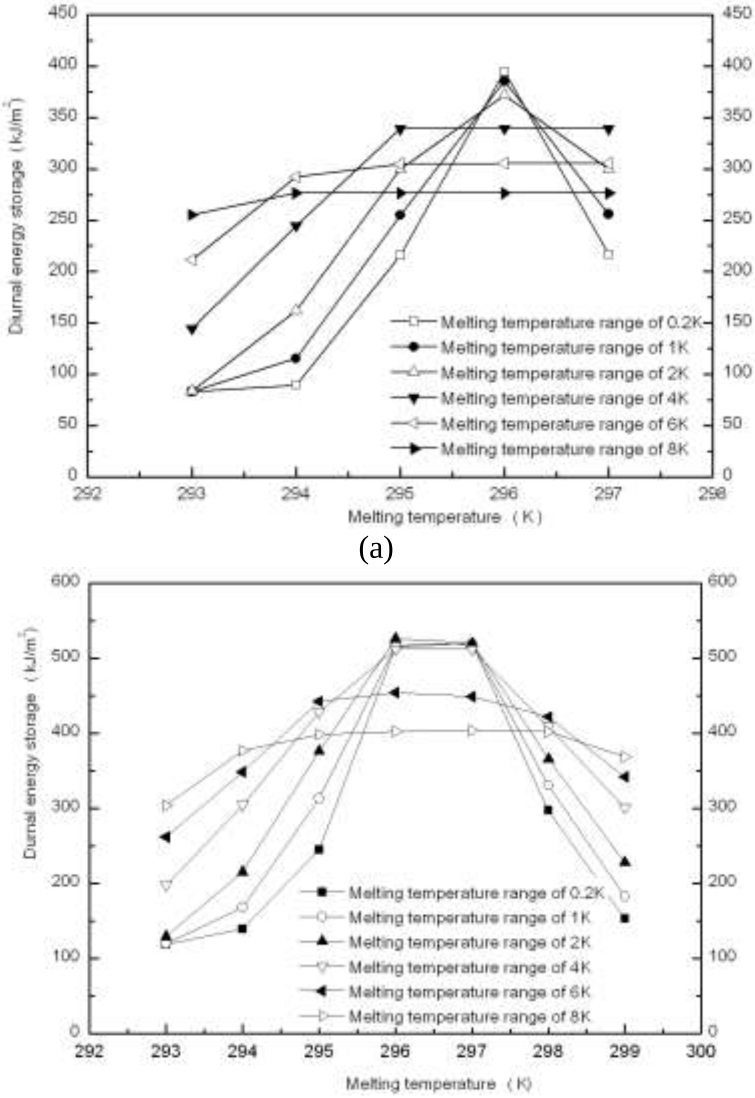
Figure 4 Comparison between the current simulation result and the data in [26]



(a)

(b)

Figure 5 Effect of melting temperature on inner surface temperature history: (a) interior PCMW; (b) exterior PCMW.



(a)

(b)

Figure 6 Effects of the melting temperature and its range on the diurnal energy storage of (a) interior PCMW and (b) exterior PCMW.

