

Climate applicability study of building envelopes containing phase change materials

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Abstract

Building envelopes incorporating phase change materials (PCMs) can contribute to reducing the energy consumption of buildings and enhance indoor thermal environment comfort. In this study, two building models were developed in EnergyPlus to explore the applicability of using PCMs in different climate zones. Six significantly different cities from five climate zones in China have been investigated. The simulation results reflected that for climates with small fluctuation weather conditions, PCMs with appreciate transition temperature T_R can contribute to positive influences on energy saving. For example, in Guangzhou, PCMs with T_R of near 26°C and 22°C contribute to the highest energy saving rates of 12.0% and 12.4%, for external and internal PCMs addition. And the ideal transition temperature for each climates is subjected to its own outdoor comprehensive temperatures and its indoor set temperature, for external and internal PCMs addition, respectively. For other climates with the big fluctuation weather condition, PCMs' latent heat function to the energy savings is not significant.

Keywords: Phase change material; applicability study; building envelopes; different climates.

1 Introduction

In recent decades, the energy demand of our society is continuously increasing, especially from the building sector [1]. As a major energy consuming sector (about 40% of world total primary energy [2]), buildings are always required to provide comfortable indoor environment for the occupants, and this has led to great challenges to the application of energy [3]. Therefore, energy saving of building and improving the efficiency of their energy systems become necessary for sustainable development. For example, nearly net-zero energy buildings are a popular concept for future building development, and this can be achieved by different energy saving methods [4], such as passive design methods, system efficiency improvement and renewable energy usage. Among these methods, passive design is considered as an effective one [5].

In real applications, renovation design of building envelop plays an important role in passive design. Existing literatures have given two main types of energy efficient wall systems, namely, high-thermal insulation system [6-9] and thermal storage system, e.g. using phase change materials (PCMs) [10-15].

The use of thermal energy storage for building envelops has received great attention in recent years [16]. Numerous studies have explored the use of PCMs in building envelopes to enhance the indoor thermal environment and energy performance of buildings. In this research area, firstly, some researchers focused on the development of PCM-based technologies [17-22]. For example, Wang et al. [17] developed a new

method for preparing PCMs, through investigating the effect of various methods on both the structures and thermal. Sari [19] and Mankel [20] prepared a form-stable PCMs/cement composite after using characteristic techniques. Secondly, some other researchers studied the incorporation methods of PCMs into building envelopes [23-26]. For instance, Boussaba et al. [23] prepared a composite bio-based PCM with low-cost and eco-friendly for use in building envelopes. Thirdly, some were also researchers doing experimental research on potential factors of energy saving effect of PCMs [26-28]. For example, Berardi [28] found that PCMs with different transition temperatures is effective in climates with large yearly temperature fluctuations. Fourthly, there were some researchers analysing the energy storage mechanism of PCMs [29-31]. For example, Zhou et al. [31] study the heat-transfer mechanism of wallboards containing PCMs, and proposed that it would be affected by the melting temperature, thickness and so on. Finally, the heat discharge of PCMs is also an important part for its comprehensive utilization in buildings. For example, the thermal storage can be discharged with natural night ventilation, daily temperature fluctuation, or active systems [32-33].

Actually, there are numerous studies have explored the use of PCMs in building envelopes to enhance the indoor thermal environment and energy performance. However, there are few studies systematically exploring climate applicability of PCMs in building envelopes, especially in China. So it is needed to investigate the PCMs' heat mechanism firstly, then indicate the selection reference of PCMs, finally give the optimum phase transition temperature range for some adaptive climates.

This study, therefore, was conducted and two building models (a simple cabin model and a more complicated model) were developed to discuss the PCMs' latent heat mechanism and give optimum transition temperature ranges for different climatic conditions, respectively.

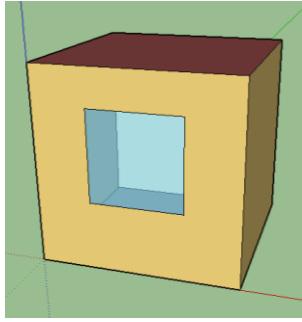
2 Methodology

In this study, EnergyPlus with the CondFD algorithm has been used to predict the building's energy performance, due to its existing rigorous validation and verification studies for PCMs [34-37]. Here, the time discretization for calculation is 3min.

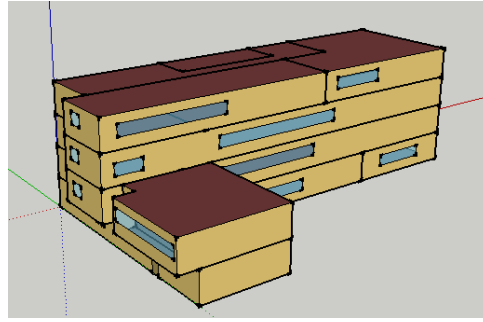
2.1 Model descriptions

Two simulation models, including a simple cabin model (Model-S) and a more complicated building model (Model-C), were developed as shown in Figure 1a and 1b, respectively. The Model-S was developed here to reveal the basic heat storage mechanism of PCMs when incorporated into building. The Model-C was developed according to a real building located in Beijing, as shown in Figure 1c, to justify the implementation of the main findings obtained from the simple model, and gave optimum transition temperature ranges for each climate.

In this study, the simple cabin model has dimensions of 2.6m×2.6m×2.6m, with one south-facing window (1.5m×1.5m). Secondly, to do applicability research of PCMs in the building envelope in different climates, a more complicated building model with 3956m² was further applied, and its interior load and HAVC system schedule will be considered.



(a) A simple cabin model



(b) A more complicated building model



(c) A real building

Figure1: Simulation models used in this study

Table 1: Basic thermo-physical properties of construction materials

Materials	Thickness (mm)	Thermal conductivity (W/(m·K))	Density (kg/m ³)	Specific heat (J/(kg·K))	Latent heat of fusion (kJ/Kg)
Concrete	150	1.442	2400	750	/
Solid PCMs	10	0.2	810	2100	/
Brick	100	0.89	1920	790	/
Reinforced Concrete	200	1.9	2240	900	/
Gypsum board	19	0.16	800	1090	/
PCMs	10/50	0.2	810	2100	134

Table 1 has listed some basic thermo-physical properties for the construction materials used in this study. For Model-S, three different material compositions were used, namely, 1) a benchmark model (Model-S-1) with 150mm concrete floor, walls and roof; 2) a model (Model-S-2) with a 10mm PCM layer added to Model S-1; and 3)

a model (Model-S-3) without PCMs but with the same U-values as Model S-2. In Model-S-2, the PCM layer was attached to the inner and outer surface of the building envelope separately to give indications on its impact.

