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THE IMPACTS OF BUILDING ENVELOPES INTEGRATED WITH PHASE CHANGE MATERIALS ON THE NIGHTTIME COOLING LOAD REDUCTION IN A BEDROOM IN SUB-TROPICS

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ABSTRACT

In this paper, a simulation study on analyzing the impacts of building envelopes integrated with phase change materials (PCMs) on the night time cooling load reduction in a bedroom in sub-tropics is reported. Firstly, the efficacy of incorporating PCMs into a west-facing external wall for night time cooling load reduction in a bedroom in subtropics was investigated in the benchmark study. Results showed that incorporating PCMs into the west-facing external wall effectively reduced the night time cooling load and improved the thermal comfort in sleeping environments. Secondly, parametric studies were carried out to reveal important factors and underlying mechanisms that governed thermal performance of building envelopes integrated with PCMs. Results showed that proper selection of PCM with suitable phase change temperatures, shapes of enthalpy–temperature curve and the thicknesses of PCM was critical to reduce nighttime cooling load in bedrooms in subtropics.

Keywords: Phase Change Material (PCM), Night Cooling Load, Phase Change Temperature, Energy Performance

NONMENCLATURE

Abbreviations	
C_p	Specific enthalpy (J·Kg $^{-1}$ K $^{-1}$)
h	User defined function of the specific enthalpy of PCM (J·Kg $^{-1}$ K $^{-1}$)
PCM	Phase change material
RR	The reduction rate of SUM compared with that in the baseline case
SUM	Sum of the hourly total nighttime cooling load from 21:00-07:00 in the following day
T	Temperature (^{o}C)
Symbols	
i, j	Node

1. INTRODUCTION

With a great improvement in people's living standard, air-conditioning has become an essential provision in people's daily life. In the subtropical regions, it is common that air-conditioning is usually required to maintain an appropriate indoor thermal environment in a bedroom when occupied at nighttime during summer months. This was reflected in a survey about the use of air conditioning (A/C) in bedrooms in residential buildings in Hong Kong. It was shown that approximately two-third of respondents would leave their room air conditioners (RACs) on at nighttime [1]. Electricity consumption and indoor climate of residential buildings can be affected by various building envelope characteristics such as building shape, orientation, thermal insulation, thermal mass, wall color, window size, adding the air gap etc. One of the approaches for cutting down building energy consumption and enhancing indoor thermal environment is to integrate phase change material (PCM) into a building envelope. PCMs were capable to absorb and release massive latent heat during phase transition in a narrow temperature range and function as thermal mass. Building envelopes integrated with PCMs have been extensively studied in different countries including China, European countries and the US[2-4].

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However, very few studies reported the application of PCMs to residential building envelopes in subtropical climates. The performance of building envelopes incorporating PCMs in bedrooms in the subtropical climate could be very different. First, the limited diurnal temperature variation implies high potential of the incomplete melting–freezing cycle of PCMs. It was pointed out the diurnal ambient temperature variation should exceed 10 ^{o}C to ensure effective thermal storage of PCM as passive cooling strategy [5]. Second, the bedroom has a different operating schedule of A/C unit, maybe being from 11:00pm to 7:00 am. The heat energy released into the bedroom at nighttime will increase the cooling energy of the A/C at night [6]. Therefore, with the year-round subtropical climate, the adoption of PCMs for bedrooms in Hong Kong faced unique challenges.

Therefore, in this paper, a simulation study on analyzing the impacts of building envelopes integrated with PCMs on the nighttime cooling load reduction in a bedroom in sub-tropics is reported. A west-facing bedroom in a high-rise residential block in Hong Kong was used in a previous related study [6]. The adoption of PCMs to the west-facing external wall for the west-facing bedroom, was also used as a platform to carry out the simulation study. Firstly, the detailed description of the numerical method and the model development are presented. This is followed by influences of the phase change temperatures, the shapes of enthalpy curve, and the thicknesses of PCMs on the resultant nighttime cooling load reduction.

