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THERMAL COMFORT AND ENERGY SAVING POTENTIAL OF A PHASE CHANGE MATERIAL BOARD (PCMB) FOR BUILDING APPLICATIONS IN HOT WEATHER

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ABSTRACT

Phase change material board (PCMB) is considered high potential as an efficient passive solution to energy saving in building applications, especially in hot weather. A numerical investigation is conducted on PCMB, with both sides subjected to periodical temperature variations to examine its thermal behaviour. The experimentally validated model is based on the enthalpy method. The inner surface temperature variation is used as a comparison factor, further with two newly introduced parameters, thermal comfort ratio (TCR) and energy saving potential (ESP), to parametrically analyse the influencing factors in terms of both thermal comfort and energy saving aspect. Melting range, latent heat capacity, convective heat transfer coefficients for inner/outer surfaces, thermal conductivity and PCMB thickness are studied parametrically. Furthermore, the optimal heat storage capacity of a PCMB placed on the inner side of a traditional brick-concrete exterior wall is theoretically obtained.

Keywords: PCMB; energy efficient buildings; latent heat storage; thermal comfort; influencing factor; optimal thickness.

NONMENCLATURE

c_p	specific heat capacity (kJ/(kg·K));
H	enthalpy (kJ);
H_m	latent heat (kJ/kg);
h	convective heat transfer coefficient (W/(m²·K));
k	thermal conductivity (W/(m·K));
L	thickness (m);
P	a 24-hour period (hour);
R	thermal resistance (m²·K/W)
T	temperature (°C);
$\overline{T}$	average temperature (°C);
ΔT	amplitude of air temperature fluctuation;
x	direction through thickness (m);
Greek symbols	
ρ	density (kJ/kg);
τ	time (s);
Δτ	time gap (s);

Subscripts	
dis	discharge;
i	inner;
ini	initial;
l	liquid state;
m	melting;
max	maximum;
min	minimum;
o	
opt	outer;
p	optimum;
r	PCM;
s	room;
sol	solid state;
	solar;
stor	storage.
c_p	specific heat capacity (kJ/(kg·K));
H	enthalpy (kJ);
H_m	latent heat (kJ/kg);
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1. INTRODUCTION

A report by Delay et al. [1] from the Carbon Trust™ suggests that the U.K. building sector represent 45% of its whole carbon emissions, which is largely due to poor insulation and consequent additional energy consumption to maintain a desirable level of thermal comfort. Thermal energy storage with phase change materials (PCMs) has attracted ever-growing attention due to its tremendous capability to save energy in heating and cooling. Deng et al. [2] pointed out one of the problems of renewable energy in building applications being the mismatch between energy supply and energy demand can be addressed by energy storage system, in which thermal energy storage is the most common. The increase of thermal inertia by incorporating PCMs into traditional building structures is an effective method. Potential building structures where PCMs can be incorporated include walls, wallboards, floors, roofs, windows and shutters, insulation materials, furniture and indoor appliances [3-6]. Installing phase change material boards (PCMBs) at the inner side of an exterior or interior wall is, to date, the most popular method due to its potential and ease of use in refurbishing existing buildings.

Kuznik et al. [7] conducted an experimental research on a PCMB called Energain® under the controlled thermal and irradiative effects, showing that a 5 mm-thick PCMB can double the energy stored and released. Later, Kuzinik and Virgone [8] tested a full-scale room in summer hot weather, mid-season mild weather and winter cold weather, showing that the PCMB largely reduced the room air temperature fluctuations in all cases. Meng et al. [9] tested a room envelope incorporated with two PCMs of different melting temperatures, showing that the indoor air temperature fluctuation can be decreased by 4.3°C in summer and 14.2 °C in winter. Jin et al. [10] experimentally optimised the location of PCM thermal shields (PCMTS) within the cavity of a typical North American residential wall using a dynamic wall simulator. The greatest impact on the peak flux reduction was found by them when the PCMTS was placed next to the internal face of the wallboard. Gounni and Alami [11] experimentally studied the optimal location of PCM, showing that highest energy saving was achieved when the location was next to the interior rather than the exterior, which reconfirmed the accepted fact that placing PCMB at the inner side of the wall is effective to maintain thermal comfort. Kong et al. [12] built PCM panels for two full-size rooms, being installed on the walls and roofs at their outside and inside surfaces, respectively. Their conclusion was that the panels kept the thermal comfort in all situations but the room with PCM installation at the inner surface performed better than that at the outer surface.

The thermal performance of a PCMB primarily depends on the thermal properties of the PCM inside. Analytical and numerical investigations can provide useful instructions to guide the design and installation of PCMBs in buildings by evaluating their thermal performance. Neeper [13] proposed the optimal melting temperature of a gypsum wallboard of fatty acid and paraffin wax for interior and exterior use based on the diurnal energy stored and released. He concluded that the optimal value of the melting temperature is largely related to the average room temperature, which varies from building to building and from season to season. Xiao et al. [14] found the optimal melting temperature is not only related to the average room temperature but also to the absorbed radiation. Not only does the optimal melting temperature exist, but also the optimal thickness exists. Kuznil et al. [15] found the optimal thickness was 1 cm in their simulation by an in-house software called CODYMUR, while Koo et al. [16] found the optimal thickness was around 15 mm depending on the given heat transfer rate in their investigation of several wallboard design parameters.

