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Thermal analysis of Phase Change Material Wallboard (PCMW) under weather conditions in the summer

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Abstract:

A Phase Change Material Wallboard (PCMW) has been considered as an effective way to improve the thermal comfort in either new or existing buildings. In the summer, PCMW can work efficiently for passive applications. In this work, the thermal performance of both internal and external PCMW is investigated under both idealised and real weather conditions. The optimal melting temperatures of internal and external PCMWs are given and the optimal heat storage capacities are obtained under the idealised circumstance of considering sinusoidal changes of the room and outdoor temperatures during a day. To study the potential energy saving from applying a PCMW, a case study of lightweight office with real environmental conditions is carried out. The air conditioning is switched on in the model to keep the indoor temperature within thermal comfort. Using the daily energy consumption and daily thermal comfort rate as the performance criteria, the effects of major influencing factors including melting temperature, latent heat and thermal conductivity of PCMW are studied parametrically. The results show that both the external and internal PCMW can achieve better performance when the melting temperature is chosen to be slightly higher than the average indoor air temperature. In the summer, the external PCMW has a better performance than the internal PCMW because the external PCMW works not only as a heat storage system whose function is similar to the internal PCMW, but also as a thermal connection between the outdoor and indoor environment due to its thermal insulation function, which reduces the influence of the changing outdoor environment.

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

Nomenclature

T	temperature	K
T_m	melting temperature	K
$\overline{T}$	average air temperature	K
ΔT	temperature amplitude	K
P	a period of 24 hours	s (second)
h	convective heat transfer coefficient	W/m^2•K
q_s	solar radiation to external wall surface	W/m^2
$q_{i,s}$	solar radiation flux to inner wall surface	W/m^2
$q_{i,n}$	radiation by indoor heat sources	W/m^2
R	thermal resistance	(m^2•K)/W
L	thickness	m
k	thermal conductivity	W/(m•K)
H	enthalpy	kJ/kg
H_m	latent heat	kJ/kg
C	specific heat	kJ/(kg•K)
ρ	density	kg/(m^3)
τ	time	s (second)
A_i	area of the PCMW	m^2

Subscripts

ex	outside
i	phase interface
in	inside
l	liquid state
m	melting
o	outdoor
opt	optimised
r	room air
s	solid state
stor	stored energy

Acronyms

DSC	Differential Scanning Calorimetry
PCM	Phase Change Materials
PCMW	Phase Change Materials Wallboard

1. Introduction

Energy and environmental sustainability continues to be one of the most important issues in the world. The U.K. government targets an 80% reduction of greenhouse gases by 2050 based on the 1990 levels [1]. The building sector, including both commercial and residential, is one of the leading energy consumers, accounting for almost 40% of the whole fossil fuel consumption [2]. Meanwhile, the energy consumption in buildings for heating, cooling, ventilation and air conditioning devices has not stopped rising due to the increasing demand for better thermal comfort. To solve the contradiction between thermal comfort and energy consumption, a concept of energy-efficient building has gained extensive research interests. The traditional way to reduce energy consumption includes reducing heat transfer rates between indoor and outdoor environment by incorporating high quality thermal insulation and construction materials into building envelopes. However, the efforts to improve energy efficiency should not be limited to these passive approaches like heat loss reduction. Active approaches like heat recovery and reuse could also be useful.

Latent heat storage using PCMs (Phase Change Materials) has the capability to smooth the mismatch between heat supply and heat demand within a narrow temperature range. Existing technologies and research developments in applying latent heat storage to buildings have been reviewed and are classified into active applications and passive applications [3-8]. A more easily achievable way is passive application by incorporating PCMs into a traditional building structure, including concrete/brick wall, wallboard, ceiling, floor, window and shutter. Energy saving is achieved by PCMs collecting and storing extra heat when the temperature exceeds their melting point and then distributing it back to environment when the temperature goes below their melting point to keep the indoor temperature within a certain thermal comfort range, without the use of mechanical or electrical devices.

Among all the passive applications of latent heat storage, Phase Change Material Wallboard (PCMW) has been suggested as the most efficient approach due to its flexible installation, easy incorporation and leakage control, low cost and zero reduction to the building mechanical strength. Athientis et al. [9] and Kuznik et al. [10, 11] built up their test rooms to investigate the PCMW effects on indoor thermal comfort. Their investigations showed that both external and internal PCMWs worked well to maintain thermal comfort. To better use the PCMW in practical applications, a set of comprehensive guidelines containing several different criteria are required to evaluate the thermal performance. The two widely accepted criteria are the inner surface temperature history [12-14] and the thermal energy storage capacity [15-17]. Zhou et al. [18] provided a detailed parametric analysis of the effects of all major influencing factors on the PCMW thermal performance (in both criteria), including melting temperature, melting range, latent heat, thermal conductivity and surface heat transfer coefficients. They concluded that the optimal meting temperatures of both the internal and external PCMW depended on the indoor temperature and indoor heat source while a latent heat of at least 50 kJ/kg was needed (at an affordable cost).

Application of PCMW can save energy consumption for cooling and heating services in buildings. Therefore, the most important and immediate performance criteria should be the daily energy consumption of the whole building. In this paper, the optimal melting points and thermal energy storage capabilities of the internal and external PCMWs are studied theoretically under idealised (sinusoidal) circumstances to understand the different functions of the PCMWs. A few commercial software packages are useful to evaluate the energy consumption of a building, among which, ESP-r®, TRNSYS® and EnergyPlus® were favoured for PCM simulation by Soares et al. [19] due to their versatility and reliability. In some previous studies, rather simple constructions such as single material in building envelope were used to provide a qualitative analysis. However no building is comprised of a single material because each component like the floor, the roof and the wall should follow the relevant construction regulations. Therefore, a further study with a more complicated model is needed. This work aims to build a more practical lightweight building model (a one-story office with most common traditional construction structures) in EneryPlus® for summer application and to investigate the effects of thermal properties of PCMW, including melting temperature, latent heat and thermal conductivity based on the daily energy consumption and thermal comfort rate.

2. PCMW

A number of companies have been developing commercial PCMWs. Due to the inherent problems and leakage issues of PCMs, only a few commercial PCMWs are available at the moment. DuPont™ has produced a PCMW called Energain® thermal mass panel, with a small sample shown in Figure 1. The core material is a compound of paraffin wax (60% loading) reinforced by a copolymer that helps to maintain a reasonable mechanical stability when the paraffin is in its liquid state. The core material is encapsulated by aluminium sheets.

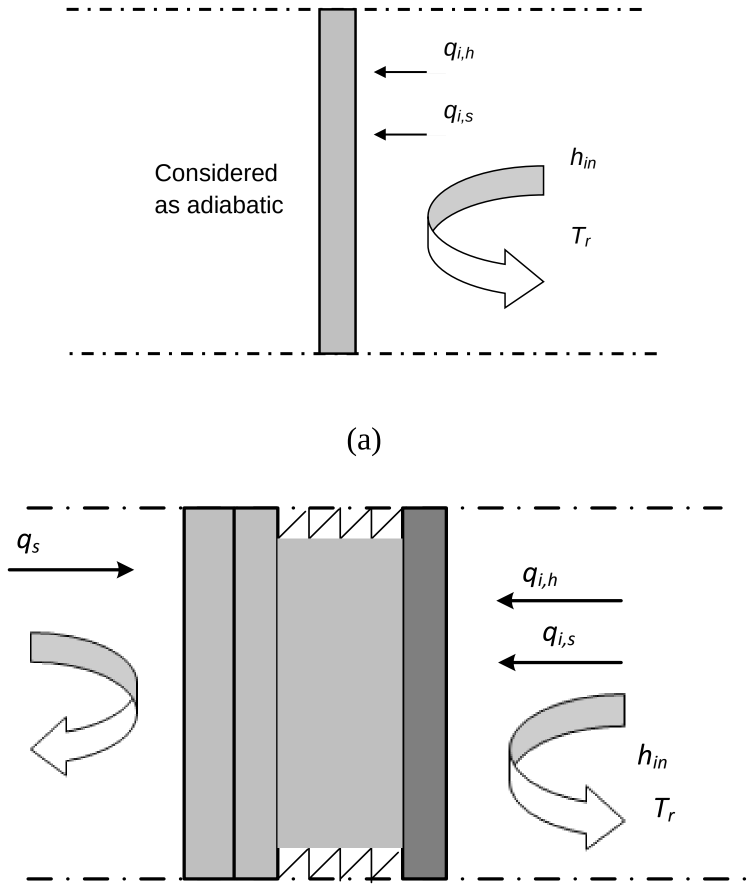
Figure 1: Photos of an Energain® thermal mass panel sample.