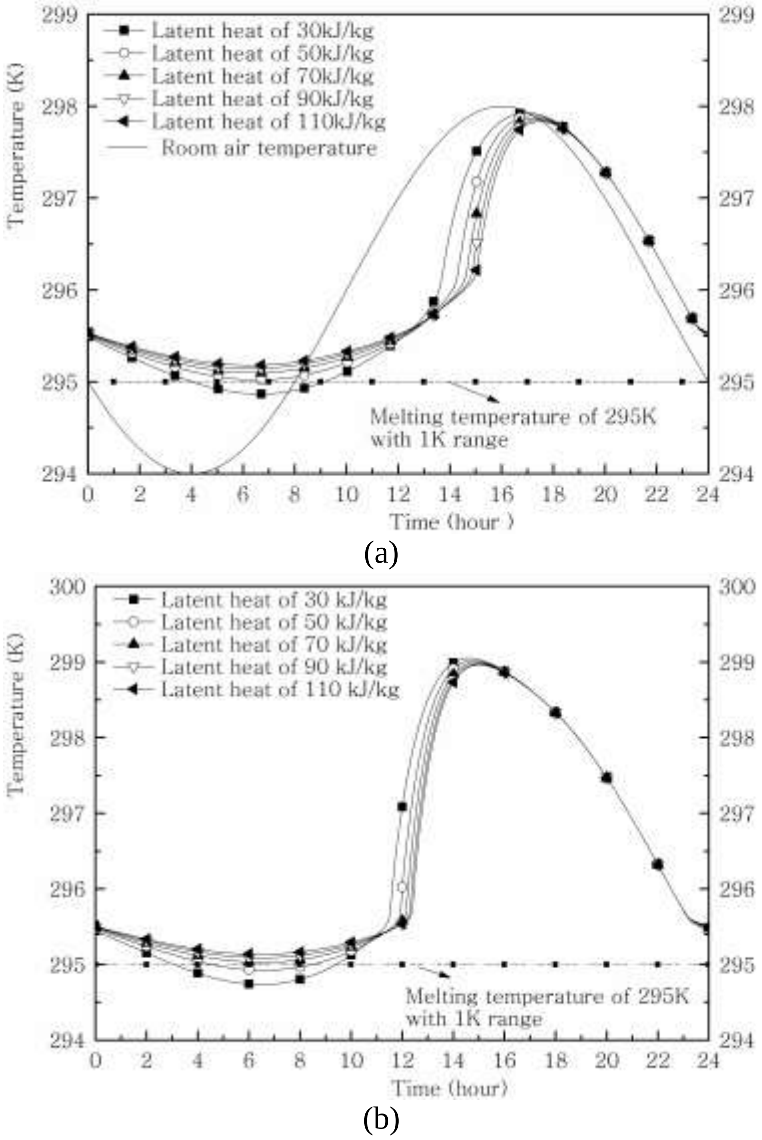
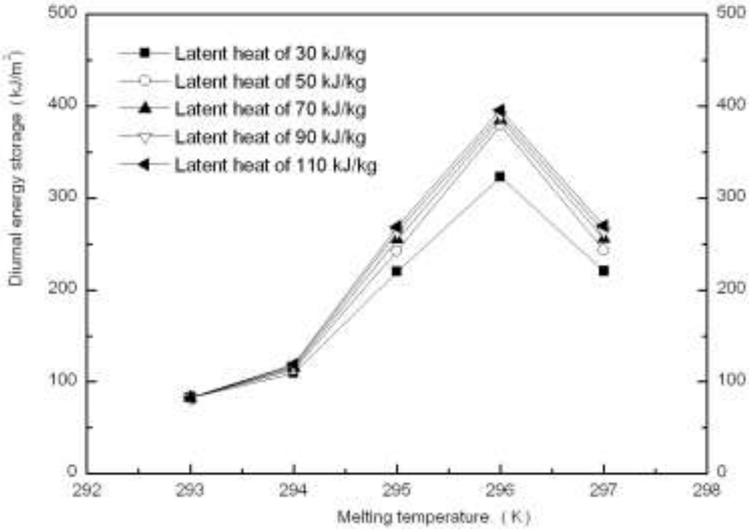
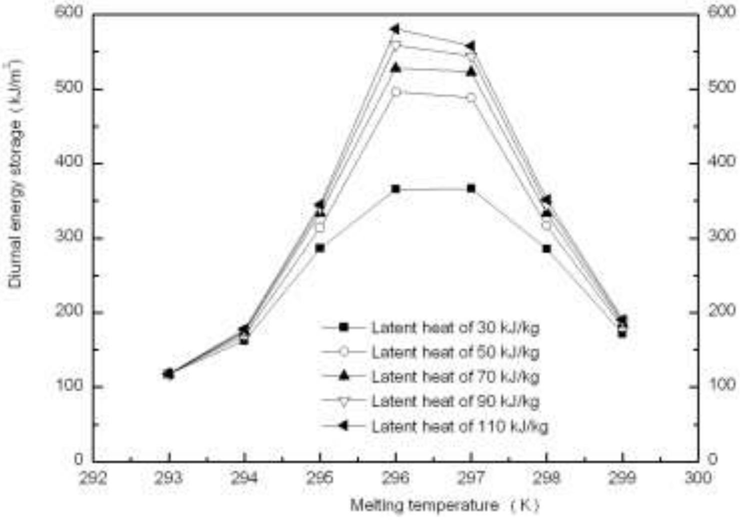


Figure 7 Effect of latent heat on the inner surface temperature history: (a) interior PCMW; (b) exterior PCMW.

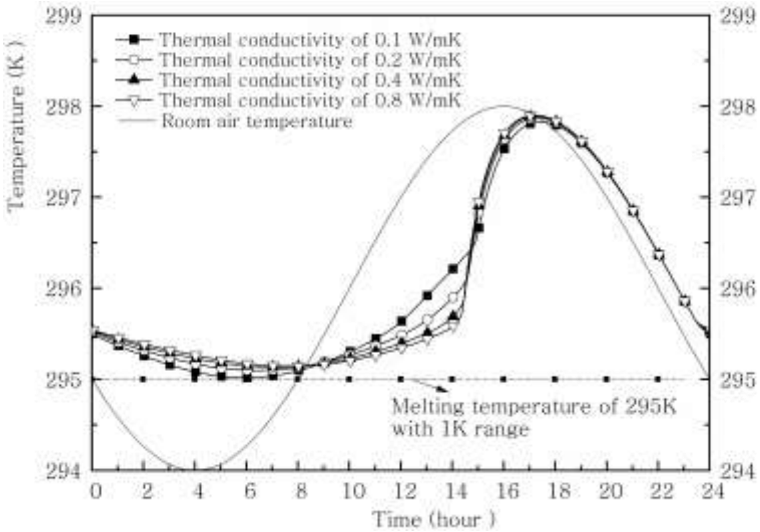


(a)