2. NUMERICAL METHOD AND MODEL DEVELOPMENT

2.1 Numerical Method

The well-known building energy simulation program, EnergyPlus [7], was adopted in the simulation study. The one-dimensional conduction finite difference (CondFD) solution is employed as the heat balance algorithm in EnergyPlus to simulate the thermal performance of PCMs. Version 9.0.1 of EnergyPlus with the CondFD algorithm solved by a fully implicit finite difference scheme, coupled with an enthalpy-temperature function to account for phase change energy was used in this study. The specific heat capacity of PCMs is updated in each iteration according to the following equation:

$$C_p = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \quad (1)$$

A few guidelines for using the PCM module in EnergyPlus are recommended by Tabares-Velasco et al. [8]:

- ➢ The time step should be equal to or less than three minutes. In this study, the time step is at one minute;
- ➢ Accuracy issues may arise when modeling PCMs with strong hysteresis;
- ➢ Smaller nodal space (1/3 of the default value in EnergyPlus) should be used for accurate hourly results.

2.2 Model Development

2.2.1 The benchmark study

In the previous related study [6], the west-facing bedroom in a hypothetic high-rise model residential building, as shown in Fig. 1, was used as a study platform. The detail settings, including the construction, and the physical properties of the materials used in envelope components, the schedules and air conditioning settings were referred to the related paper [6]. Moreover, the specific heat capacity, density and thermal conductivity of the PCM are 2150 (J·Kg^{-1} K^{-1}), 814 (Kg· m^{-3}) and 0.35 /0.15 (W·K^{-1} m^{-1}) , respectively

Simulation period of the summer design day (21th July) was carried out to study the underlying mechanisms of applying the PCMs in the building envelope for nighttime cooling load reduction in a bedroom in Hong Kong. Under the outdoor cooling design conditions, outdoor design dry-bulb (DB) temperature, wet-bulb (WB) temperature and the daily temperature variation range are 33.2℃, 26.1℃ and 4.5℃, respectively [9].

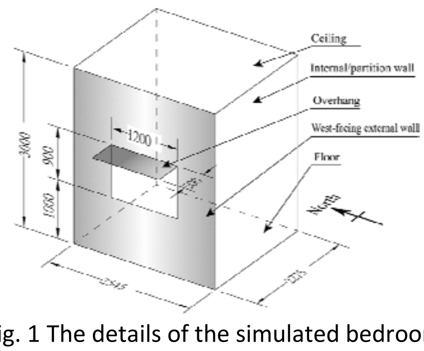

Fig. 1 The details of the simulated bedroom

From the previous study [6], the results showed that the nighttime cooling load from building envelopes took the lion's share of the total nighttime cooling load

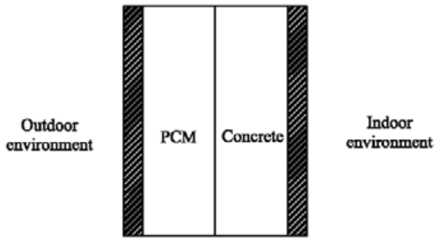

Fig. 2 Construction of the west-facing external wall with

in every hour. The bedroom model without the PCM layer was simulated as the baseline case (Case 1).

The concrete layer with a thickness of 50 mm of the west-facing external wall was placed replacing with the PCM layer with a thickness of 50 mm (Case 2). The construction of the west-facing external wall is shown in Fig.2. In addition, an idealized PCM (Shape A) with a phase change temperature of 30℃, close to the average diurnal temperature in Hong Kong, was used for the benchmark study (Case 2). Fig. 3 illustrates the user defined specific enthalpy–temperature curve of the idealized PCM. A sharp increase of enthalpy over a very small temperature range of 0.1℃ (30–30.1℃) was adopted to describe the instant and complete phase change of the idealized PCM once the phase change temperature is reached. The thermal conductivities of the solid and the liquid PCM are 0.35 and 0.15 W/m K, respectively [10]. The thermal conductivity of the PCM in the mushy state, i.e. mixtures of solid and liquid phases, was determined through linear interpolation.

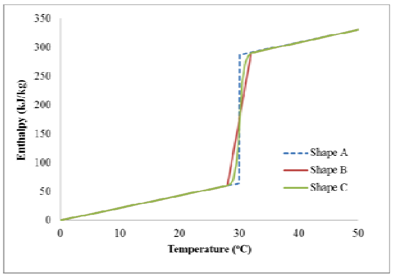

Fig.3 PCM Three shapes of enthalpy-temperature curve

2.2.2 Parametric studies

Parametric studies were carried out to investigate the factors that affect the performance of the west-facing external wall integrated with PCMs for nighttime cooling load reduction in a bedroom in subtropics. The same bedroom model, as detailed in Section 2.2.1 and simulation period on 21th July were adopted. The related factors include the phase change temperature, the shapes of enthalpy–temperature curve and the thickness of PCM. All the cases were grouped as follows:

(1) Cases 2-9: idealized PCM (Shape A) in the benchmark study with different phase change temperatures between 27 °C and 34 °C with a step of 1°C were adopted to study the influence of phase change temperatures on the thermal performance of PCMs on the nighttime cooling load in a bedroom.