Solomon [17] pointed out that the purpose of installing a PCM/wall is to make room thermal comfort and to store heat and he suggested that the temperature of the room surface of the wall should vary as little as possible. Inner surface temperature history and diurnal energy storage capacity are the two most important criteria to measure the thermal performance of a PCMB. Some parameters were proposed by researchers to evaluate the inner surface temperature history, such as 'time lag', 'decrement factor' and 'phase transition keeping time'. Zhou et al. numerically studied these parameters in a single shape-stabilised PCMB under periodically changing temperatures [18] and periodically changing heating fluxes [19]. Diurnal energy storage is another useful parameter to evaluate the thermal performance, which Neeper [13] and Peippo et al. [20] used to optimise the melting temperature of PCM walls with valuable results obtained. Zhou et al. [21] conducted a comprehensive parametric analysis of the thermal performance of interior and exterior PCMWs by examining both the surface temperature variation and the diurnal energy storage capacity which gave a useful guide for the selection of PCMs in energy-efficient buildings. In addition to these, several other parameters were also proposed. Zhang et al. [22] suggested two parameters, which are the modifying factor of the inner surface heat flux ‘a’ and the thermal storage ratio ‘b’ for exterior and interior wall, respectively. Evola et al. [23, 24] pointed out that operative temperature was more important than room air temperature, and therefore in order to measure the thermal comfort improvement, they used four indicators: ‘intensity of thermal discomfort (ITD)’, ‘frequency of thermal comfort (FTC)’, ‘frequency of activation (FA)’ and ‘storage efficiency (η_{PCM})’, which were all based on the whole building rather than a single wall.

PCMBs can be placed on the inner surface of an interior or exterior wall, but the roles are rather different. An interior PCMB works only as thermal energy storage system, storing heat when the room temperature is above the melting temperature and releasing heat when the room temperature is below the melting temperature to keep the room temperature more stable. An exterior PCMB works not only as a thermal energy storage system but also as insulation between the indoor and outdoor environment. A PCMB placed on the exterior wall is expected to perform better than the same PCMB placed on the interior wall in terms of keeping room thermal comfort under the same conditions in summertime [25].

It is of great interest to know the effect of some important influencing factors on the thermal performance of an exterior PCMB with both sides subjected to periodical temperature variations. In most existing studies relating to PCMB performance simulation, their room air temperature was always kept constant. However, due to varying internal heat loads, outside environment conditions, solar radiation from the window and many other factors, the room air temperature will inevitably have a periodic change within a small amplitude even under well-equipped thermal control by air conditioning. To account for this, a periodically changing room air temperature is adopted in the current study. To further and better understand the inner surface temperature variation, two new parameters, thermal comfort ratio (TCR) and energy saving potential (ESP) are introduced to evaluate the thermal performance in terms of both thermal comfort and energy saving aspect, for the first time. A series of influencing factors are parametrically studied, including PCM melting range, latent heat capacity, thermal conductivity, convective heat transfer coefficients for inner/outer surfaces and PCMB thickness. Through a theoretical analysis, the optimal thermal energy storage capability and thickness are given for a PCMB placed on the inner side of a traditional brick-concrete wall.

2. THERMAL ANALYSIS MODEL OF A PCMB

2.1 *Numeric model*

Figure 1 shows the schematic of a PCMB with both sides under sinusoidal conditions. T_o and T_r are the outdoor and room air temperatures, respectively; h_o and h_i are the convective heat transfer coefficient of inner and outer surface, respectively.

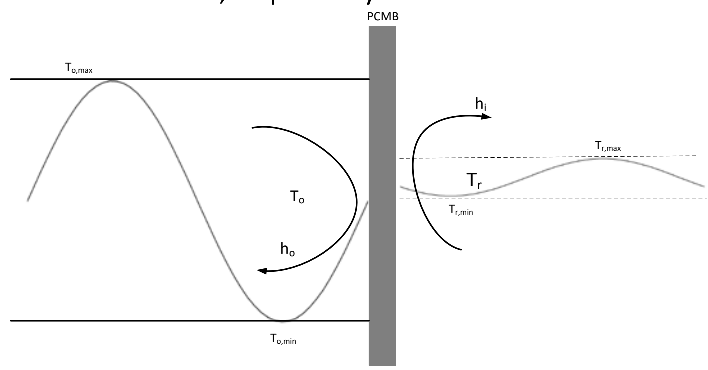


Figure 1. Schematic of a PCMB with both sides under sinusoidal conditions.

To simplify the simulation, some assumptions have been made in this study: (1) the thermal properties of PCMB are temperature independent; (2) constant convective heat transfer coefficients of inner surface (h_i) and outer surface (h_o) are used; (3) one-dimensional heat transfer is analysed through the wall thickness direction, considering that the PCMB thickness is small compared to its length and width; (4) PCMB has a single and uniform initial temperature. Based on such assumptions, an enthalpy method is applied in the simulation to solve the phase change heat transfer problem. The energy conservation equation for PCMB is:

$$\rho_p \frac{\partial H}{\partial \tau} = k_p \frac{\partial^2 T_p}{\partial x^2} \tag{1}$$

where ρ_p and k_p are the density and thermal conductivity of PCMB, respectively; T_p is the temperature; H is the enthalpy, which is a function of temperature:

$$\mathrm{H} = \begin{cases} \int_{\tau_0}^{\tau} c_{p,s} d\tau & \tau < \tau_1 \\ \int_{\tau_0}^{\tau_1} c_{p,s} d\tau + \int_{\tau_1}^{\tau} c_{p,m} d\tau & \tau_1 \le \tau \le \tau_2 \\ \int_{\tau_0}^{\tau_1} c_{p,s} d\tau + \int_{\tau_1}^{\tau_2} c_{p,m} d\tau + \int_{\tau_2}^{\tau} c_{p,l} d\tau & \tau > \tau_2 \end{cases} \tag{2}$$

where τ_0 is the temperature point when enthalpy is zero; τ_1 and τ_2 represent the start and finish time of phase change, respectively; $c_{p,s}$ and $c_{p,l}$ are the specific heat capacity (under constant pressure) in the solid and liquid state, respectively. In this simulation, the specific heat capacity values in the solid and liquid states are set to be equal. $c_{p,m}$ denotes an equivalent specific heat capacity during phase change, calculated from a widely accepted formula $c_{p,m} = H_m/(\tau_1 - \tau_2)$, where H_m is the latent heat.

2.2 *Boundary conditions*

The boundary and initial conditions are given by Equations (3-5).

$$h_o\left(T_{sol-air} - T_p\right)\big|_{x=0} = -k_p \frac{\partial T_p}{\partial \tau}\bigg|_{x=0} \quad (3)$$

$$h_i\left(T_r - T_p\right)\big|_{x=L_P} = k_p \frac{\partial T_p}{\partial \tau}\bigg|_{x=L_P} \quad (4)$$

$$\mathrm{T}_p(x,\tau)\big|_{\tau=0} = T_{ini} \quad (5)$$

where $T_{sol-air}$ is the outdoor air temperature reflecting the combined effects of the actual outdoor temperature and the incident solar radiation; L_P is the thickness of PCMB; T_{ini} is the initial temperature (T_{ini}=15 °C). PCMB is subjected to convective heat transfer boundary conditions on both sides. For the outside boundary, the 'sol-air temperature' is used, which could also be considered as sinusoidal variation during a 24-hour period [15]. In the current study, the daily sol-air temperature is assumed to vary sinusoidally between 18 °C and 32 °C, as follows:

$$\mathrm{T_{sol-air}} = 25 + 7 \times \sin(2\pi\tau/\mathrm{P} - 2\pi/3) \quad (6)$$

where P is a 24-hour period with the highest sol-air temperature appearing at 14:00. Despite that the room temperature is thermally controlled by the air conditioning, the room temperature is still usually considered as varying sinusoidally during a 24-hour period as the room temperature is influenced by many factors: internal heat loads, outside environment conditions, solar radiation from the window. In this study, the room temperature is assumed as follows:

$$\mathrm{T_r} = 22 + \sin(2\pi\tau/\mathrm{P} - 2\pi/3 - 2\pi\Delta\tau/\mathrm{P}) \quad (7)$$

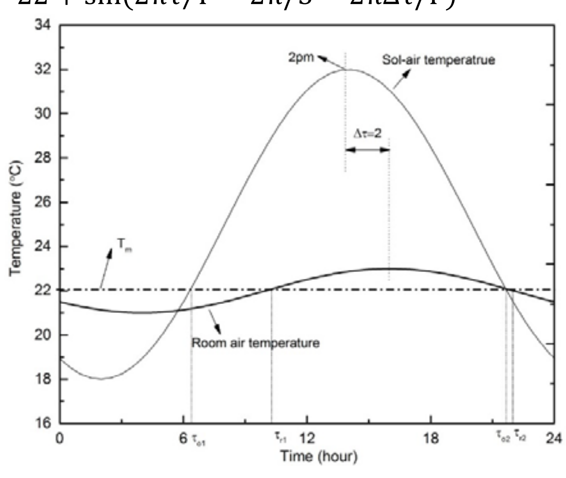


Figure 2. Profiles of sol-air temperature and room air temperature variation with a 2-hour delay.

In Eq. (7), $\Delta\tau$ is the time delay between the peaks of sol-air temperatures and room air temperatures. A positive time delay is considered favourable for thermal comfort and energy saving purpose in summer. Figure 2 schematically gives an example of the sol-air temperature variation and room air temperature variation with a 2-hour delay.

2.3 *Numerical procedure and validation*

In order to specify the effects of influencing factors on the thermal performance of PCMB with both sides subjected to convective heat transfer with periodically changing temperatures, a standard set of parameters should be clarified. A commercial PCMB called DuPont™ Energain® was used, whose thermo-physical properties are: melting temperature of 22 °C, melting range of 1 °C, density of 885 kg/m^3, thermal conductivity of 0.2 W/(m·K), sensible heat of 2.4 kJ/ (kg·K), latent heat of 70 kJ/kg and thickness of 1 cm.

A convective heat transfer coefficient between 5 W/(m^2·K) and 12 W/(m^2·K) is usually adopted for the inner surface according to the existing literature: 5.67 W/(m^2·K) and 8.3 W/(m^2·K) in Ref. [13], 7 W/(m^2·K) in Ref. [15], 8 W/(m^2·K) in Ref. [20], 8.7 W/(m^2·K) in Ref. [22], 9 W/(m^2·K) in Ref. [26] and 12 W/(m^2·K) in Ref. [16]. The selection of heat transfer coefficient for the outer surface varies from case to case: 17 W/(m^2·K) was used in Ref. [26] and 25 W/(m^2·K) in Ref. [15]. In the current study, the standard heat transfer coefficients for the inner and outer wall surface are set to be 8 W/(m^2·K) and 17 W/(m^2·K), respectively.

