NANYANG TECHNOLOGICAL UNIVERSITY

PHASE CHANGE MATERIALS FOR PASSIVE COOLING OF BUILDINGS IN TROPICS

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ABSTRACT

Phase Change Materials (PCMs) are capable to absorb massive heat during phase transition in a narrow temperature range. PCMs have the potential to be used in the building envelope to reduce the heat transferred into indoor environment and to achieve cooling energy savings of HVAC system. However, the efficiency and selection of PCM are subject to the climate where it is applied. This study focused on the efficacy of PCMs applied to building envelope for passive cooling in tropical climate, Singapore for example.

This study was conducted by using a whole building energy simulation program, EnergyPlus. PCM applied to an air-conditioned concrete cubicle was studied followed by parametric studies on phase change temperature, temperature range of phase change, shape of enthalpy profile, location and thickness of PCM to optimize the efficiency of PCM for passive cooling. In addition, the potential synergy to apply PCM with the advanced coating system, such as solar reflective paint and thermal insulation paint was investigated to further improve the performance for cooling energy savings.

The main objective of this study is to provide informative knowledge and guideline to the design and application of PCMs in tropical climate for passive cooling of buildings.

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Chapter 1 INTRODUCTION

1.1 Research background

In Singapore, buildings consume about one-third of the total end-use electricity, of which around 60% is used for space cooling. It is showed that air-conditioners, the highest electricity-consuming appliance at home, are increasingly popular used in households to meet the demand for internal thermal comfort. The ratio of households equipped with air-conditioner has increased to 75% in year 2007/2008 (Wilson and Yap 2012). It is also predicted that there will be a growing trend of energy consumption in the future due to the climate changes and the rising living standard. Consequently, due to increased concerns on the diminished fossil fuel reserves and on the environmental impacts of greenhouse gas emission, to reduce building energy consumption and to design energy efficient buildings have become critical topics.

Phase Change Materials (PCMs) applied to buildings are expected to contribute to the energy saving of air-conditioners and a more comfortable indoor environment. PCMs are capable to absorb and release massive latent heat during phase change in a narrow temperature range, which is called latent heat storage (LHS). Compared with sensible heat storage that is storing heat by changing temperature, LHS has higher heat storage density and ability to stabilize temperature due to its nearly constant phase change temperature. In the PCMs' application to buildings, solid-liquid phase change cycle is utilized because the volume change of the material is small. Due to the diurnal temperature range, PCM can absorb the heat penetrating into buildings when temperature is high during the day and release the heat when the ambient cools down at night. Considering this property, PCMs have been used in building envelope to stabilize the indoor temperature and reduce the cooling and heating load by the HVAC (i.e. heating, ventilation, and air conditioning) unit.

Applying PCM to light weight buildings is a good example showing the efficacy of PCM to stabilize the indoor temperature. Large fluctuation of indoor air temperature in light weight buildings is often observed due to their low thermal mass attributing to low fraction of massive construction materials such as concrete and brick are used in the light weight buildings. The indoor temperature changes quickly in response to the outdoor temperature variation, causing thermal discomfort. PCM has high volumetric heat capacity during the phase transition, which could be 30 times higher than that of the normal massive construction material like concrete or brick (Mehling and Cabeza 2008). The addition of a thin layer of PCMs with suitable phase change temperature into building envelope can increase the thermal mass of light weight building significantly and the indoor temperature becomes stable due to the heat absorbing and releasing during phase change.

Studies on PCM applied to building for LHS have started since 1970s and have been remarkably increased in the last decade due to increasing concerns on global warming (Zhang, Zhou et al. 2007). In the beginning, studies and applications of PCM mainly focus on solar heating in cold regions. Solar energy is harvested by PCMs in the day and released in the night to provide space heating. Peippo et al. (1991) have concluded that energy saving of 5-20% could be expected by using PCM-impregnated plaster board in building envelope. An experiment (Athienitis, Liu et al. 1997) conducted in Montreal, Canada, showed that using PCM gypsum board as the interior lining in the building could effectively reduce the heating load by around 15%.