Such a thermal panel can absorb and store heat from the surroundings when the temperature rises above 295 K, and release the heat back to the surroundings when the temperature drops to below 291 K. The latent heat storage capacity and total heat storage capacity at 273 K – 303 K were found to be 70 kJ/kg and 140 kJ/kg respectively according to DSC (Differential Scanning Calorimetry) test (1 K/min). Such thermal mass panels have already been used in residential and commercial buildings. They can maintain the indoor thermal comfort effectively and also help to reduce the heating consumption by up to 15% and cooling consumption by up to 35% [20].

3. Thermodynamics of PCMW

3.1. Optimal melting temperature

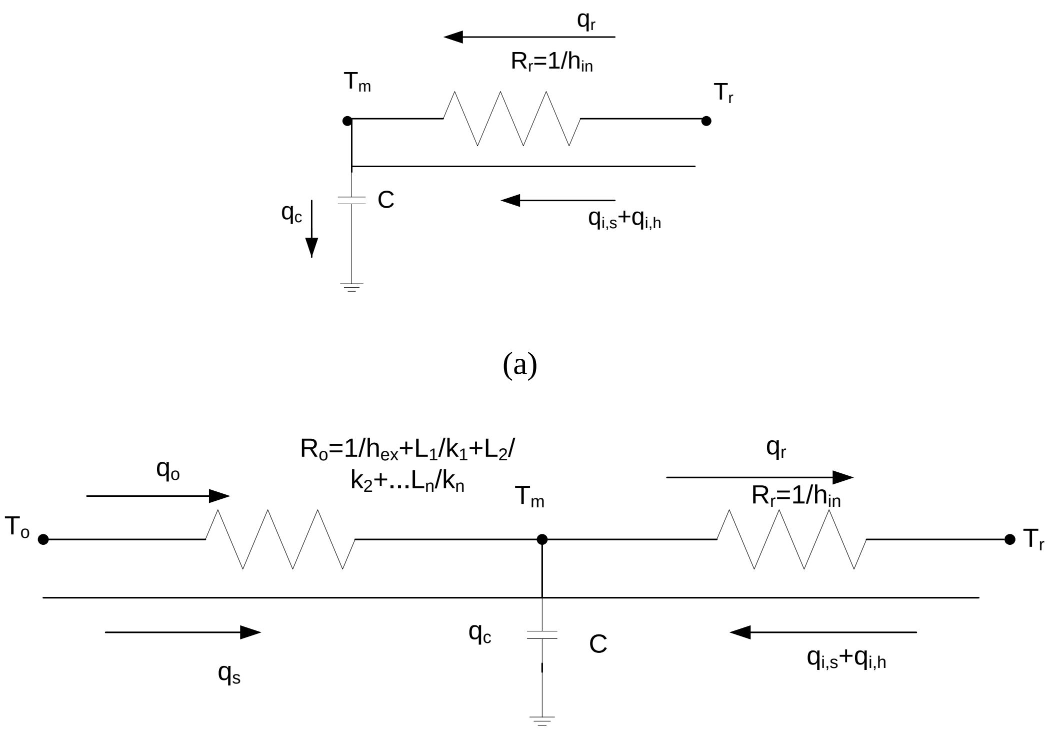
The internal and external PCMW undergo different heat transfer conditions. Figure 2 shows their physical models. Internal PCMW is used to achieve the thermal comfort by storing heat from an indoor environment during the daytime and releasing the heat back during the night time. Its inner surface is usually under a combined effect of convection heat transfer (with indoor air) and radiation (with inner heat sources and outer solar radiation through the window), whilst its outer surface can be considered as adiabatic because it shares the symmetrical thermal boundary conditions with the adjacent room. External PCMW is not only used as a heat capacity (the same function as inner PCM) but also as a heat resistance like insulation materials. Its inner surface has similar heat transfer conditions to those of an internal PCMW. The difference is that its outer surface is under heat conduction to the outdoor environment through the insulation or other construction materials. In Figure 2, T_r and T_o are the indoor and outdoor air temperature; h_{in} and h_{ex} are the indoor and outdoor convective heat transfer coefficient; $q_{i,s}$ and $q_{i,h}$ denote the solar radiation flux through the window and the radiation from the indoor heat sources, respectively; q_s is the heat flux by solar radiation to the external wall surface; T_m represents the melting temperature of the PCMW. According to Deeper's method [21], typical corresponding conceptual analogue circuit schematics of the internal and external PCMWs are shown in Figure 3. The optimal melting temperatures of internal and external PCMWs can be written in Equations (1) and (2), in which, L_m and k_m $(m = 1,\cdots,n)$ are the thickness and thermal conductivity of the construction material and P stands for 24 hours (86,400 s).



(a)

(b)

Figure 2: Physical models (a) internal PCMW; (b) external PCMW.



(a)

(b)

Figure 3: Conceptual analogue circuit schematics (a) internal PCMW; (b) external PCMW.

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

$$T_{m,opt} = \frac{\frac{1}{h_{in}} \cdot \overline{T}_o + \left(\frac{1}{h_{ex}} + \sum_{m=1}^{n} \frac{L_m}{k_\mathrm{m}}\right) \cdot \overline{T}_r + \frac{1}{h_{in}} \cdot \left(\frac{1}{h_{ex}} + \sum_{m=1}^{n} \frac{L_m}{k_\mathrm{m}}\right) \cdot \left(\frac{1}{P} \int_P \left(q_s + q_{i,s} + q_{i,h}\right) d\tau\right)}{\frac{1}{h_{in}} + \frac{1}{h_{ex}} + \sum_{m=1}^{n} \frac{L_m}{k_\mathrm{m}}} \tag{2}$$

3.2. Heat storage analysis of internal PCMW under idealised circumstance

The indoor air temperature can be ideally considered to have a sinusoidal change within a period of 24 hours as shown in Equation (3). $\overline{T}_r$ is the average indoor air temperature and ΔT_r is temperature amplitude.

$$T_r = \Delta T_r \sin\left(\frac{2\pi\tau}{P}\right) + \overline{T}_r \tag{3}$$

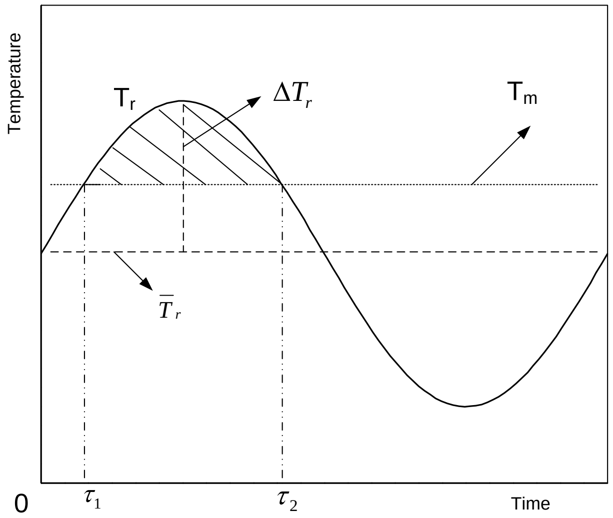


Figure 4: Internal PCMW under idealised circumstance of a day.