The phase change heat transfer equations of PCMB were solved by a finite difference method (FDM) and executed in Fortran. An implicit computational scheme was adopted to solve parabolic equations for better stability and rapid convergence [27]. The stopping criterion was to terminate iterations when the relevant difference was less than 10^{-6} (0.0001%). The meshing along the thickness and time direction were carefully chosen to ensure the mesh accuracy and independence. It was found that 1500 nodal points along the thickness and a time step of 2 s were sufficient, as further refining the mesh could not increase the accuracy.

The data was recorded for the 7th to 9th simulated day by which time the variation in temperatures became completely periodic and the effect of the initial conditions had disappeared. To fully understand the inner surface temperature variation, two parameters were introduced to value the thermal performance of the PCMB, 'Thermal Comfort Ratio (TCR)' and 'Energy Saving Potential (ESP)'. As the room temperature is thermally controlled between 21 °C and 23 °C, TCR is defined as the percentage of the total time within a day when the inner surface temperature of PCMB is within such a comfortable temperature range. ESP is defined as the energy needed for air conditioning (both heating and cooling) to keep the room air temperature within that range divided by the energy needed with a 10 mm–thick traditional wallboard. Such two parameters are used to evaluate the thermal performance of the PCMB in the aspect of thermal comfort and energy saving.

To validate the reliability of the model and numerical method used, a simulation was conducted for the melting process of paraffin RT 27 [28] which has a similar melting point to those used in buildings. Figure 3 shows the simulation results against experimental data. For such a complicated phase change heat transfer problem, a very good agreement was observed between the two, only with very small discrepancy, which can be attributed to uncertainties in experimental data affecting the accuracy and those assumptions in the simulation: constant thermophysical properties and natural convection neglected in the liquid phase. The most evident discrepancy only appears in the closing stage of phase change at 15 mm away from the heating board, because the start of natural convection accelerates heat transfer. Since the overall agreement is sufficient, natural convection was safely neglected. In fact, in our study the PCM inside the PCMB only became jelly-like at its liquid state due to high viscosity and therefore natural convection was not strong. More importantly, PCM should not fully finish phase change under design conditions, because heat storage capacity beyond phase change becomes significantly small and is therefore not desirable.

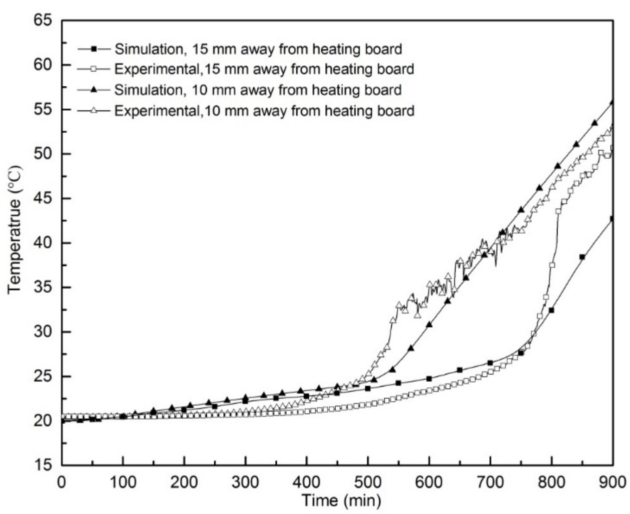


Figure 3. Comparison of the experimental data [28] and simulation results for paraffin RT27.

3. RESULTS AND DISCUSSION

3.1 *Effects of PCM thermal properties*

Melting temperature is one of the most important influencing factors. Based on the method by Zhou et al. [25], the optimal melting temperature of PCMB in this case is 22 °C, which is perfectly equal to the selected standard melting temperature. Most low-temperature organic PCMs melt with a temperature range rather than a single and sharp melting point. Figure 4 shows the inner surface temperature variations with different melting temperature ranges. Since the current study is based on the summer hot environment, the decrease rate of the highest daily temperature is an important evaluating factor. From Figure 4, it can be seen that the melting range has little effect on decreasing either the highest daily temperature or the lowest daily temperature. However, the surface temperature variation of the PCMB during the phase change process is slightly different due to different melting ranges.