Here, in order to investigate the ideal parameters of PCMs, the applied PCMs is a hypothetical material. In addition, to investigate PCMs' latent heat storage function on building energy use, "Solid PCMs" was carried out to keep Model-S-3 have the same U-values as Model-S-2. As shown in Table.1, basic thermo-physical properties in both "Solid PCMs" and PCMs were the same, while "Solid PCM" had no latent heat of fusion.

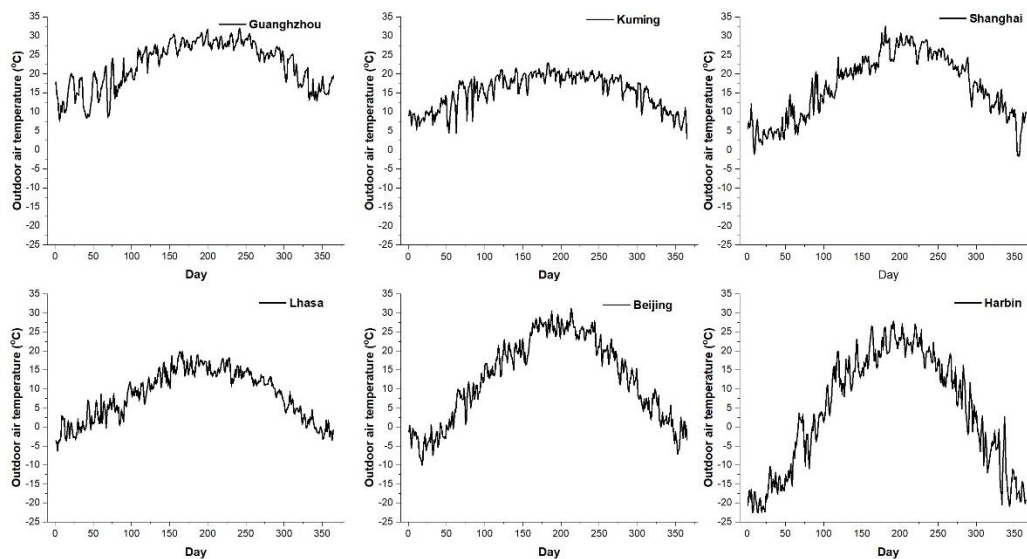
For Model-C, two kinds of construction compositions were applied. For Model-C-1, all exterior envelopes were made of base constructions, including three layers: a 100 mm brick, a 200 mm reinforced concrete and a 19 mm gypsum board from outside to inside. For Model-C-2, a 50mm PCM layer was placed on the exterior surfaces of all vertical walls and roof.

2.2 Indoor and outdoor meteorological parameters

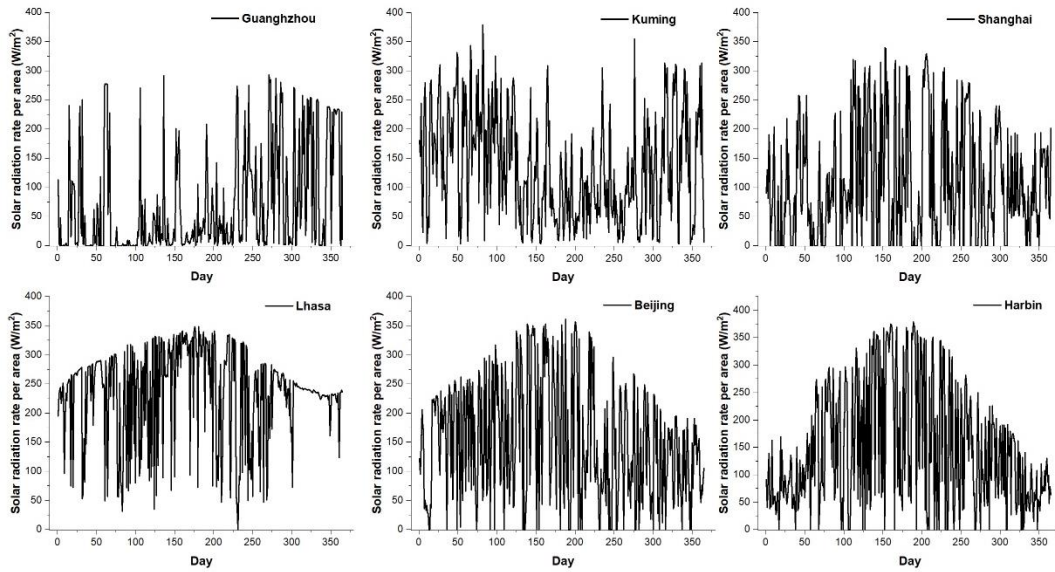
For the simulation in Model-S, Guangzhou, as a represented city in summer hot & winter warm zone, was used as a weather file. For Model-C, six weather files for Guangzhou, Kunming, Shanghai, Lhasa, Beijing, and Harbin were applied as the input files, which represented respectively different kinds of weather zones, including summer hot & winter warm zone with cooling supply needs, warm zone, summer hot & winter warm cold with cooling supply needs, cold zone with and without high solar radiation, frozen zone with heating supply needs. Here, all wall and roof surfaces were

set to expose to the outdoor environment.

Figure 2 indicated that annual mean outdoor temperature and solar radiation intensity are 22.3 °C, 15.3 °C, 16.7 °C, 8.3 °C, 12.6 °C, 4.1 °C, 67.4 W/m², and 133.5 W/m², 107.0 W/m², 232.4 W/m², 151.2 W/m², 148.0W/m² for Guangzhou, Kunming, Shanghai, Lhasa, Beijing, and Harbin, respectively. Figure 2 also indicated that for both Guangzhou and Kunming, the fluctuations of mean outdoor temperature are weak, which will be good for the application of the PCMs due to the limit of PCMs' transition temperature (T_R). In addition, it can also be found that, for Lhasa, the solar radiation intensity in winter is high, leading to small fluctuation in its outdoor comprehensive air temperature, which will also result in a good function to its application of the PCMs.