It is assumed that the phase change temperature of the PCMW is within the range of room air temperature. The PCMW absorbs the heat when the room temperature is higher than the phase change transition temperature. The shaded area in Figure 4 is the absorbed heat by convective heat transfer because of the temperature difference between the PCMW and the indoor air. The storing period is between τ_1 and τ_2 which can be calculated from Equation (4). The stored heat and released heat during a cycle can be calculated from Equations (5) and (6).

$$\Delta T_r \sin(\frac{2\pi\tau_1}{P}) + \overline{T}_r = \Delta T_r \sin(\pi - \frac{2\pi\tau_2}{P}) + \overline{T}_r = T_m \tag{4}$$

$$Q_{stor} = h_{in} A_i \int_{\tau_1}^{\tau_2} (T_r - T_m) d\tau + \int_P (q_{i,s} + q_{i,h}) d\tau \tag{5}$$

$$Q_{\mathrm{out}} = h_{in} A_i \int_0^{\tau_1} (T_m - T_r) d\tau \tag{6}$$

where A_i is the area of the PCMW.

After solving and integration operation of above equations, the stored heat and released heat during a cycle can be expressed as Equations (7) and (8).

$$Q_{stor} = h_{in} A_i \left\{ \frac{\Delta T_r P}{\pi} \cdot \sqrt{1 - (\frac{T_m - \overline{T}_r}{\Delta T_r})^2} + (\overline{T}_r - T_m) \left[\frac{P}{2} - \frac{P}{\pi} \arcsin(\frac{T_m - \overline{T}_r}{\Delta T_r}) \right] \right\} + \int_P (q_{i,s} + q_{i,h}) d\tau \tag{7}$$

$$Q_{\text{out}} = h_{in} A_i \left\{ (T_m - \overline{T}_r)\left[\frac{P}{2} + \frac{P}{\pi}\arcsin\left(\frac{T_m - \overline{T}_r}{\Delta T_r}\right)\right] + \frac{\Delta T_r P}{\pi} \cdot \sqrt{1 - \left(\frac{T_m - \overline{T}_r}{\Delta T_r}\right)^2} \right\} \tag{8}$$

With radiation neglected, the stored heat and released heat during a whole cycle are the functions of $(T_m - \overline{T}_r)/\Delta T_r$ only. As seen from both Equation (7) and Figure 4, the stored heat decreases when reducing the difference between the PCM phase change temperature and the average indoor temperature. Under the optimal condition, the stored heat equals the released heat during a cycle. Substituting Equation (1) into Equation (7), the optimal stored heat can be written in Equation (9).

$$\begin{aligned} Q_{stor,opt} = {} & h_{in} A_{\text{i}} \left\{ \frac{\Delta T_r P}{\pi} \sqrt{1 - \left(\frac{\int_P (q_{i,s} + q_{i,h}) d\tau}{h_{in} A_i P \Delta T_r} \right)^2} + \frac{\int_P (q_{i,s} + q_{i,h}) d\tau}{h_{in} A_i P} \cdot \left[\frac{P}{2} - \frac{P}{\pi} \arcsin\left(\frac{\int_P (q_{i,s} + q_{i,h}) d\tau}{h_{in} A_i P \Delta T_r} \right) \right] \right\} \\ & + \int_P (q_{i,s} + q_{i,h}) d\tau \end{aligned} \tag{9}$$

When $\frac{\int_P (q_{i,s} + q_{i,h}) d\tau}{h_{in} A_i P \Delta T_r} < 1$ (the melting temperature of the PCMW is within the range of indoor air temperature change), the optimal heat storage of the PCMW wallboard can be simplified to Equation (10).

$$Q_{stor,opt} = \frac{h_{in} A_i \Delta T_r P}{\pi} \sqrt{1 - \left(\frac{\int_P (q_{i,s} + q_{i,h}) d\tau}{h_{in} A_i P \Delta T_r} \right)^2} + \left(\frac{3}{2} - \frac{\arcsin\left(\frac{\int_P (q_{i,s} + q_{i,h}) d\tau}{h_{in} A_i P \Delta T_r} \right)}{\pi} \right) \cdot \int_P (q_{i,s} + q_{i,h}) d\tau \tag{10}$$

If $\frac{\int_P (q_{i,s} + q_{i,h}) d\tau}{h_{in} A_i P \Delta T_r} \geq 1$, the phase change temperature of the PCMW is higher than the room air temperature all the day. The heat storage can be calculated by Equation (11).

$$Q_{stor,opt} = \int_P (q_{i,s} + q_{i,h}) d\tau \tag{11}$$

3.3. Heat storage analysis of external PCMW under idealised circumstance

The heat storage of an external PCMW is more complicated than that of an internal PCMW. Both outdoor environment and indoor environment contribute to the heat storage of PCMW. Figure 5 shows idealised circumstances of an external PCMW. Both outdoor temperature and the indoor temperature have a sinusoidal change with a time delay ($\Delta\tau$). Their definitions are given in Equation (12). It is assumed that melting temperature of the PCMW is within both outdoor and indoor temperature ranges. As seen from Figure 5, the heat storage periods are (τ_1, τ_2) and (τ_3, τ_4) respectively. τ_1, τ_2, τ_3 and τ_4 can be calculated from Equations (13) and (14).

$$T_o = \Delta T_o \sin(\frac{2\pi\tau}{P}) + \overline{T}_o \quad \text{and} \quad T_r = \Delta T_r \sin(\frac{2\pi(\tau - \Delta\tau)}{P}) + \overline{T}_r \qquad (12)$$

$$T_m = \Delta T_o \sin(\frac{2\pi\tau_1}{P}) + \overline{T}_o = \Delta T_o \sin(\pi - \frac{2\pi\tau_2}{P}) + \overline{T}_o \qquad (13)$$

$$T_m = \Delta T_r \sin(\frac{2\pi(\tau_3 - \Delta\tau)}{P}) + \overline{T}_r = \Delta T_r \sin(\pi - \frac{2\pi(\tau_4 - \Delta\tau)}{P}) + \overline{T}_r \qquad (14)$$

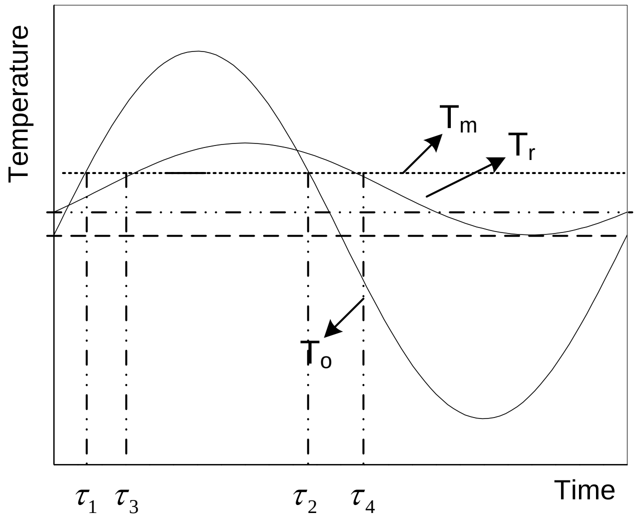


Figure 5: External PCMW under idealised circumstance of a day.

The stored heat coming from two parts: through the insulation by outdoor circumstance and by indoor circumstance. The total stored heat during a day is calculated by Equation (15). From Figure 5, it can be seen that the PCMW absorbs heat from outdoor circumstance but releases the heat to the indoor circumstance between (τ_1, τ_3), whilst it absorbs heat from indoor environment and releases the heat to the outdoor environment between (τ_2, τ_4). During the periods of (τ_1, τ_3) and (τ_2, τ_4), the total charged heat Q_{out} can be calculated from the Equation (16), supposing the area of PCMW is A_i.

$$Q_{stor} = \left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) A_i \int_{\tau_1}^{\tau_2} (T_o - T_m) d\tau + \int_P q_s d\tau + h_{in} A_i \int_{\tau_3}^{\tau_4} (T_r - T_m) d\tau + \int_P (q_{i,s} + q_{i,h}) d \tag{15}$$

$$Q_{\mathrm{out}} = h_{in} A_i \int_{\tau_1}^{\tau_3} (T_m - T_r) d\tau + \left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) A_i \int_{\tau_2}^{\tau_4} (T_m - T_o) d\tau \tag{16}$$

where A_i is the area of the PCMW.