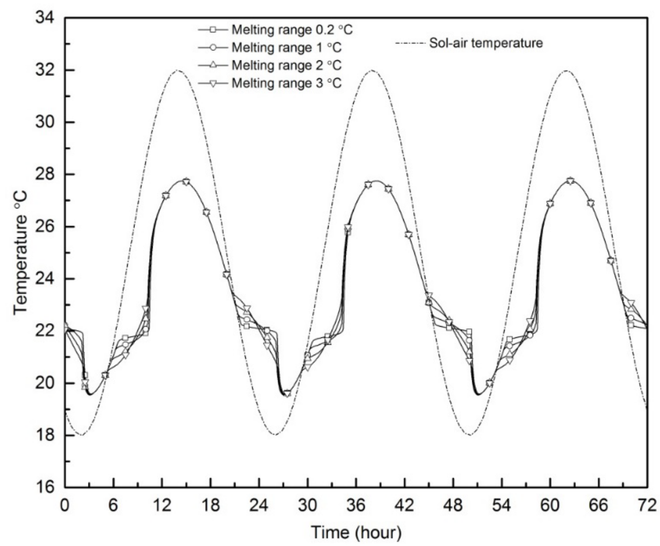
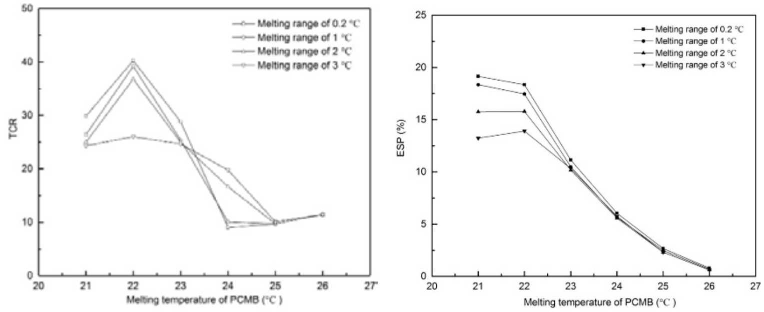


Figure 4. Inner surface temperature variations with different melting temperature ranges.

Figure 5 shows the influence of the melting temperature ranges on TCR and ESP. No matter what melting temperature is, as long as the melting temperature is within the room air variation range [21 °C, 23 °C], the narrower the melting temperature, the higher TCR and ESP are. For the same melting range, the TCR for the optimal melting temperature is always the highest among all the cases. When the melting temperature of the PCMB is far above the optimal temperature, for example when T_m = 25 °C and 26 °C, both TCR and ESP are very low, being only around 10% for TCR and less than 5% for ESP in both cases. When T_m = 24 °C, a higher melting range results in a higher TCR, that is because of a large melting range, sometimes the PCMB melting happens within the room air temperature variation range which is beneficial to the TCR. However, no matter what melting range it has, the ESPs for T_m = 24 °C are still very low, being around 6.5%.



(a) (b)

Figure 5. Melting temperature range effects on (a) TCR and (b) ESP.

Latent heat is another important influencing factor on thermal performance. Figure 6 shows the effect of PCMB latent heat on the inner surface temperature variation. The latent heat has little effect on the daily highest temperature decrease, but only about 1 °C of reduction in the daily lowest temperature when latent heat increases from 50 kJ/kg to 110 kJ/kg. However, in the summer time, change of the daily lowest temperature would not be a concern in term of thermal comfort. Furthermore, a higher latent heat also leads to a longer time staying around melting temperature, meaning a longer phase change period.

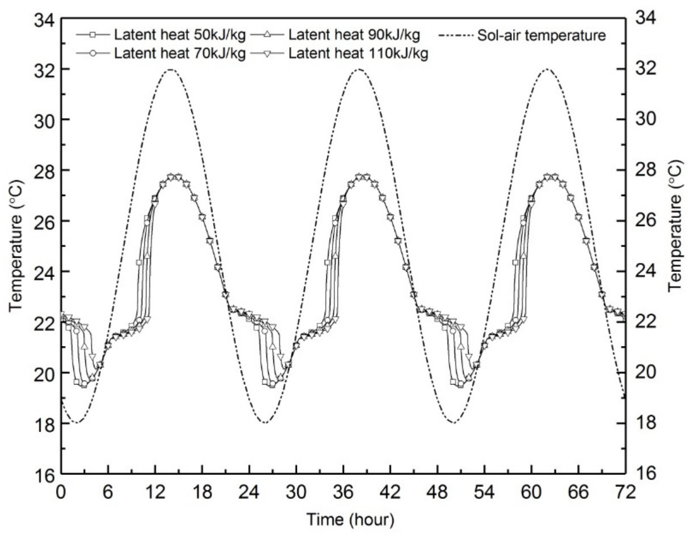


Figure 6. Effect of PCMB latent heat on the inner surface temperature variation.

The increase of the latent heat capacity has a positive effect on both TCR and ESP, seen in Figure 7. The effect of latent heat capacity on the TCR is almost linear, with an increased TCR from 33.3% to 39.2%, to 44.8% and then to 50%, when latent heat is increased from 50 kJ/kg to 110 kJ/kg with a 20 kJ/kg increase rate. Meanwhile, the ESP can also be increased from 12.8% to over 23.2%. Therefore, the latent heat of PCMB can be said 'the higher the better'. However, the latent heat of PCMB depends on the quantity and latent heat capacity of PCM inside. It is known that the solid-liquid phase change can lead to a potential leakage problem. The commercial PCMB is better to be shape-stabilised. Supporting materials, such as polymers, can be used in the manufacture of PCMB. In order to enhance the total thermal mass of the PCMB, the minimum amount of supporting materials should be suggested.

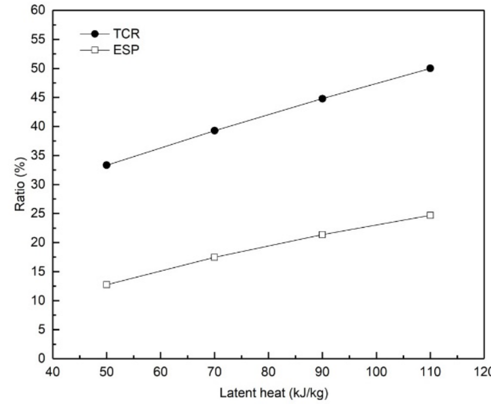


Figure 7. Latent heat capacity effects on ESP and TCR.