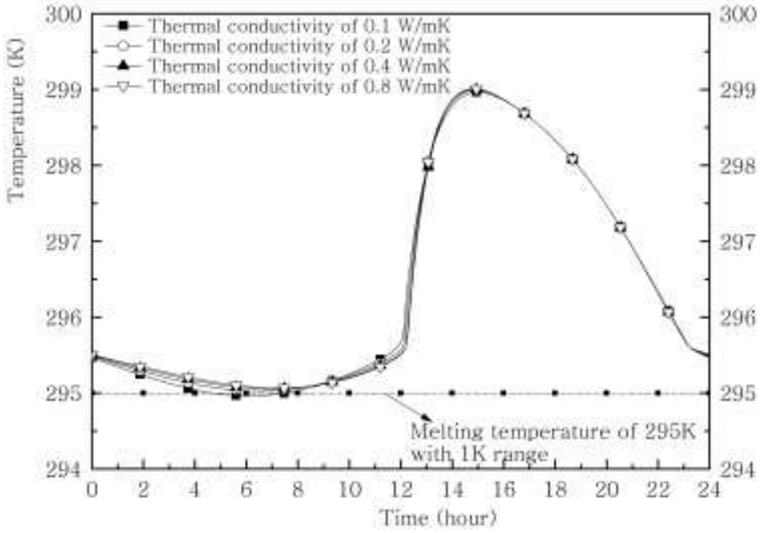


(b)

Figure 8 Effect of latent heat on the diurnal energy storage: (a) interior PCMW; (b): exterior PCMW.

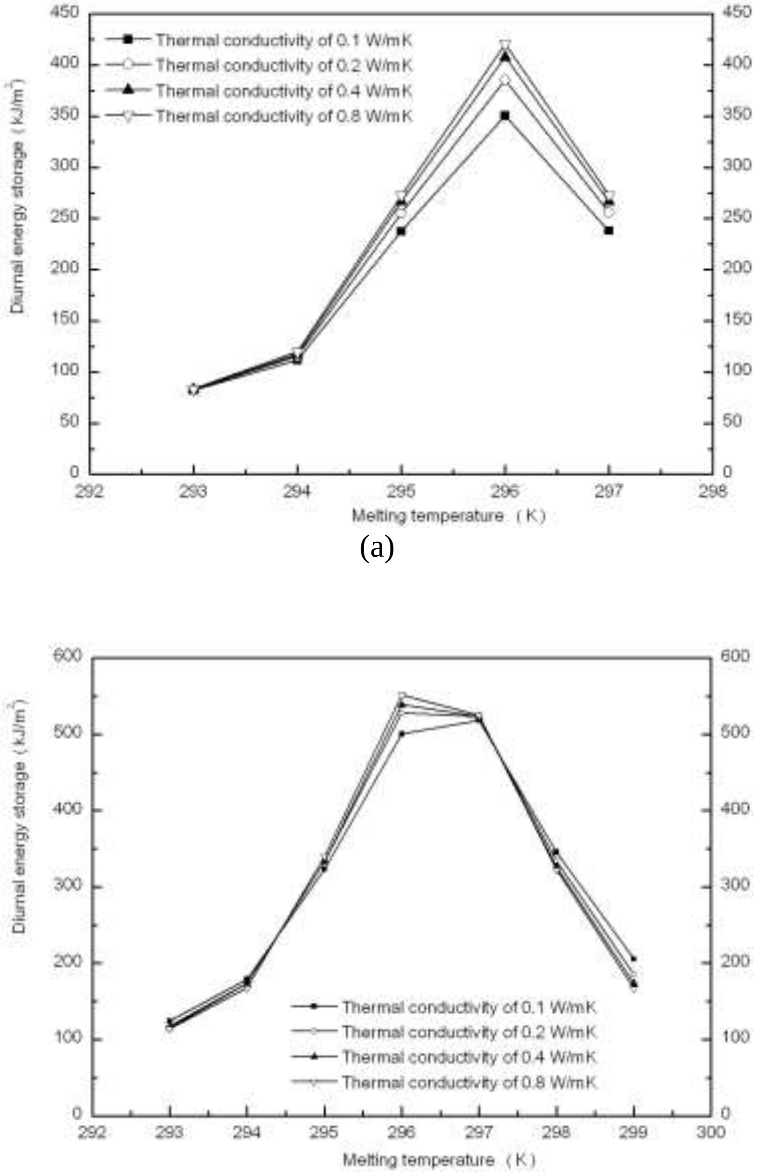


(a)



(b)

Figure 9 Effect of thermal conductivity on the inner surface temperature history: (a) interior PCMW; (b) exterior PCMW.