After solving and integration operation of above Equations (13-16) with Equation (2), the optimal heat storage expression is shown as Equation (17).

$$\begin{aligned}
Q_{\mathrm{stor,\ opt}} = \frac{A_i P}{2\pi}\{ & \left[\left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) \cdot \Delta T_o + h_{in} \cdot \Delta T_r \cos\frac{2\pi \cdot \Delta\tau}{P}\right] \sqrt{1 - X_1{}^2} \\
& + \left[\left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) \cdot \Delta T_o \cos\frac{2\pi \cdot \Delta\tau}{P} + h_{in} \cdot \Delta T\right] \cdot \sqrt{1 - X_2{}^2} + \left[\left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) \cdot \Delta T_o X_1 + h_{in} \cdot \Delta T_r\right] \arcsin X_1 \\
& + \left[\left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) \cdot \Delta T_o + h_{in} \cdot \Delta T_r X_2\right] \arcsin X_2 \\
& + \left[h_{in} \cdot \Delta T_r \sin\frac{2\pi \cdot \Delta\tau}{P} - \left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) \cdot \Delta T_o \pi - \left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) \cdot \Delta T \cdot \frac{2\pi \cdot \Delta\tau}{P}\right] X_1 \\
& + \left[\left(\frac{1}{1/h_{ex} + \sum_{m=1}^{n} L_m / k_{\mathrm{m}}}\right) \cdot \Delta T \sin\frac{2\pi \cdot \Delta\tau}{P} - h_{in} \cdot \Delta T_r \pi - h_{in} \cdot \Delta T_r \cdot \frac{2\pi \cdot \Delta\tau}{P}\right] X_2 + \int_P (q_s + q_{i,s} + q_{i,h}) d\tau
\end{aligned} \tag{17}$$

where $X_1 = \frac{T - \overline{T_o}}{\Delta T_o}$ and $X_2 = \frac{T - \overline{T_r}}{\Delta T_r}$. It can be seen from the above equations that the heat storage for an exterior PCM wallboard is rather complicated. It is affected by outdoor environment, indoor environment, the insulation material, the convective heat transfer coefficients at the outside/inside surfaces, and the peak temperature difference between the outdoor and indoor air. In most cases $X_1 < 1$ and $X_2 < 1$, so the heat storage is shown as Equation (17). If $X_1 < 1$ and $X_2 \geq 1$, the temperature of the PCM wallboard is higher than the indoor temperature, in which condition the PCM wallboard always discharges heat to the room. If $X_1 \geq 1$ and $X_2 \geq 1$, the heat storage of PCM wallboard is dependent only on the radiation: $Q_{stor,opt} = \int_P \left(q_s + q_{i,s} + q_{i,h}\right) d\tau$, which means that the PCMW works only as a normal wallboard.

3. Model description

3.1. EnergyPlus® Enthalpy Model for PCM

EnergyPlus® is a powerful analytical tool in calculation of the thermal load for a specified building and evaluation of the influencing factors related to the thermal performance. Evola et al. [22, 23] used EnergyPlus® to investigate the effectiveness of PCMW installed on a partition wall for summer thermal comfort in buildings. Soares et al. [24] also used EnergyPlus® to simulate the impact of PCM-drywalls in annual and monthly energy consumption. In the program, the heat balance method is applied. This software package can conduct simulations for the materials with time-dependence thermal properties thanks to the modified finite difference algorithm included. The melting/solidification process of PCM is a moving boundary problem which makes the solving process complicated. However the problem can be overcome by employing enthalpy method, in which both solid and liquid phases are mathematically described by a common piecewise enthalpy function introduced [25]. The enthalpy form of the energy equation is given as Equation (18).

$$\nabla \cdot (k \cdot \nabla T) = \rho \frac{\partial H(T)}{\partial t} \tag{18}$$

where k is the thermal conductivity, ρ is the density, H is the enthalpy.

The correlation between enthalpy and temperature is assumed to be a step function for the isothermal phase change process and a linear function for the sensible heat process. Both relations are shown in Equation (19) and Equation (20).

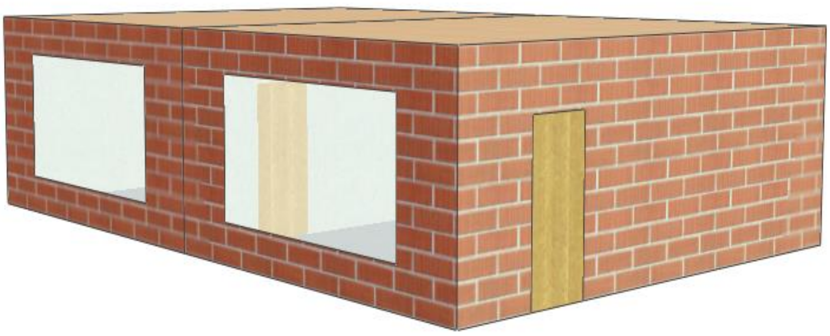
$$H(T) = \left.\begin{cases} C_s T & T \leq T_m \quad solid\ phase \\ C_l T + H_m & T > T_m \quad liquid\ phase \end{cases}\right\} \tag{19}$$

$$H(T) = \left.\begin{cases} C_s T & T < T_s \quad solid\ phase \\ C_i T + \frac{H_m(T-T_s)}{(T_l-T_s)} & T_s \leq T < T_l \quad phase\ change \\ C_l T + H_m + C_i(T_l - T_s) & T \geq T_s \quad liquid\ phase \end{cases}\right\} \tag{20}$$

where C is the specific heat and H_m is the latent heat; the subscripts: s, l and i stand for the solid, liquid and phase interface, respectively. In EnergyPlus®, heat transfer through the building structures usually employs Conduction Transfer Function (CTF) algorithm to calculate the conduction. However, for high performance building designs, such as PCMW, a Conduction Finite Difference method (Cond-FD) coupled with the enthalpy method is adopted to simulate the phase change process of PCM [26, 27].

3.2. Physical model

A one-story model is considered in this study, which comprises two same-size rooms separated by a south-north crossing internal partition wall. The three-dimensional drawing of the model is given in Figure 6. The whole building has a length of 12 m, a width of 8 m and a height of 3 m. The total floor area is 96 m^2. There are two identical-size windows in each room: one is facing the south and the other is facing the north. The window area accounts for 40% of its wall area. There also are two wooden doors: one on the east wall (external), and the other on the partition wall (internal). This research investigates the benefits brought by PCMWs to the traditional buildings, so the most common traditional building structures are used in this model, as shown in Table 1. The thermal properties of the PCMWs are based on the Energain® Thermal Mass Panel.



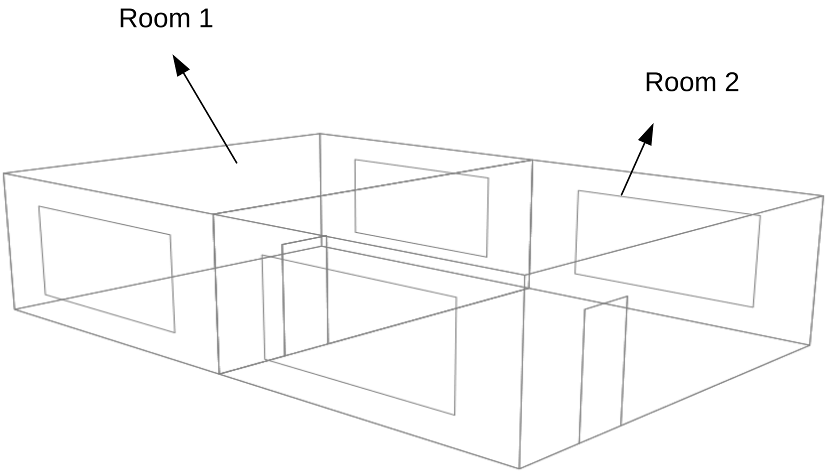


Figure 6: The 3-D drawing of the model.

Table 1 Constructions and materials of the model.