The thermal conductivity of PCMB has an effect on the daily highest temperature. As seen in Figure 8, the highest daily temperature rises with the increase of thermal conductivity. From keeping thermal comfort aspect, increasing the thermal conductivity of PCWB is not beneficial to improve the thermal performance. When the thermal conductivity of PCMB is increased from 0.2 W/(m·K) to 0.3 W/(m·K), the daily highest temperature is increased by about 0.5 °C. The PCMB used on the exterior wall functions partly as insulation and partly as thermal energy storage. As insulation, low thermal conductivity prevents heat from going through both ways (into and out of the room). However, as thermal energy storage, low thermal conductivity prolongs the charging and discharging process, which is undesirable. In this study, both sides of PCMB are exposed to convective heat transfer with periodical temperature variation. The PCM in a 10 mm-thick PCMB will be fully charged and discharged rapidly due to a large temperature difference and a low thermal resistance between the outdoor and indoor environment. When there is no ongoing phase change process, the PCMB functions fully as the insulation, thus, a low thermal conductivity is better for the overall thermal performance of the PCMB.

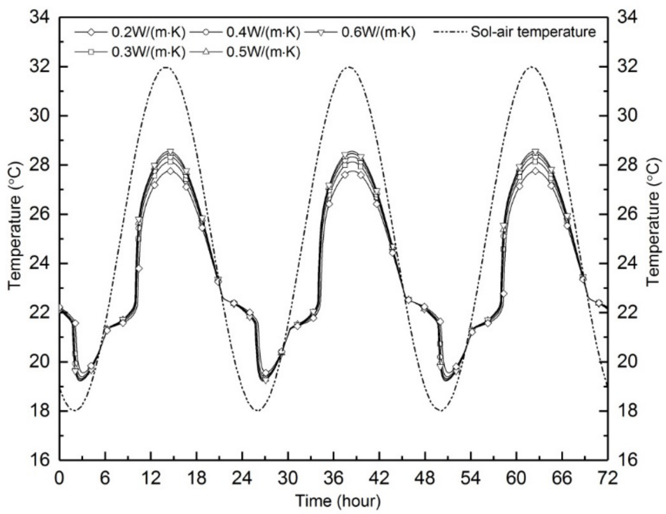


Figure 8. Effect of PCMB thermal conductivity on the inner surface temperature variation.

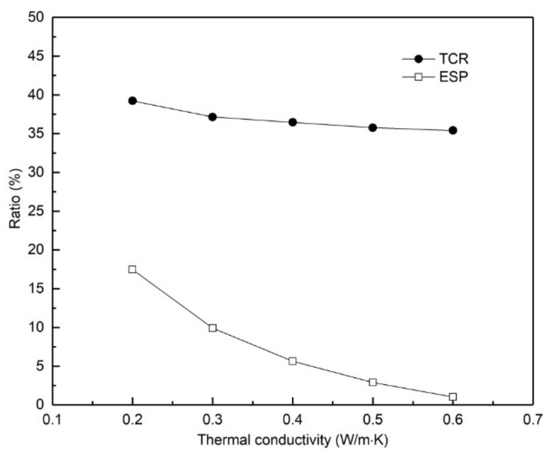


Figure 9. Thermal conductivity effects on TCR and ESP.

Figure 9 shows the TCR and ESP influenced by different thermal conductivities. There is no doubt that increasing the thermal conductivity in this study has a negative effect on both factors. The TCR decreases from 39.2% to 37.1% when thermal conductivity increases from 0.2 W/(m·K) to 0.3 W/(m·K). However, the decrease of TCR slows when further increasing the thermal conductivity to 0.5 W/(m·K) with an average decrease of 0.7 % per 0.1 W/(m·K) increase. There is only 0.4% decrease when the thermal conductivity increases from 0.5 W/(m·K) to 0.6 W/(m·K). Increasing the thermal conductivity can also decrease the ESP. However, the effect of thermal conductivity on ESP decrease is more significant than that on TCR decrease, seen from Figure 9. The ESP for a PCMB with a thermal conductivity of 0.6 W/(m·K) is only 1%, meaning it works almost the same with a traditional wallboard. Therefore a lower thermal conductivity of an exterior PCMB proves good in terms of both thermal comfort and energy saving purpose.

3.2 Effects of PCWB thickness

The PCMB thickness has the largest effect on the inner surface temperature variation among all, because a thicker PCMB not only has a larger total latent heat capacity but also a larger thermal resistance benefited from the thickness. As shown in Figure 10, the decrease rate of peak daily highest temperature is almost even with every 5 mm thickness of increase, being about 0.6 °C, when the PCMB thickness changes from 0.005 m to 0.02 m. However, the daily lowest temperature changes differently. For a PCMB with a thickness of 0.02 m, the daily lowest temperature peak almost disappears. The daily time when the inner surface temperature is within the thermal comfort temperature range should be the longest.