(a)

(b)

Figure 10 Effect of thermal conductivity on diurnal energy storage: (a) interior PCMW; (b) exterior PCMW.

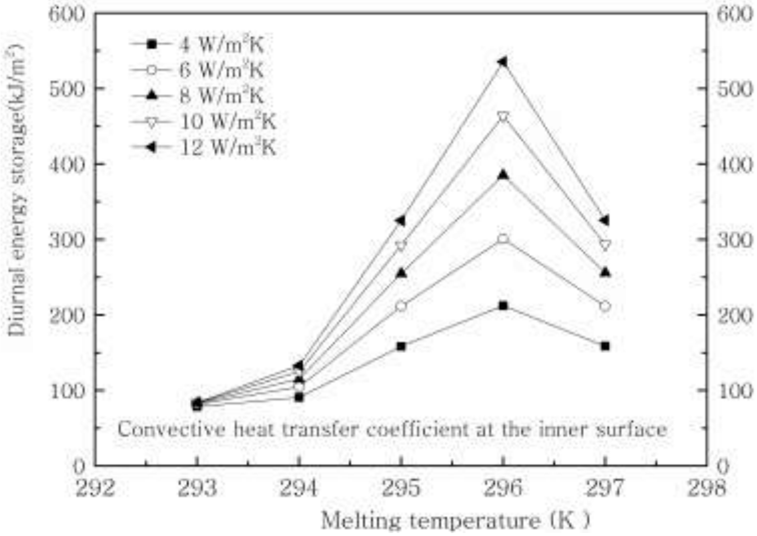
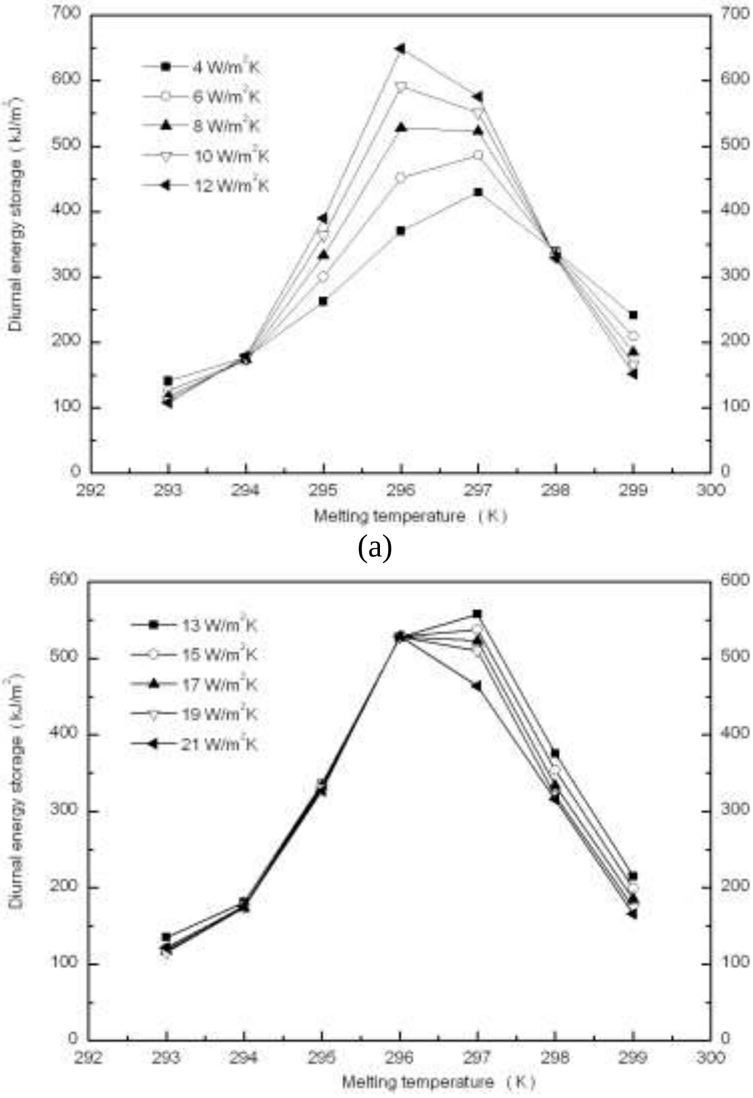


Figure 11 Effect of heat transfer coefficient on thermal storage of interior PCMW.



(a)

(b)

Figure 12 Effect of heat transfer coefficient on thermal storage of exterior PCMW: (a) inner surface; (b) external surface.