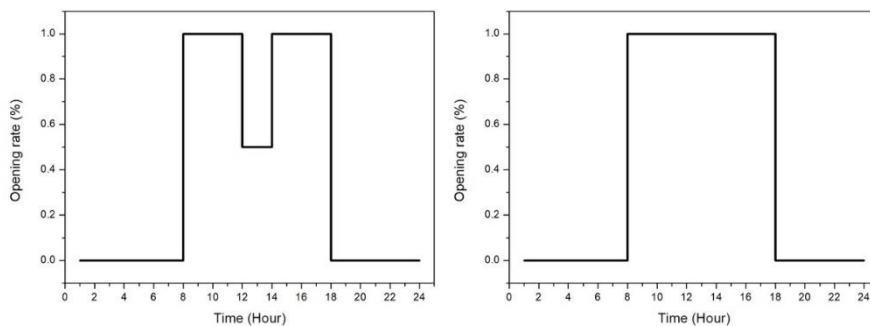
(a) Outdoor air temperature



(b) Solar radiation rate per area

Figure 2: Annual outdoor meteorological parameters of six weather zones

To run both simulation models, the ideal load HVAC system was applied, which could keep the indoor air temperature at between 18°C and 26°C. In addition, for Model-C, to give a more accurate predictive analysis of PCMs applicability, interior heat source, such as people, lights, electric equipment, was considered. Figure 3 gave the schedule of interior heat source and energy supply system.



(a) Interior heat source

(b) Energy supply system

Figure 3: Schedules of interior heat source and energy supply system

2.3 Evaluation indexes

For Model-S, to reveal heat storage mechanism of PCMs, daily and hourly heating or cooling loads (L_{D-heat} , L_{D-cool} , L_{H-heat} , and L_{H-cool}) on special days and envelope surface temperatures (T_{in} and T_{out}) were applied as evaluation indexes. For Model-C, annual mean heating and cooling load (L_A) was used as an index. In addition, in the Model-C, energy saving rate ($\eta/\%$) was applied to evaluate the energy saving performance of PCMs, which was calculated by Equation (1), where L_{A-1} and L_{A-2} are annual heating and cooling load per square meter caused by the Model-C-1 and Model-C-2 without and with PCMs, respectively.

$$\eta = \frac{L_{A-2} - L_{A-1}}{L_{A-1}} \quad (1)$$

3 Results and discussion

3.1 Heat transfer mechanism of PCMs

In this section, the simulation studies were conducted in Model-S in Guangzhou and PCMs was separately integrated on the exterior and interior surfaces of building envelopes. Then daily and hourly heating or cooling loads (L_{D-heat} , L_{D-cool} , L_{H-heat} , and L_{H-cool}) on special days and the corresponding envelop surface temperatures were analyzed.

3.1.1 Daily Load study

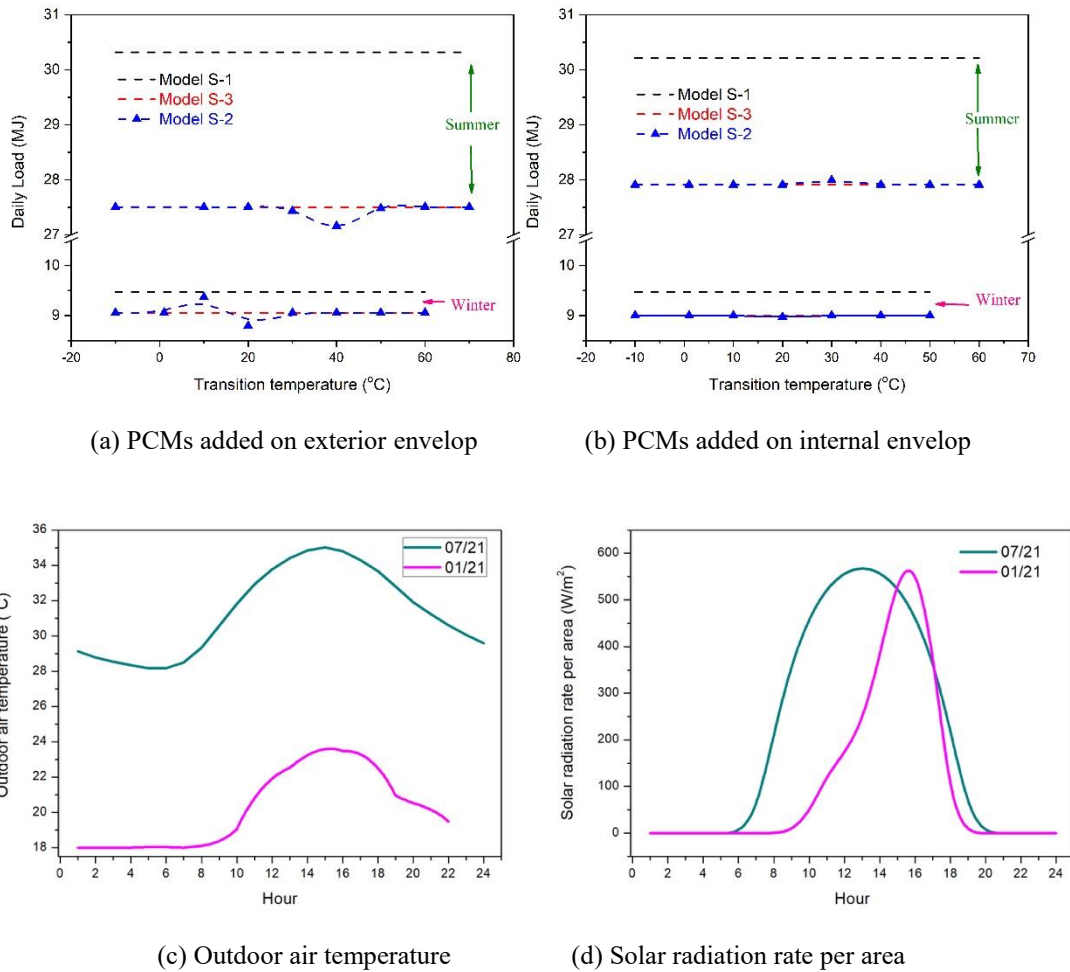


Figure 4: Daily loads and outdoor specially day weather condition for a simplified cabin model located in Guangzhou

Figure 4 indicates the daily loads for Model-S located in Guangzhou and the weather condition in special day. It shows that there are three lines in each picture, which represents loads from three models (Black dotted line for Model-S-1, the normal building with only concrete envelope; Blue dotted line for Model-S-2, the building with PCMs addition envelope; Red dotted line for Model-S-3, the building with the same U-values as Model-S-2).