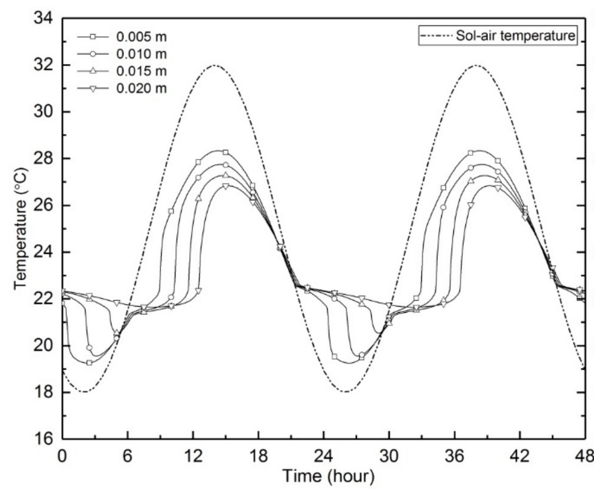


Figure 10. Effect of PCMB thicknesses on the inner surface temperature variation.

The same results are obtained from Figure 11. The TCR is hugely increased to 62% when the thickness is 0.02 m. The ESP is also increased by a thicker PCMB, for example, the ESP increase is 12% when the PCMB thickness increases from 0.01 m to 0.015 m. However, further increasing the thickness leads to a slower increase of ESP, because the PCM inside the PCMB would not be fully charged or discharged in a daily cycle. From this aspect, the optimal thickness of the PCMB in this model is considered to be 0.15 m. In this model, both sides of the PCMB are directly subjected to periodical temperature variations. The large daily temperature variation of outdoor environment enhances the heat transfer to PCMB, thus requiring for a thicker PCMB to store the heat from outside. In practical applications, one side of the PCMB is supposed to connect with outdoor environment by thermal conduction through other traditional exterior envelops and then by convective heat transfer with outdoor environment. In that case, the total thermal resistance between outdoor environment and PCMB is larger compared to the case in this model that will require a thinner PCMB.

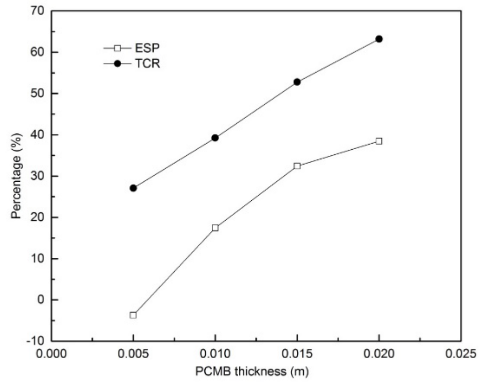


Figure 11. PCMB thickness effects on ESP and TCR.

3.3 Effects of convective heat transfer coefficients of the inner and outer surfaces

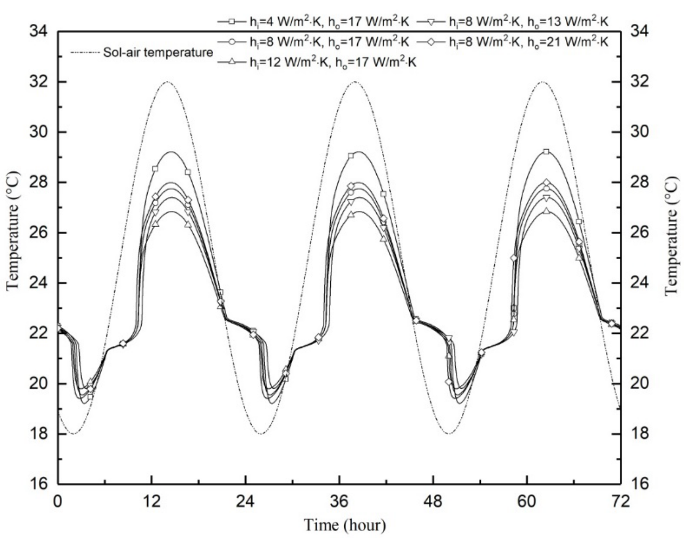


Figure 12. Effect of convective heat transfer coefficients on the inner surface temperature variation.

Figure 12 shows the effect of inner and outer convective heat transfer coefficients on the inner surface temperature variation. In general, the smaller the difference between the inner and outer convective heat transfer coefficients is, the larger the daily highest temperature decreases, for example, the most two decreases of the daily highest temperature happen at when h_i = 12 W/m^2·K and h_o =17 W/m^2·K and h_i = 8 W/m^2·K and h_o =13 W/m^2·K, respectively. With the same difference, higher inner and outer convective heat transfer coefficients result in smaller temperature variation. The outer convective heat transfer coefficient is largely influenced by the local environment. In practical applications, the outer surface of the PCMB always connects with outer environment by other wall structures. Therefore, the convective heat transfer coefficient of an inner surface has a larger effect on the thermal comfort and heating/cooling loads in a room than that of an outer surface. Thus, when designing a PCMB, the convective heat transfer coefficient for an inner surface should be selected carefully by considering PCMB location, occupants, furniture, window location and other influencing factors.

4. CONCLUSION

This paper conducted a numerical investigation on the thermal performance of PCMB. The model was validated by experimental data before being used in parametrical simulations to examine the effects of all influencing factors on the thermal performance. The inner surface temperature variation was used as the main evaluation. Two new parameters, 'Thermal Comfort Ratio (TCR)' and 'Energy Saving Potential (ESP)' were introduced to help further understand the thermal performance of PCMB. When the PCMB is at its optimal melting temperature, melting range has little effect on the daily highest and lowest temperature. A narrower melting range leads to a higher TCR and higher ESP. If the PCMB temperature is over 3 °C above the optimal melting temperature, both TCR and ESP become very low, being around 10% for TCR and less than 10% for ESP.