Construction	Thickness [mm]	Thermal conductivity [W/(m•K)]	Density [kg/m^3]	Sensible heat capacity [J/(kg•K)]
External wallboard (Outside to inside) U-value is 0.922 W/(m^2•K) and h_o is 25 W/(m^2•K).				
Brickwork, outer leaf	100	0.84	1700	800
Air gap (R=0.18 m^2•K/W)	50			
Concrete block (lightweight)	100	0.19	600	1000
Gypsum Plasterboard	10	0.25	900	1000
or:				
PCMW	10	0.2	885	2400
Flat roof (Outside to inside) U-value = 1.024 W/m^2•K，$h_{o\text{-}roof}$ = 25 W/m^2•K.				
Stone chipping for roofs	10	0.96	1800	1000
Bitumen/Felt layers	5	0.5	1700	1000
CAST concrete	150	1.13	2000	1000
Glass fibre quilt	13	0.04	12	840
Air gap (R=0.18 m^2•K/W)	100			
Ceiling tiles	10	0.056	380	1000
Ground floor (Outside to inside) $h_{in\text{-}floor}$ is 5.88 W/(m^2•K)				
Clay underfloor	500	1.5	1500	2085
Brickwork, outer leaf	250	0.84	1700	800
CAST concrete	100	1.13	2000	1000
Insulation-polyurethane foam	50	0.028	30	1470
Chipboard	25	0.15	800	2093
Synthetic carpet	10	0.06	160	2500
Internal partition wall				

$h_{in\text{-}p}$ is 7.7 W/(m^2•K)				
Gypsum Plasterboard	10	0.25	900	1000
Brickwork, inner leaf	100	0.62	1700	800
Gypsum Plasterboard	10	0.25	900	1000
Or:				
PCM incorporated				
PCMW	10	0.2	885	2400
Brickwork, inner leaf	100	0.62	1700	800
PCMW	10	0.2	885	2400
Glazing				
Low-e double glazing 6 mm air, total solar transmission is 0.562, the U-value is 2.4 W/(m^2•K)				

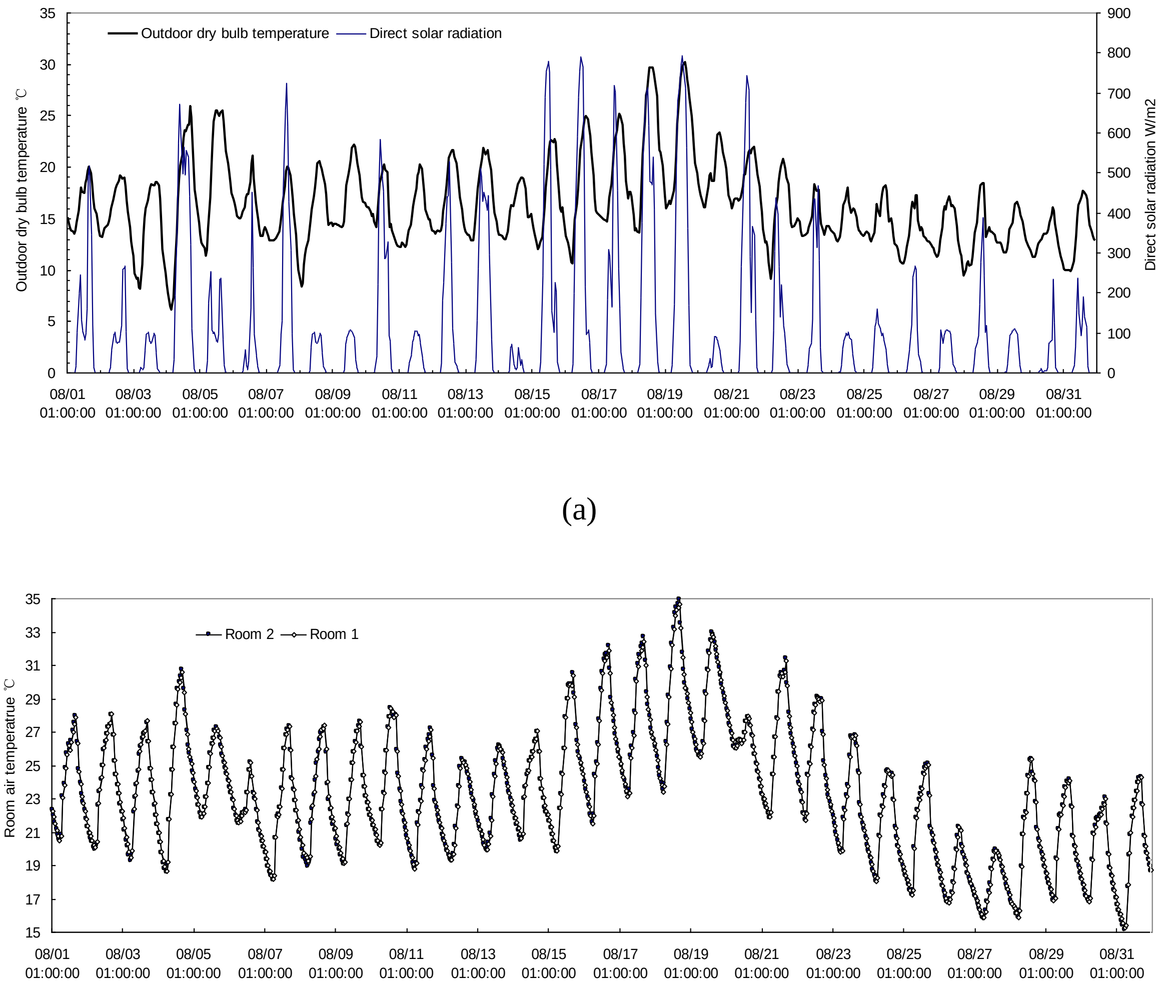
This building is used as an office with four people in each room. The thermal loads inside the building are mainly from human activities, including lighting, computers and other appliances which produce heat. The filtration and natural ventilation are also considered in the model. Table 2 shows the thermal loads and ventilations with the schedules of heating resources.

Table 2 Thermal loads and ventilations.

Parameter	Output	Schedule
People	8 in total, 4 in each room	Working from 9:00 to 17:00; One-hour lunch break at 12:00–13:00, about half occupied.
Lighting	10 W/m^2	On at 7:30 –18:30.
Computer and other equipment	9.5 W/m^2	On at 8:00–18:00.
Filtration	0.5 ACH (air changes per hour)	All day.
Natural ventilation	9.2 litre/s/person	The same schedule with the people's working time.

3.3. Weather conditions

The real weather data of Birmingham in UK during the year of 2013 is used for the modelling. The modelling works focus on the month of August, which is usually the hottest month in the U.K. across the year. The outdoor dry bulk temperatures and the solar radiation in August are shown in Figure 7(a). Figure 7(b) shows the simulated temperatures of the two rooms without PCMWs, from which it can be seen that the air temperatures of room I and room II are almost the same and there is very little difference even on the days with the high direct solar radiation. Therefore, for each room the internal partition wall can be regarded as thermally insulated, which can also be deduced from the symmetrical thermal boundary condition.



(a)

(b)

Figure 7: (a) Outdoor dry bulk temperature and direct solar radiation, in Birmingham, UK, in August; (b) Simulation results of the air temperatures of two rooms without PCMW.

3.4. Simulation Process

Thermal comfort can be defined by indoor temperatures that vary as the time of year. It could also change in different countries. ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) has the suggested temperatures and air flow rates in different types of buildings and environmental circumstances. Generally, the suggested indoor temperature is 294 K– 298 K considering both summer and winter. In the following work, this building without PCMW is simulated under the above situations for the month of August, where the indoor temperatures are controlled within the thermal comfort ranges, from 294 K to 298 K, as ASHRAE recommended. The heating is turned on when the indoor air temperature is below 294 K and the cooling is turned on when the indoor air temperature is above 298 K. Then the simulation studies are also carried out under the energy-efficient situation in which the gypsum plasterboards on internal partition walls or the external walls without the glazing are replaced by the PCMWs.