(2) Cases 10-11: Case 10 with Shape B, Case 11 with shape C and Case 1 with Shape A were to investigate the effects of the shapes of the enthalpy–temperature curve of PCMs on the nighttime cooling load in a bedroom.

(3) Cases 12-17: the thickness of PCMs integrated into building envelopes was another critical factor that influences the cooling load. Therefore, the idealized PCMs with the thickness ranging from 20 mm to 80 mm with as step of 10mm (Case 2, Cases 12-17) placed on the west-facing external wall were studied.

In order to carry out the investigations, the index RR, defined by:

$$\mathrm{RR} = \frac{SUM_{case1} - SUM_{casej}}{SUM_{case1}} \times 100\% \qquad (2)$$

3. RESULTS AND DISCUSSIONS

3.1 Benchmark study

The one-day (21h July) results of the nighttime hourly cooling load under Case 1 ad Case 2 are shown in Fig. 4. It can be seen that at most hours, the nighttime hourly cooling load under Case 2 were smaller than that under Case1, especially between 22:00 to 24:00. The total cooling load reduction, RR, is 16.6%, which means replacing the concrete with PCM reduced the total cooing load of the bedroom on the design day.

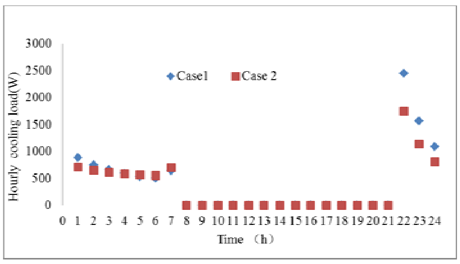

Fig.4 The nighttime hourly cooling loads under Case 1 and Case 2

Fig. 5 shows the inside temperatures of the west-facing external wall under Case 1 and Case 2. It is obvious that replacing the concrete with PCM reduced the inside temperature of the west-facing external wall, which will improve the thermal comfort in the bedroom. This is attributed to the "buffering effect" and latent heat storage of the PCMs, i.e. heat is absorbed by the PCMs during the day, resulting in the larger decrease in surface temperature between 14:00-23:00. The heat was released slowly during the night when ambient air cools down. Therefore, even after the A/C is turned on, the inside temperature of the west-facing external wall under Case 2 were smaller than that under Case 1.

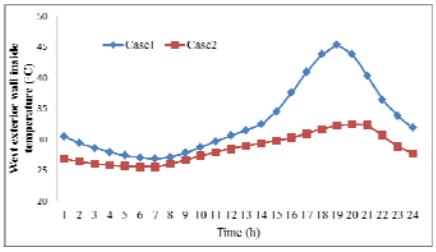

Fig.5 The inside temperatures of the west-facing external wall under Case 1 and Case 2

3.2 Parametric studies

3.2.1 Influence of phase change temperatures

Fig.6 the relationship between the values of RR and the phase change temperatures (Case 2 to Case 9). It can be seen that the value of *RR* increases by increasing the phase change temperature and peaks at 31 °C. After that, it decreases with the continuous increase of the phase change temperature. The least total cooling load reduction was observed when the PCM with phase change temperature of 34 °C.