Latent heat also has little effect on decreasing the daily highest temperature, but the daily lowest temperature is smoothed and therefore TCR is largely improved, with ESP also improved slightly. In general, the latent heat can be said 'the higher the better'. To avoid leakage potential, a supporting material can be used to shape-stabilise the PCM inside PCMB, but doing so will affect the overall heat storage capacity. Therefore, the minimum amount of supporting materials should be suggested when designing PCMB in order to have the maximum heat capacity.

A larger thickness not only results in a higher heat capacity, but also a larger thermal mass of the building envelopes. In order to get the optimal thickness, a theoretical analysis was also conducted. Different from the simulation, a brick-concrete exterior wall structure was added to the analysis. The effects of the outdoor environment and convective heat transfer were investigated. For most studied cases, a 10 mm- thick PCMB worked sufficiently well as a heat storage system.

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REFERENCE

[1] Delay T, Farmer S, Jennings T. Building the future today-transforming the economic and carbon performance of the buildings we work in. Carbon Trust Report 2009.

[2] Deng S, Wang RZ, Dai YJ. How to evaluate performance of net zero energy building- A literature research. Energy 2014; 71: 1-16.

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

[4] Zhu N, Ma ZJ, Wang SW. Dynamic characteristics and energy performance of buildings using phase change materials: A review. Energy Convers Manage 2009; 50: 3169-3181.

[5] Pomianowski M, Heiselberg P, Zhang YP. Review of thermal energy storage technologies based on PCM application in buildings. Energy Build 2013; 67: 56-69.

[6] Kalnæs SE, Jelle BP. Phase change materials and products for building applications: A state-of-the-art review and future research opportunities. Energy Build 2015; 94: 150-176.

[7] Kuznik F, Virgone J, Noel J. Experimental assessment of a phase change material for wall building use. Appl Energy 2009; 86: 2038-2046.

[8] Kuznik F, Virgone J, Roux JJ. Energetic efficiency of room wall containing PCM wallboard: A full-scale experimental investigation. Energy Build 2008; 40: 148-156.

[9] Meng E, Yu H, Zhan GY, He Y. Experimental and numerical study of the thermal performance of a new type of phase change material room. Energy Convers Manage 2013; 74: 386-394.

[10] Jin X, Medina MA, Zhang XS. On the placement of a phase change material thermal shield within the cavity of buildings walls for heat transfer rate reduction. Energy 2014; 73: 780-786,

[11] Gounni A, Alami MEI. The optimal allocation of the PCM within a composite wall for surface temperature and heat flux reduction: an experimental approach. Appl Therm Eng 2017; 127: 1488-1494.

[12] Kong XF, Lu SL, Huang JY, Cai Z, Wei SS. Experimental research on the use of phase change materials in perforated brick rooms for cooling storage. Energy Build 2013; 62: 597-604.

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

[14] Xiao W, Wang X, Zhang YP. Analytical optimization of interior PCM for energy storage in a lightweight passive solar room. Appl Energy 2009; 86: 2013-2018.

[15] Kuznik F, Virgone J, Noel J. Optimization of a phase change material wallboard for building use. Appl Therm Eng 2008; 28: 1291-1298.

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

[17] Solomon AD. Design criteria in PCM wall thermal storage. Energy 1979; 4: 701-709.

[18] Zhou GB, Yang YP, Wang X, Cheng JM. Thermal characteristics of shape-stabilized Phase Change Material Wallboard with periodical outside temperature waves. Appl Energy 2010; 87: 2666-2672.

[19] Zhou GB, Yang YP, Xu H. Performance of shape-stabilized Phase Change Material Wallboard with periodical outside heat flux waves. Appl Energy 2011; 88(6): 2113-2121.

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

[21] Zhou D, Shire GSF, Tian Y. Parametric analysis of influencing factors in Phase Change Material Wallboard (PCMW). Appl Energy 2014; 119: 33-42.

[22] Zhang YP, Lin KP, Jiang Y, Zhou GB. Thermal storage and nonlinear heat transfer characteristics of PCM wallboard. Energy Build 2008; 40 (9): 1771-1779.

[23] Evola G, Marletta L, Sicurella F. A methodology for investigating the effectiveness of PCM wallboards for summer thermal comfort in buildings. Build Environ 2013; 59: 517-527.

[24] Sicurella F, Evola G, Wurtz E. A statistical approach for the evaluation of thermal and visual comfort in free-running buildings. Energy Build 2012; 47: 402-410.

[25] Zhou D, Tian Y, Qu Y, Chen YK. Thermal analysis of phase change material board (PCMB) under weather conditions in the summer. Appl Therm Eng 2016; 99: 690-672.

[26] 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 Build 2006; 38: 673-681.

[27] Tian Y, Zhao CY, Heat Transfer Analysis for Phase Change Materials (PCMs). 11th International Conference on Energy Storage (Effstock 2009), Stockholm, Sweden, 14th – 17th June 2009.

[28] Zhou D, Zhao CY. Experimental investigations on heat transfer in phase change materials (PCMs) embedded in porous materials. Appl Therm Eng 2011; 31(5): 970-977.