Firstly, Figure 4 shows that there are of four groups' daily loads (L_D), according to PCMs application position (external and internal of building envelope) and weather

condition (summer and winter day). For all of four groups, the L_D of Model-S-3 (Red dotted line) is always low than that of Model-S-1 (Black dotted line), which is due to an increase of thermal resistance of building envelopes incorporated by the “Solid PCMs” (i.e., the function of sensible heat of PCMs).

Secondly, compared with Model-S-3, L_D of Model-S-2 (Blue dotted line) shows different trends in these four groups, and that is to say, latent heat of PCMs play a different role in building energy saving, subjects to its application position and weather condition. Specifically, Figure 4a shows L_D curves for models with PCMs added on exterior envelope. In summer, comparing to L_D in Model-S-3 (Red dotted line), L_D in Model-S-2 (Blue dotted line) is further reduced in an appropriate range of PCMs' transition temperature (T_R) of 30~50°C. In winter, there are two trends. For high T_R range of about 15~30°C, L_D is also reduced; while for low T_R range of about 10~15°C, L_D increases instead. Then Figure 4b shows L_D curves for models with PCMs added on internal envelope. Different from the trends in Figure 4a, Figure 4b indicates that in summer L_D in Model-S-2 is slightly raised in a range of T_R of near 30°C, while in winter for a T_R range of near 20°C, L_D decreases a little.

3.1.2 Hourly Load study

In order to further explain the heating mechanism of PCMs attached different surface of building envelopes, hourly load (L_H), envelope surface temperatures (T_{in} and T_{out}), and hourly heat storage quality (Q_S) for Model-S will be discussed as follow. Here, as shown in Figure 4, only some PCMs with a specific transition temperature range will contribute to the building energy use change by latent function, so PCMs with specific

T_R would be used to explain the trend in daily load curve.

3.1.2.1 PCMs attached to the external surface

Here, according to the results in above section (Figure 4a), PCMs with specific T_R is used for explaining daily load curve trend, i.e. T_R of 36°C for summer, and T_R of 11°C and 18°C for winter curve, respectively.

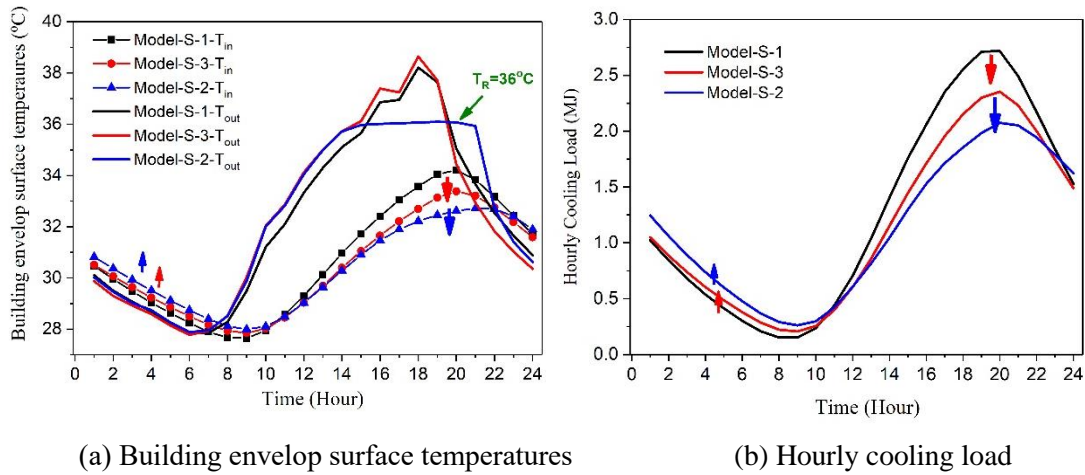


Figure 5: Hourly cooling load and building envelop surface temperatures on summer special day for Model-S with PCMs attached on external surface

First, PCMs with T_R of 36°C is used for explaining the summer curve trend in Figure 4a. As shown in Figure 5a, for Model-S-3, the building envelope internal surface temperature (T_{in} -S-3) is reduced in the daytime between 12 and 22 o'clock, compared with T_{in} -S-1; while in the early morning before 10 o'clock T_{in} -S-3 is increased a little. Then it can be found in Figure 5b, the hourly cooling load of Model-S-3 (L_H -S-3) is reduced and increased in the corresponding time period, respectively. This is caused by the envelope's thermal resistance increase by adding "Solid PCMs" (i.e. the function of the sensible heat of PCMs). Thus, as mentioned in Figure 4a, daily cooling loads (L_{D-cool}) of Model-S-3 (Red dotted line) is reduced compared with the L_D of Model-S-1

(Black dotted line).

In addition, Figure 5a indicates that, for Model-S-2, envelop external surface temperature ($T_{out-S-2}$) is reduced in the daytime compared with $T_{out-S-3}$, leading to further reduction of T_{in-S-2} . And it is interesting to note that there is a platform area on the $T_{out-S-2}$ curve of 36°C, which is the same as the T_R value of applied PCMs ($T_R = 36^\circ\text{C}$). This is attributed to that, in Model-S-2, PCMs undergoes a phase change at this time, and the $T_{out-S-2}$ is kept at 36°C in this period, thus reducing the heat transfer from the outdoor to the indoor. Hence, as showed in Figure 5a| and b, the corresponding T_{in} and L_{H-cool} of Model-S-2 in this time period are further decreased compared with Model-S-3, that is to say, that PCMs further provides thermal insulation during the day. While, like the trends in Model-S-3, in the early morning T_{in} and L_{H-cool} in Model-S-2 is only slightly reduced and increased in this corresponding time period, respectively. Therefore, as mentioned in Figure 4a, daily loads (L_D) of Model-S-2 (Blue solid line) is further reduced compared with the L_D of Model-S-3 (Red dotted line).