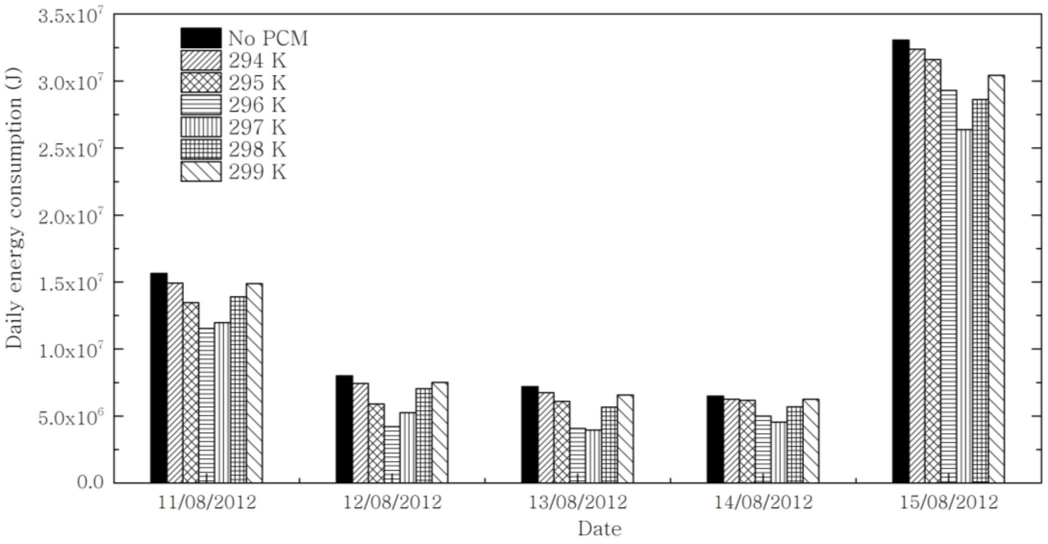
A standard set of parameters should be determined firstly. According to the technical data of the Energain® thermal mass panel, the standard thermophysical properties are melting temperature of 295 K, melting range of 1 K, density of 885 kg/m^3, thermal conductivity of 0.2 W/(m•K), sensible heat and latent heat of 2.4 kJ/(kg•K) and 70 kJ/kg respectively. Different from the sample, 1 cm-thickness is used as the standard here. Effects of melting temperature, heat of fusion and thermal conductivity on the thermal performance of the PCMWs are discussed by daily energy consumption. The potential energy saving by the installation of the PCMWs of the whole building in the summertime (from May to September) are given. In the U.K., the heating is not usually turned on in the period from May to September. Therefore, the model is also conducted under the situation in which only the cooling is on when the indoor air temperature exceeds 299 K. The thermal performance of PCMWs with different melting temperatures and different locations are discussed. The cooling load saving is also compared. This work gives a detailed recognition of the PCMWs for summertime applications.

4. Case results and discussion

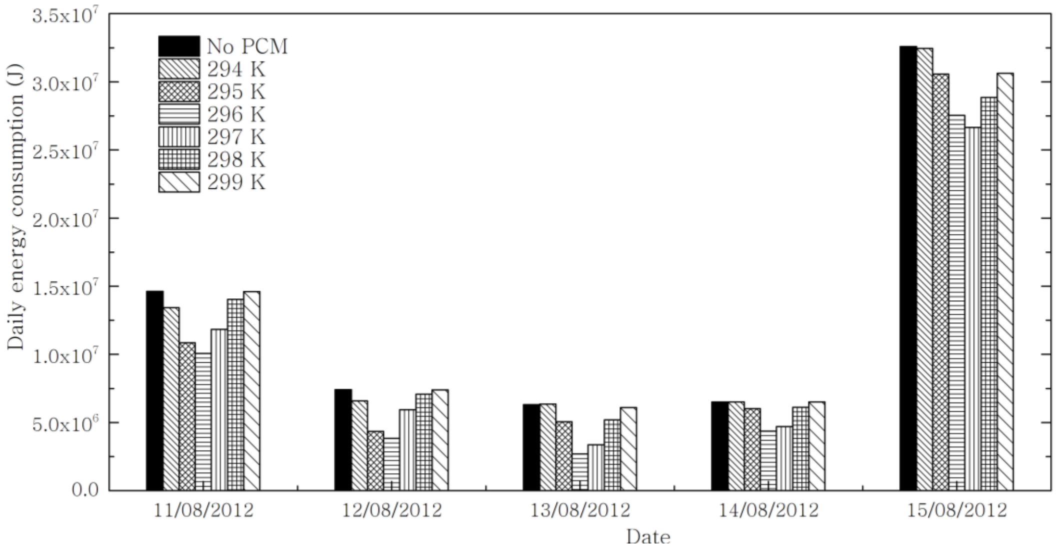
4.1. Effect of melting temperature

Figures 8(a) and 8(b) show how the melting temperature affects daily energy consumptions, including the heating loads and cooling loads, during the period from 11th August to 15th August. Lower energy consumption means the better melting temperature of the PCMW . It can be seen that the best melting temperature is different every day. For example, 296 K is the best on 11th - 12th August, but with a best of 297 K on other days for internal PCMW. As aforementioned in Equation (1), the best melting temperature depends on the average indoor air temperature and inner heat sources. According to the work conducted in our previous work [18], the best melting temperature for internal PCMW is the same as the average indoor air temperature without considering the inner heat sources. Here, the average indoor air temperatures on these individual five days are 295.7 K, 295.8 K, 296 K, 296.1 K and 296.6 K, respectively. With the consideration of the inner heat gains, the optimal melting temperature in each day is slightly higher than the daily average indoor air temperature.

Similar to the external PCMW, the optimal melting temperatures on the previous four days before 15th August are 296 K and it is 297 K on 15th August. The optimal melting temperature is related to the daily average indoor air temperature, outdoor environment temperature, the solar radiation and inner heat gains, as shown in Equation (2). The PCMW is installed on the inner surface of the external wall, thus, the average indoor environment influences the optimal melting temperature more significantly to the outdoor environment. The influences of melting temperature on thermal performance of the PCMW agree very well with the theoretical analysis and the simulation work for the single wallboard [18].



(a)



(b)

Figure 8: Daily energy consumption for different melting temperatures during 11th August and 15th August: (a) PCMWs on internal partition wall; (b) PCMWs on external wall.

It can also be seen that the energy consumption on 15th August is once to twice more than that on 11th August and almost three times more than those on 12th, 13th and 14th August, because the weather on the 15th had a large change with much higher outside temperatures and more direct solar radiation, which means more cooling loads and the increased total daily energy consumption. In this case, a much higher melting temperature would save the energy consumption. Therefore, for passively applications, both internal and external PCMWs have better performance when the outdoor temperature is moderate not far away from the temperature range of thermal comfort.

4.2. Effect of latent heat

Figure 9 gives the daily energy consumption values for PCMWs with different latent heat values, on the internal wall and external wall respectively. Overall, PCMW with an identical size on the external wall can save more energy than that on the internal partition wall, provided that they have the same latent heat. The reason is that the external PCMW is not only for the energy storage/release but also for the thermal insulation between the outdoor and indoor environment. PCMW on the external wall can, to some extent, prevent the heat outside from entering/exiting the indoor environment thanks to the phase change. It can also partly release some heat back to the indoor environment when the indoor air temperature is below its melting temperature to keep within the thermal comfort and a part of the heat stored can release to the outdoor environment by the heat conduction through the other constructions, which is also good for the energy saving in the summer time by reducing the chances that the indoor air temperatures are overheated.

As shown in Figure 9, increasing the latent heat can save the energy consumption, especially when the melting temperature of the PCMW equals the optimal temperature. However, it is less significant when the melting temperature of the PCMW is far away from the optimal temperature. On the day of 14th August, the energy consumption of internal PCMWs with different latent heat has only a slight difference because the average indoor air temperature on that day almost equals the optimal melting temperature of internal PCMW. On each day, the performance of an external PCMW is not as good as an internal PCMW of the same latent heat because that the real melting temperature used in the case modelling is closer to the optimal melting temperature for the internal PCMW, which positively affects the energy saving.