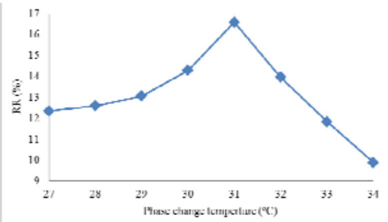

Fig.6 The relationship between the values of RR and the phase change temperatures

The PCM with a phase change temperature below 26 °C, cannot solidify and stays in a liquid state for a whole day. As a result, the latent heat during phase change was not utilized to reduce the envelope heat gains. When the phase change temperature increased, the discharged heat from the outer layer was easier to be removed by the cool outdoor environment before 21:00. However, when the A/C is turned on at 21:00, the discharged heat from the inner layer was easier to be removed by the cool indoor environment. Partial PCM layer was expected to go through the phase change if the phase change temperature of the PCM is between 26 and 30 °C. Therefore, a higher phase change temperature enables larger portions of the PCMs to go through a melting–freezing cycle and enhances the efficiency of the PCM layer. The whole PCM layer can go through the full melting–freezing cycle and the latent heat of the PCM is fully employed until the phase change temperature of 30°C or above is adopted. As a result, RR increases with the increasing phase change temperature from 27 to 30°C as shown in Fig. 6.

The above discussion suggests that when PCMs are placed on the external walls of the bedroom, a proper selection of PCMs with a suitable phase change temperature for nighttime cooling load reduction in the subtropics is critical.

3.2.2 Influence of the PCM thickness

Fig. 7 shows the effects of the shapes of the enthalpy–temperature curve on the values of RR. As can be seen, the values of RR under Shape B and Shape C were larger than that under Shape A. This is attributed to wider phase change temperature range (4°C) under Shape B and Shape C, which improved the adaptive of PCMs to ambient climate changes.

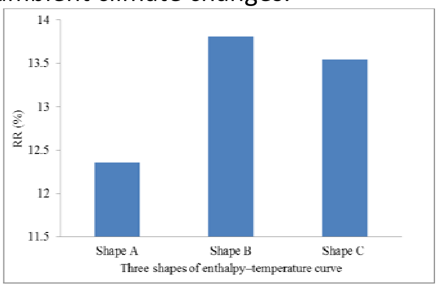

Fig.7 The values of RR under three different shapes of enthalpy–temperature curve

Conclusively, the shapes of the enthalpy–temperature curve influenced the energy performance of the PCM. The larger phase change temperature range improved the adaptivity of the PCMs to the temperature variations, but may compromise the optimum energy performance that the PCM can achieve.

3.2.3 Influence of the PCM thickness

Fig. 8 shows the nighttime cooling load reduction rate with the thickness of the PCM. As can be seen, the nighttime cooling load reduction rate increased as more PCMs were used because increasing amounts of incoming heat can be absorbed by the PCM layer. However, when the thickness is more than 70 mm, increasing the thickness will decrease the cooling load reduction rate. After the A/C is turned on, the indoor environment is constant at 23°C. Part of the heat storage in PCM will release into the outdoor environment, and part of that into indoor environment. Therefore, with the increase in the thickness of the PCM, the portion of the heat released into indoor environment will be increased, resulting in the increase in the nighttime cooling load.

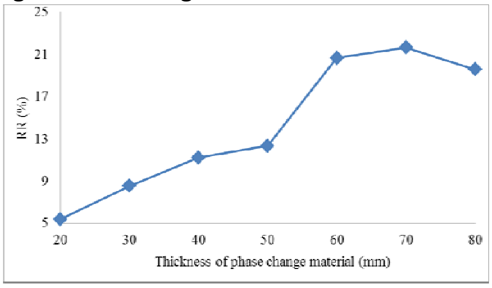

Fig.8 The values of RR with the thickness of the PCM

The above discussion suggests that when PCMs are placed on the external walls of the bedroom, an optimal thickness of PCMs should be selected to reduce the nighttime cooling load.

4. CONCLUSIONS

In this paper, a simulation study on analyzing the impacts of building envelopes integrated with phase change materials on the nighttime cooling load reduction in a bedroom in sub-tropics is reported.

The efficacy of incorporating PCMs into west-facing external wall for nighttime cooling load reduction in a bedroom in subtropics was investigated in the benchmark study where a 50 mm PCM layer with a phase change temperature of 30°C was added to the west-facing external wall in a bedroom. Results showed that PCM can effectively reduce the nighttime cooling load and improve the thermal comfort in sleeping environments.

For further investigating the application of PCMs in bedrooms in subtropics, parametric studies were carried out to reveal important factors and underlying mechanisms that governed the performance of building envelopes integrated with PCMs for nighttime cooling load reduction in bedrooms in subtropics. Results showed that proper selection of PCM with suitable phase change temperatures, shapes of enthalpy–temperature curve and the thickness of PCM were critical to reduce nighttime cooling load reduction in bedrooms in subtropics.

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