To further explain the latent heat function of PCMs, hourly heat storage quality (Q_S) for this case is shown in Figure 6. It can be seen that in the daytime Q_S for Model-S-3 and Model-S-2 is positive, which means that these two building envelopes with “Solid PCMs and PCMs absorb outdoor heat, then prevent heat into the building, thus reduce its hourly cooling load. Moreover, Figure 6 shows that from 12 o’clock, Q_S for Model-S-2 begins to higher than that for Model-S-3, which is caused by the phase change of PCMs, i.e. heat absorb by melting. Due to the melting of PCMs, there is more heat storing in this envelope, then more positive Q_S is got. Thus heat entering the

building is further reduced, resulting in a lower T_{in-S-2} , which reduces the building's cooling load $L_{H-cool-S-2}$ (Figure 5). While, in the evening and early morning, the PCMs solidification let more heat releasing from this envelope, then more negative Q_S is generated. Thus some heat is released into the outdoor air, and some enter the interior of the building, resulting in a little higher T_{in-S-2} and a slightly higher $L_{H-cool-S-2}$ (Figure 5). Therefore, the whole day cooling load L_D of Model-S-2 by adding PCMs with T_R of 36°C is reduced (Figure 4).

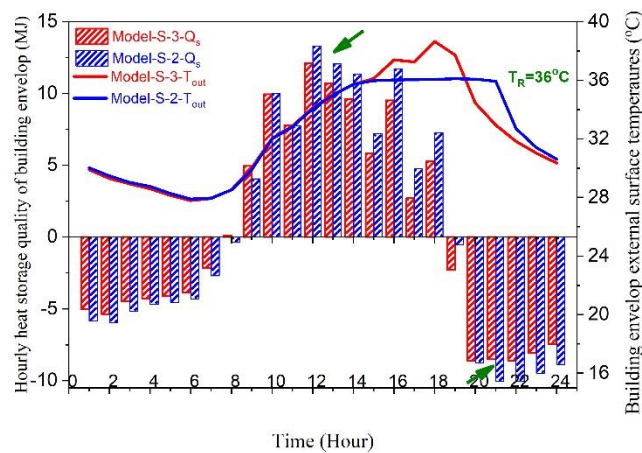


Figure 6: Hourly heat storage quality of on summer special day for Model-S with PCMs attached on external surface

Secondly, PCMs with T_R of 11°C and 18°C are applied for explaining the winter curve trends in Figure 4a. As shown in Figure 7a, for Model-S-2, the phase change of PCMs with T_R of 11°C and 18°C occur in early morning and daytime, respectively. These phase changes make their exterior surface temperatures T_{out} keep consistent with their T_R of 11°C and 18°C, respectively. For the model with PCMs of low T_R of 11°C (Blue curves), the lower T_{out} in the early morning leads to lower interior surface temperature T_{in} (Figure 7b), then resulting in higher hourly heating load L_{H-heat} shown in Figure 7c. As a result, for Model-S-2 with low T_R PCMs, a high daily heating load

L_{D-heat} will be needed, shown in winter curve in Figure 4a. For the model with PCMs of high T_R of 18°C (Green curves), in the daytime, the lower T_{out} also results in slightly higher hourly heating load L_{H-heat} . However, in the early morning, due to the heat release from PCMs, the higher T_{out} is got in this period (Figure 7a), then there is a higher T_{in} (Figure 7b), thus much lower L_{H-heat} is needed (Figure 7c). Hence, daily heating load L_{D-heat} in Model-S-2 with high T_R PCMs is increased as shown in winter curve in Figure 4a.