After that, it has been suggested to use PCM for building space cooling. The general concept for space cooling with PCM integrated into building envelope is similar to that for space heating, which is showed in Fig. 1.1. Indoor peak temperature can be cut down by storing heat in the PCM in daytime; at night, the stored heat is retrieved from the PCM and discarded by ventilation to the outside. Castell et al (2010) performed a full-scale experiment to study the macro-encapsulated PCM added to the building envelope for space cooling. The results revealed that the energy consumption was reduced by 15% after using PCM in hot summer under the Mediterranean climate. It also showed that the indoor temperature was reduced by up to 1°C and became more constant under free-floating conditions. A similar experiment (Muruganantham, Phelan et al. 2010) was also carried out in Arizona, the US. The monthly energy saving ranged from 10-26% by using PCM in the assembly walls in the summer.

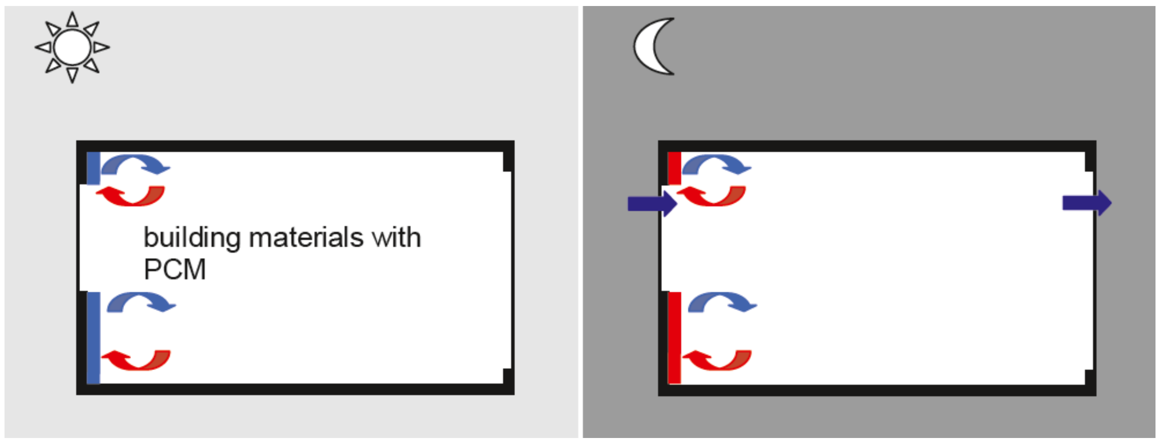

Fig. 1.1. Concept for space cooling with PCMs integrated into building envelope (Mehling and Cabeza 2008)

PCMs can be incorporated into construction materials in various forms. The incorporation method can be principally classified into: direct incorporation, immersion and encapsulation (Hawes, Feldman et al. 1993). The encapsulation method can prevent the adverse effects of PCMs on construction materials because PCMs are not in contact with the construction materials directly after been encapsulated. The encapsulation method can be generally divided into macro- and micro-encapsulation. Macro-encapsulated PCMs are in large volume containment and can be used separately as building component. Compared with this, micro-encapsulation allows the PCMs incorporated into conventional construction materials easier due to the small dimensions, which could reach micrometer level (Khudhair and Farid 2004). Micro-encapsulated PCMs have been successfully added into gypsum board, plastering mortar and concrete blocks to enhance thermal energy savings and many studies have been done on these materials (Schossig, Henning et al. 2005, Cabeza, Castellón et al. 2007, Sá, Azenha et al. 2012).

Besides the conventional construction materials stated above, micro-encapsulated PCMs also have potential to be dispersed and used as additives into building surface coatings, such as solar reflective paint and thermal insulation paint, which are commonly used on the building exterior for cooling load reduction. Solar reflective paint is characterized by its high solar reflectivity as well as thermal emissivity, which can effectively limit the temperature increase on the surface under solar exposure by reflecting the solar irradiation and emitting the absorbed solar energy. Lower surface temperatures reduce the heat transferred into building, which prevents the building from overheating and reduces the cooling load. The utilization of thermal insulation paint is also capable to reduce the cooling load by providing thermal insulation to the building envelope due to its low conductivity. Adding PCM into these coatings is supposed to further improve the performance of the coating system to reduce cooling load by absorbing the conducted heat.

1.2 Knowledge Gap

According to the working mechanism of PCM introduced above, the effective phase transition is a critical factor for the efficacy of PCM applied to buildings because large amounts of heat absorbed and released only during phase transition. In the realistic case phase change occurs in a temperature range of several Celsius degrees rather than instantaneously at one temperature point. Fig. 1.2 shows a sample of the specific heat capacity of PCM as a function of temperature.