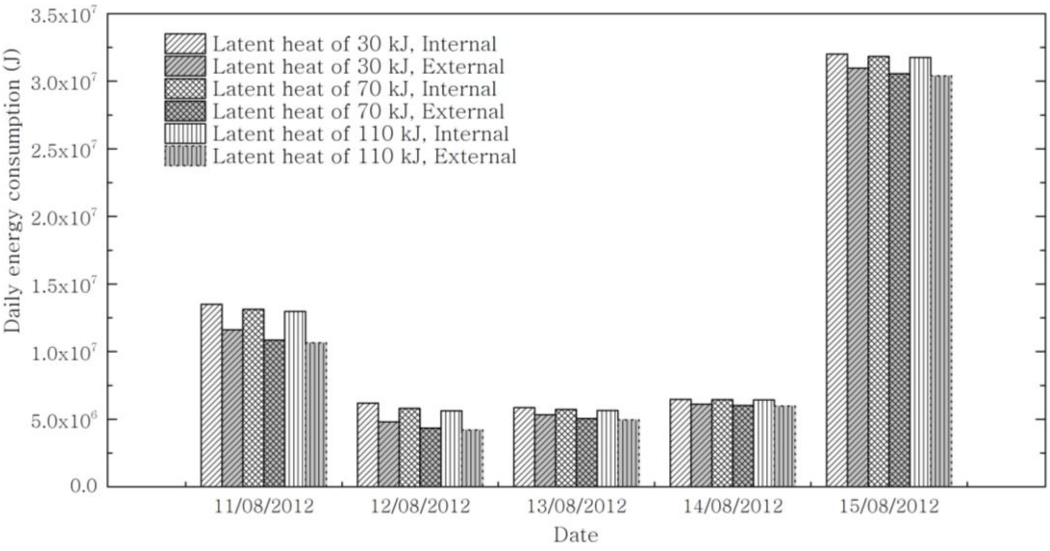


Figure 9: Daily energy consumption for different latent heat values of internal and external wallboards.

4.3. Effect of thermal conductivity

From Figure 10, it can be seen that increasing the thermal conductivity of the PCMW can reduce daily energy consumption on both internal partition wall and external wall. However, the energy saving potential of the internal PCMW is more significant than that of the external PCMW. The internal PCMW is used to store heat from the indoor air and recycle it back to the indoor air. A higher thermal conductivity means higher energy storage/release rate. Especially within such narrow transition temperature range of from 294 K to 298 K, an internal PCMW with a higher thermal conductivity can respond more quickly and the PCM inside can also complete phase change more quickly.

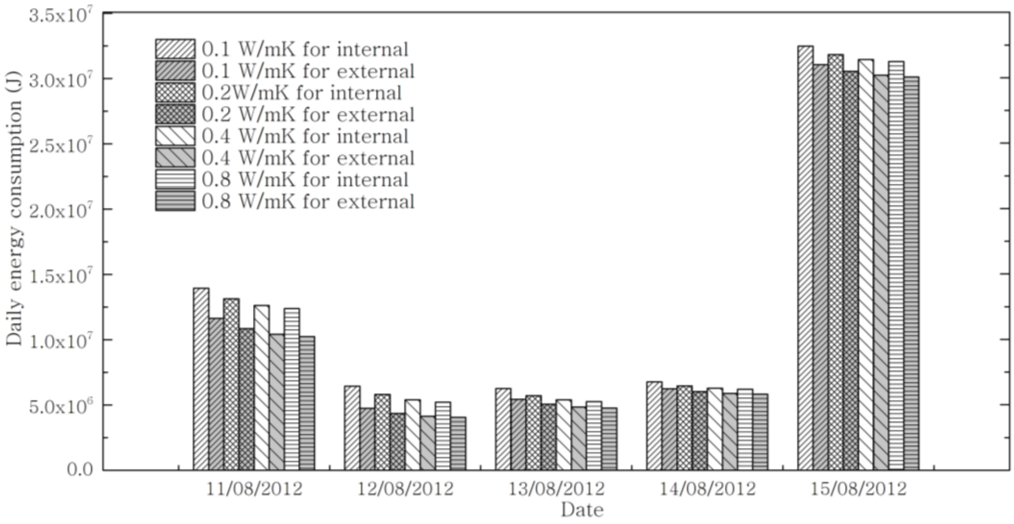


Figure 10: Daily energy consumption for different thermal conductivities of internal and external wallboards.

Figure 10 also shows that increasing the thermal conductivity from 0.1 W/(m•K) to 0.8 W/(m•K) can also reduce the energy consumption of external PCMW. However the effect is not as significant as that with internal PCMW. It is clear that enhancing the thermal conductivity can increase the heat storage/release rate, and the same in the internal PCMW. However, on the other side, higher thermal conductivity can enhance heat transfer from the outdoor environment to the indoor environment through the external wall in the summer, especially when the PCM inside the external wallboard is fully melt (only sensible heat is available). This may result in higher energy consumption.

A significant energy saving happens if the thermal conductivity is increased from 0.1 W/(m•K) to 0.4 W/(m•K), while only a minor improvement exists with an increase from 0.4 W/(m•K) to 0.8 W/(m•K). For example, during these five days, if the thermal conductivity increases from 0.1 W/(m•K) to 0.4 W/(m•K), the energy can be saved by around 7.6% and 6.3% in applications of internal PCMW and external PCMW, respectively. These increases are only 1.3% and 1.1% when enhancing the thermal conductivity from 0.4 W/(m•K) to 0.8 W/(m•K). Therefore, it is not always true that a higher thermal conductivity would significantly improve the thermal performance. High thermal conductivity has its advantage, which is to speed up the heat storage/release process in PCMWs. However, if it reaches a critical value, the heat stored in PCMWs will be released so rapidly that its storage effect can be attenuated (energy consumption is therefore increased). It is suggested that the optimal thermal conductivity of both external PCMW and internal PCMW is between 0.2 W/(m•K) and 0.4 W/(m•K).

4.4. Monthly energy saving for keeping at thermal comfort

It is of great interest to know how much heating and cooling loads can be reduced by the installation of the PCMWs for a certain period. Figure 11 shows the monthly energy savings of the building with PCMWs in the months of May, June, July, August and September. The results include the situations with the internal PCMWs and external PCMWs. Energy can be saved every month. In each month, the energy saving by external PCMW is higher than that by internal PCMW because of its different function as discussed in Section 2.

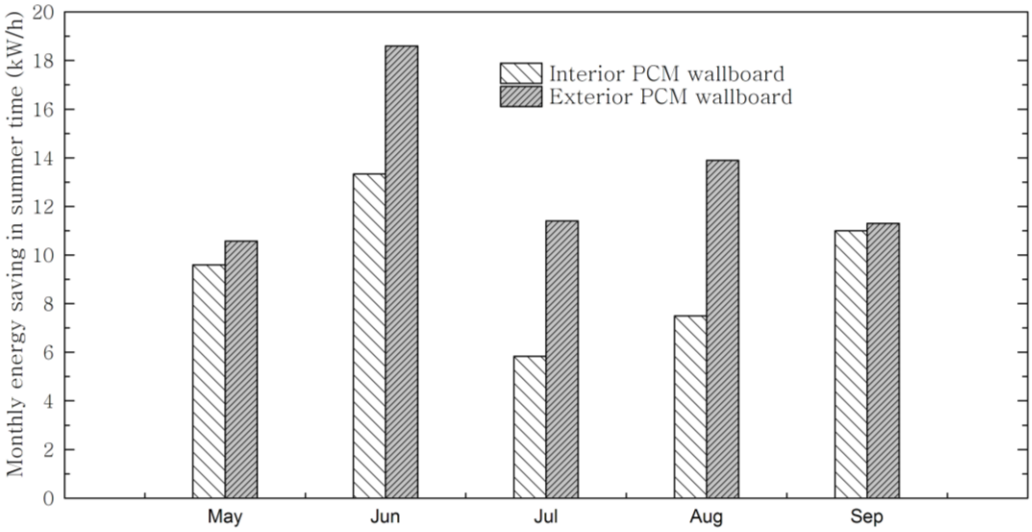


Figure 11: Monthly energy savings from April to September.

In the U.K. the period from May to August can be considered as summertime. As shown in Figure 11, for both internal PCMW and external PCMW, more energy can be saved in June among these five months. The reason is that a large percentage of indoor air temperatures of the building without these PCMWs are within or not far away from the thermal comfort. Secondly, in this month, the melting temperature of the PCMW is the closest to the average indoor air temperature with the application of PCMW. The PCMWs can work with their best performance. The external PCMW can save more energy, especially for the cooling loads, than internal PCMW, thanks to its dual roles in latent heat storage/release and insulation of the building envelope. According to the increase of the outdoor air temperatures, the benefit brought by the external PCMW is more significant that a difference of 5.3 kWh in June and 6.4 kWh in August can be found in Figure 11.