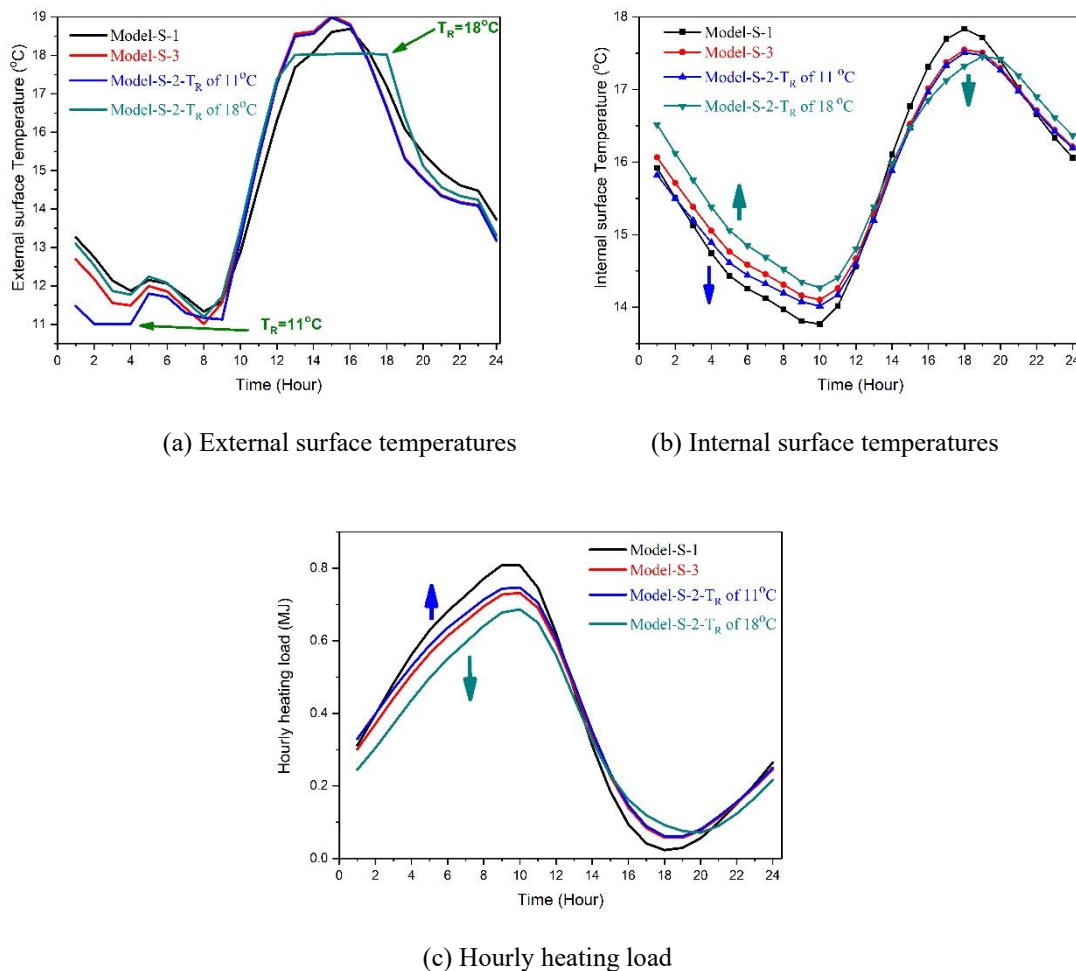


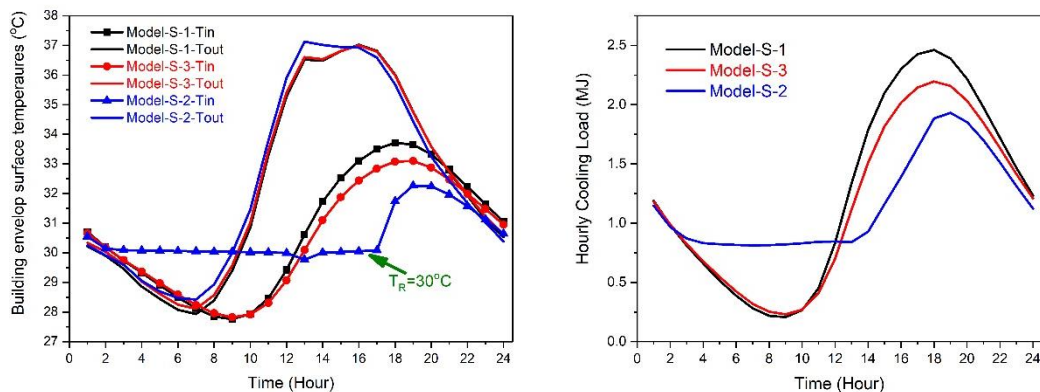
Figure 7: Hourly heating load and building envelop surface temperatures on winter special day for Model-S with PCMs attached on external surface

In conclusion, the attaching of PCM layer to the external envelope surface will

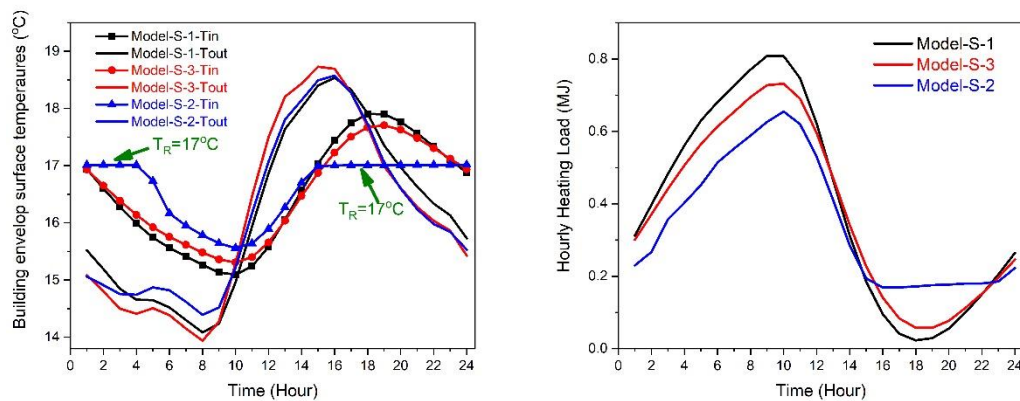
modulate the boundary conditions of the building envelope (envelope external surface temperature) to impact the heat exchanges between indoors and outdoors, resulting in the change of building energy performance. That is to say that when the PCM layer is attached to the external envelope surface, it plays as a thermal insulation material to protect buildings from the outside environment, which is due to its strong absorption and exothermic effect due to its latent heat function.

3.1.2.2 PCMs attached to the internal surface

Here, PCMs with specific T_R of 30°C , and T_R of 17°C were applied for explaining daily load curve trend for summer and winter, respectively.



(a) Building surface temperatures on summer special day (b) Hourly cooling load on summer special day



(c) Building surface temperatures on winter special day (d) Hourly heating load on winter special day

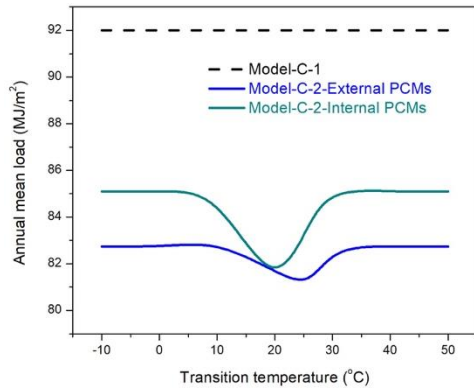
Figure 8: Hourly cooling and heating load and building envelope surface temperatures on special days for Model-S with PCMs attached on internal surface

As shown in Figure 8a and c, for Model-S-2, the phase changes of PCMs with T_R of 30°C and 17°C make their interior surface temperatures T_{in} keep consistent with the T_R of 30°C and 17°C, respectively. For both models with PCMs of T_R of 30°C and 17°C, due to the changes of T_{in} , the corresponding hourly loads L_H are got. In summer, in the early morning, higher interior surface temperature T_{in} (Figure 8b) results in higher hourly cooling load L_{H-cool} ; while in the daytime low T_{in} leads to low L_{H-cool} . As a result, for Model-S with PCMs on the internal envelope, attaching PCMs make a slightly negative role in summer, shown in summer curve in Figure 4b. In addition, in winter, the phenomenon is different. Specifically, in the early morning, heat release by PCMs leads to a higher T_{in} (Figure 8c), resulting in lower L_{H-cool} ; while in the daytime heat storage by PCMs reduces T_{in} , leading to higher L_{H-cool} . As a result, for Model-S with PCMs on the internal envelope, attaching PCMs make a slightly positive role in winter (Figure 4b). Moreover, it can be concluded that, the PCMs' function doesn't be affected by the outdoor environment, which is only subjected to the indoor environment of buildings with PCMs attaching.