It needs to be noted that in September the benefits brought by internal PCMW and external PCMW are almost the same. The reason may be that the percentage of the indoor air temperatures of the building without the PCMW is the largest during the year and the average indoor temperature without the PCMW is very close to the melting temperature used in the case modelling. Therefore, energy saving effects in September by the internal PCMWs and external PCMWs are almost the same.

4.5. Thermal performance under cooling only

In order to obtain more realistic results, the model considers air conditioning which is on only when the indoor air temperature exceeds 299 K. The thermal comfort is between 294 K and 298 K. The monthly thermal comfort rate is defined:

$$Monthly\ thermal\ comfort\ rate = \frac{Total\ hours\ when\ people\ feel\ thermal\ comfort}{Total\ hours\ in\ a\ month} \tag{22}$$

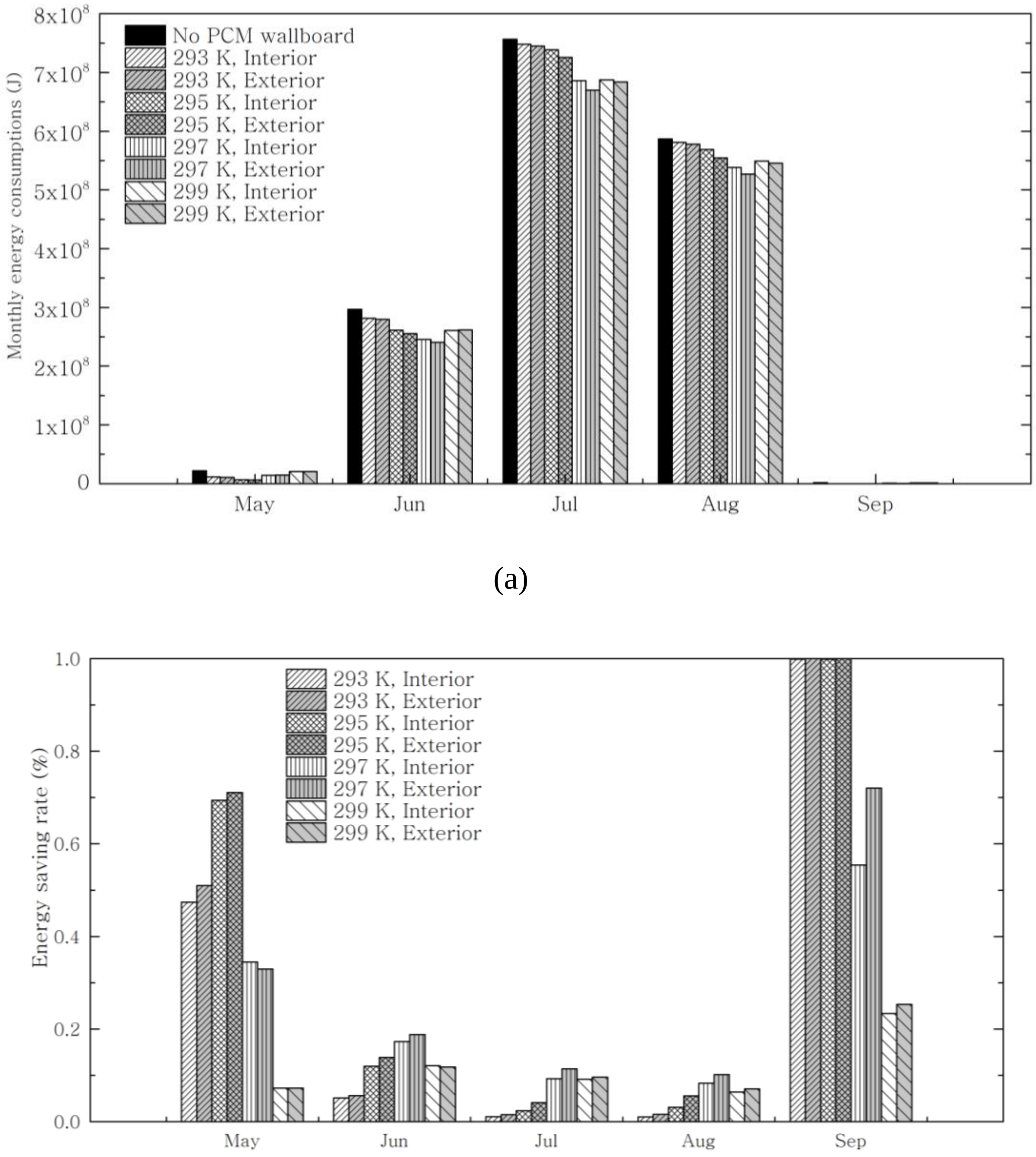
Table 3 shows the thermal comfort rates of the application of PCMWs with different melting temperatures in August. It can be seen that the optimal melting temperature is 297 K, which agrees very well with a previous work by the same authors [18]. Compared with the situation without the PCMW, the application of the PCMW can increase the thermal comfort rate. The PCMW can have a better thermal performance when its melting temperature is chosen within the thermal comfort, for example, the melting temperatures of 295 K and 297 K are better than 293 K and 299 K. Generally speaking, the external PCMW works better than the internal PCMW with the same thermophysical properties. As long as the external wall has a sufficient area to install the PCMW, it is a better location to install PCMWs than the internal partition wall.

Table 3 Thermal performance of PCMWs applications.

Melting temperature (K)	Type	Hours within the thermal comfort	Thermal comfort rate in August (%)
n.a.*	No PCMW	301	40.45
293	Internal PCMW	312	41.94
293	External PCMW	317	42.61
295	Internal PCMW	318	42.74
295	External PCMW	324	43.55
297	Internal PCMW	323	43.41
297	External PCMW	342	45.97
299	Internal PCMW	312	41.93
299	External PCMW	309	41.53

* : not applicable.

The energy consumptions and energy saving rates of months from May to September are shown in Figures 12(a) and 12(b). During a year, almost all the cooling load consumptions are in June, July and August. The optimal melting temperature of PCMW is 297 K. It can save the most cooling loads among these hottest months, about 21%, 13% and 12% for external PCMW and 18%, 11% and 10% for internal PCMW in June, July and August. For the application of PCMWs with a melting temperature of 293 K or 295 K, the cooling is not needed in September. They have one hundred percent cooling load saving rate, as shown in Figure 12(b).



(a)

(b)

Figure 12: Monthly energy consumption (a) and saving rates (b) in summer time, from May to September.

5. Conclusions

A heat transfer analysis of the internal and external PCMWs has been conducted. The optimal melting temperature and heat storage are theoretically examined to expose the influencing factors. It has been found that the stored heat of internal PCMWs decreases when the difference between the PCM melting temperature and the average indoor temperature is reduced. However the stored heat of external PCMW depends on many parameters, such as outdoor environment, indoor environment, insulation material, convective the heat transfer coefficients at the outer and the inner surface, and the peak temperature difference between the outdoor and indoor air (more complicated in external PCMW than in the internal counterpart).

The effects of the PCMW thermal properties are studied parametrically in a case study. The results from the situation keeping the indoor air temperature in thermal comfort agree very well with the theoretical study and the results from previously published work. When the melting temperature is slightly higher than the average indoor air temperature (1 K – 2 K in this project), both the external PCMW and internal PCMW have shown excellent performance. The optimal melting temperature should be around 296 K to 297 K. Latent heat does not have a large effect on the thermal performance but a value of over 30 kJ/kg is needed from the energy saving aspect. These results also show that it is worthy to enhance the thermal conductivity from 0.1 W/(m•K) to 0.4 W/(m•K). A melting temperature of 297 K is optimal for both internal and external PCMWs when only cooling consumption is considered in the summertime. It works better on an external wall with a thermal comfort increase rate of 5.5 % than that on an internal wall. Both external and internal PCMWs can save 20 % of the cooling consumption in the hottest month in the UK.

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