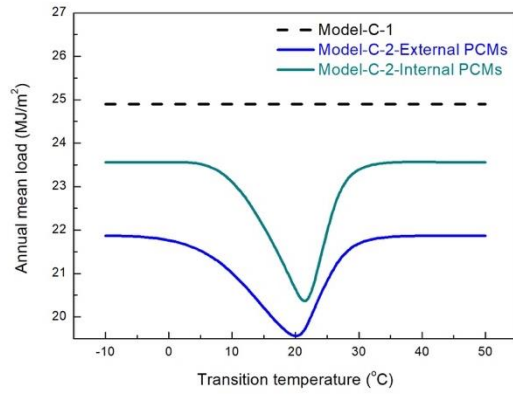
In conclusion, attaching PCMs into internal building envelope directly affect the interior temperatures of the building envelopes, leading to the change of building energy performance. That is to say that, when the PCM layer is attached to the internal envelope surface, it plays as a system with the ability of energy storage and supply, to meet parts of energy demand of building indoor environment.

3.2 Applicability research of PCMs

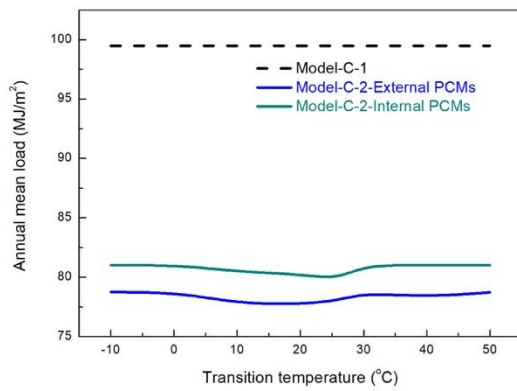
In this part, the PCMs applicability research was carried out by using Model-C, and for each climate, the optimal transition temperature range and energy saving rate would be given.



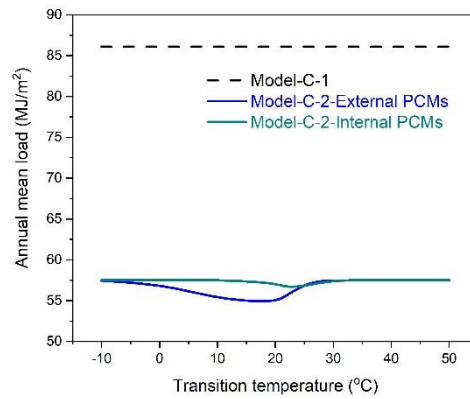
(a)Guangzhou



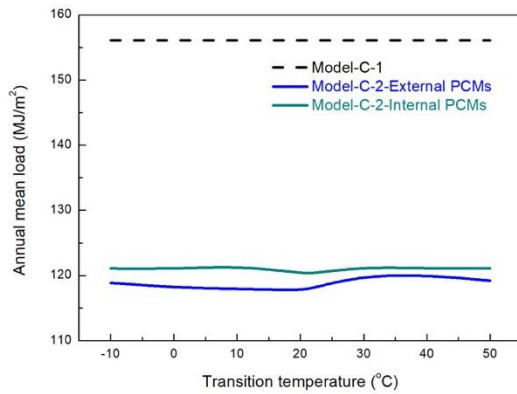
(b)Kunmin



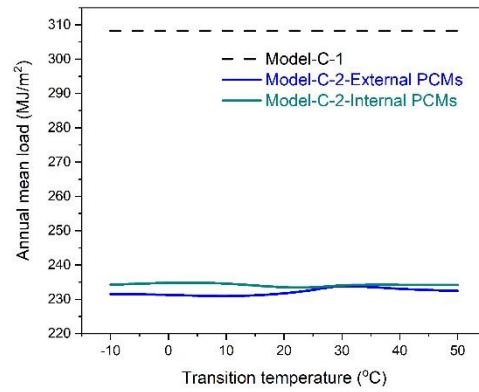
(c)Shanghai



(d)Lhasa



(e) Beijing



(f) Harbin

Figure 9: Annual mean load for Model-C with and without PCMs addition in different climates

Figure 9 indicates annual mean load for Model-C in different climates. First, for Guangzhou and Kunming, PCMs addition has a big effect on energy use as its latent heat function, which is due to their weather conditions are peaceful and not too fluctuating (as analyzed in Figure 2). Specifically, for buildings with external PCMs addition, PCMs with T_R of near 26 °C and 20 °C can contribute to a positive influence on energy saving with corresponding energy saving rates of 12.0% and 22.8%, for Guangzhou and Kunming respectively. It is interesting to found that, the ideal T_R is basically consistent with their outdoor comprehensive temperature. Moreover, for both climates, in buildings with internal PCMs addition, PCMs with T_R ranges of about 10~30 °C can contribute to a positive influence on energy saving, and the both ideal T_R for energy saving occur at about 22 °C with corresponding energy saving rates of 12.4% and 20.1%, which is subjected to its indoor set temperature.

In addition, for other climates, for both buildings no matter with internal or external PCMs addition, PCMs addition can decrease the energy use in buildings, while the contribution from PCMs' latent heat function to the energy savings is not significant.

This is attributed to that the weather conditions in these climates are of big fluctuation, which is bad to play the latent heat function of the PCMs. Especially for Harbin, it should be noted that there is particularly high annual mean load, which is due to the extremely harsh outdoor low temperature environment in winter in Harbin. Therefore, for Harbin, it can be further found that, attaching PCMs on the building envelope is not applicable. However, for Lhasa, attaching PCMs with a transition temperature range of around 16°C on the external building envelope results in a certain positive effect on energy saving, which is because Lhasa has a small fluctuation in its outdoor comprehensive air temperature due to its high solar radiation in winter.

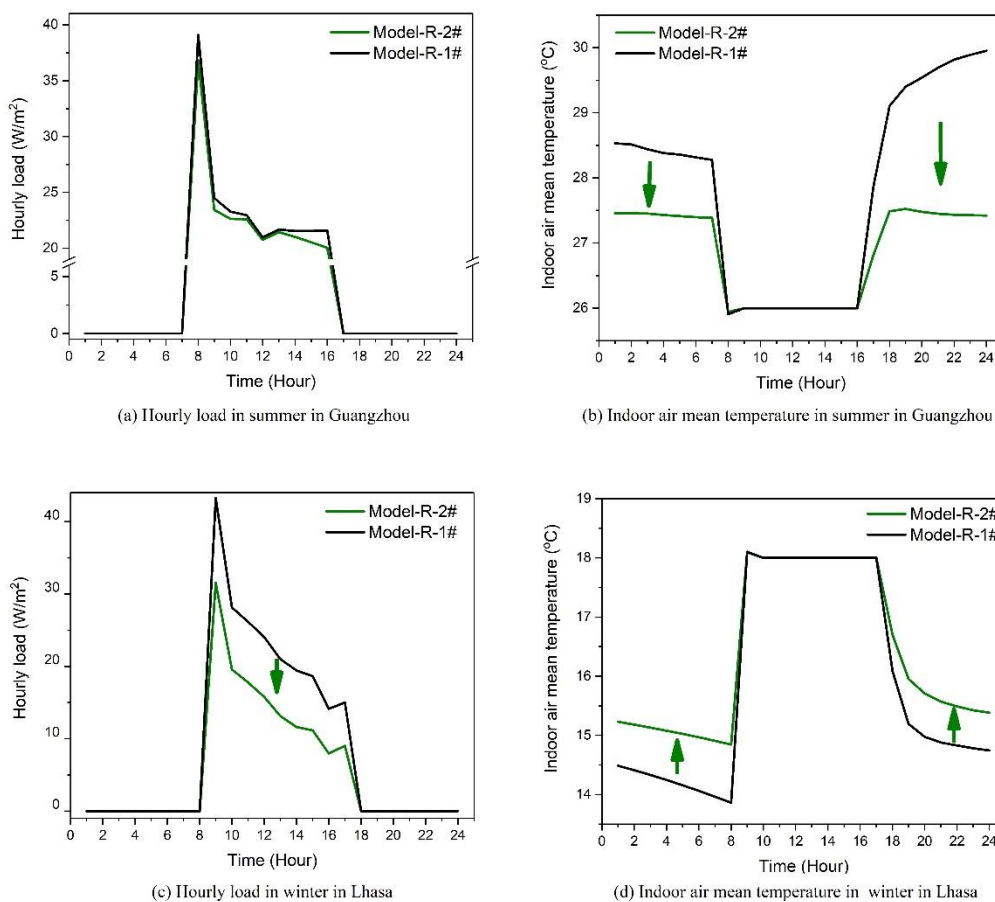


Figure 10: Hourly load and indoor air mean temperature for Model-C with and without PCMs addition in Guangzhou and Lhasa

Moreover, hourly load and indoor air mean temperature for Model-C in Guangzhou and Lhasa were shown in Figure 10. Firstly, Figure 10a and c indicate that with the addition of PCMs hourly loads of the more complicated building model decrease in both Guangzhou and Lhasa, leading to the reduction of total building energy supply. In addition, it is interesting to note that there are obvious hourly load peaks at 8 o'clock in both curves of Figure 10a and c, which is caused by the accumulated load during the whole night time, during which no energy supply system works. Specifically, during the night-times there is no energy supply system working, so at 8 o'clock when the energy supply system is just turned on, the system needs to process for the realization of the target indoor temperature of 26°C or 18°C. And it can be seen that the addition of PCMs decreases the value of hourly peak load, which means that the installed capacity of an energy supply system such as air conditioning and heating equipment, can be reduced. Secondly, Figure 10b and d indicate that, for the time period with no energy supply system working, compared to Model-C-1, indoor air mean temperature of Model-C-2 is closer to the set temperature of 26°C or 18°C in both Guangzhou and Lhasa. This phenomenon will lead to a more comfortable environment at this time period, and it is also the reason why hourly load at 8 o'clock is reduced for the models with PCMs application.

4 Conclusion

In this paper, two building models were carried out for analyzed applicability research of PCMs incorporated in building envelope by using EnergyPlus. The main findings are listed as follow:

The PCM layer separately attached to the internal and external surface of building envelopes shows a different impact. First, the external PCM layer attaching plays as a thermal insulation material to protect buildings from the outside environment, which will be affected by the external environment. Secondly, when the PCM layer is attached to the internal envelope surface, it plays as an energy storage and supply system, to meet parts of building energy demand. And this function doesn't be affected by the outdoor environment, which is only subjected to its indoor environment of buildings with PCMs attaching.

In addition, the simulation results in Model-C gave the climate applicability investigation of PCMs. First, for climates with small fluctuation weather, such as Guangzhou and Kunming, for both internal and external PCMs addition separately, PCMs with appreciate transition temperature can contribute to positive influences on energy saving. In specific, for external PCMs addition, PCMs with T_R of near 26 °C and 20 °C contribute to highest energy saving rates of 12.0% and 22.8%, for Guangzhou and Kunming respectively. And for internal PCMs addition, PCMs with nearly same ideal T_R of about 22 °C lead to energy saving rates of 12.4% and 20.1%. It is needed to note that the ideal T_R is basically subjected to its outdoor comprehensive temperatures (25 °C for Guangzhou and 20 °C for Kunming) and its indoor set temperature for external and internal PCMs addition, respectively. Secondly, for other climates with big fluctuation weather conditions in the whole year, no matter internal or external PCMs addition, PCMs' latent heat function to the energy savings is not significant, and compared with the total large building energy use, it is inappropriate for the PCMs

application.

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Table and Figure captions:

Table 1: Basic thermo-physical properties of construction materials

Figure 1: Simulation models used in this study

Figure 2: Annual outdoor meteorological parameters of three weather zones

Figure 3: Schedules of interior heat source and energy supply system

Figure 4: Daily loads and outdoor specially day weather condition for a simplified cabin model located in Guangzhou

Figure 5: Hourly cooling load and building envelop surface temperatures on summer special day for Model-S with PCMs attached on external surface

Figure 6: Hourly heat storage quality of on summer special day for Model-S with PCMs attached on external surface

Figure 7: Hourly heating load and building envelop surface temperatures on winter special day for Model-S with PCMs attached on external surface

Figure 8: Hourly cooling and heating load and building envelope surface temperatures on special days for Model-S with PCMs attached on internal surface

Figure 9: Annual mean load for Model-C with and without PCMs addition in different climates

Figure 10: Hourly load and indoor air mean temperature for Model-C with and without PCMs addition in Guangzhou and Lhasa