The large heat capacity is utilized only when PCMs undergo the phase change. If the ambient temperature is located outside the transition temperature range, the latent heat will not be used so that only small amount of sensible heat will be absorbed and released by PCMs. Hence, according to different climates in different regions, suitable phase change temperature should be selected to fully exploit the latent heat storage property of PCMs. This makes the efficacy of PCMs quite sensible to the climate.

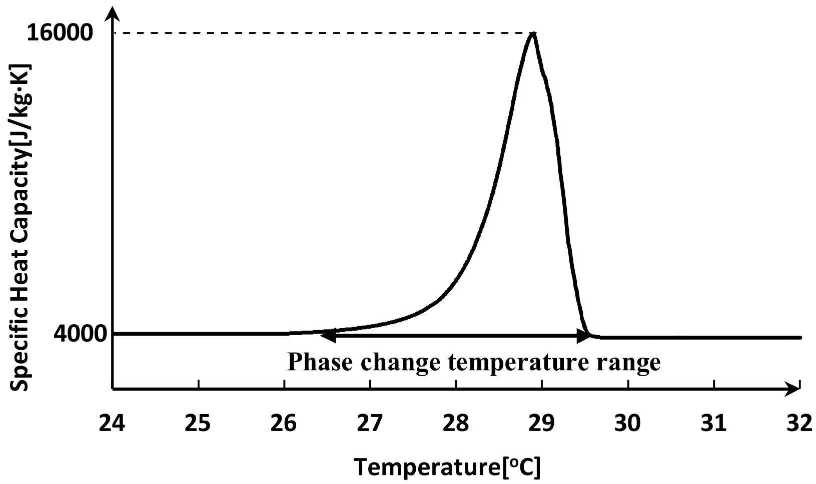

Fig. 1.2. Phase change materials: specific heat capacity as a function of temperature

PCMs applied to building envelope has been studied on a large scale and in different regions in the last decade, most located in China, Europe and the US according to the number of related paper published (Kuznik, David et al. 2011). However, almost no paper has been found related to PCM's application in the tropical climate such as Singapore.

The climate of Singapore is characterized with the uniformly high temperature and high humidity throughout the year with no distinct seasons due to its geographical location and maritime influence. It has a diurnal temperature range of minimum 23–27°C and maximum 30–34°C. Therefore no space heating is needed in the whole year. The daily temperature variation is quite small, only 5-7°C.

Challenge as well as benefit both exists for PCM's application under the climate of Singapore. One challenge is the limited daily temperature variation, which might result in the unsuccessful melting-freezing cycle of PCM. The situation that the PCM can hardly solidify may occur even at the lowest temperature of a day, will largely reduce the heat absorption in the next day. Another challenge is extra heat gains from the solidification of PCM are not desirable for buildings in Singapore due to the already high temperature at night.

On the other hand, the climate with uniform temperature all over the year and no distinct seasons in Singapore also offers a benefit when using PCM. In this kind of climate, PCM with suitable phase change temperature is expected to effectively work throughout the whole year. This is more economical than the regions in which the PCM is only effective for one season because of seasonal climate change. Therefore, to clearly understand and effectively improve the efficacy of PCM applied to buildings in Singapore is a critical topic which needs to be studied before the applications.

Another knowledge gap is the potential synergy when PCM is applied together with building surface coatings, like solar reflective paint and thermal insulation paint. PCM applied together with these coatings is expected to absorb the conducted heat and further improve the performance of the coatings on cooling load reduction. Additionally, the selection of PCM, such as phase change temperature, may be influenced when PCM is applied together with coatings. Therefore, to understand the interactions between the PCM and the coatings on the overall passive cooling performance will be another focus in this study.

1.3 Goals and methodology

Fig. 1.3 illustrates the frame work of this research. The ultimate goal is to study the efficacy of PCMs for passive cooling of tropical buildings, such as in Singapore.

This study was carried out through numerical method by using an accredited building simulation program – EnenergyPlus, which was introduced in detail in Chapter 2.

Firstly, the efficacy of PCM was investigated in an air-conditioned concrete cubicle. The indoor temperature was controlled by a HVAC system and the energy demands for cooling were analyzed. Based on the previous research, studies on the important parameters including phase change temperature, temperature range of phase change, shape of enthalpy curve, location and thickness of PCM were conducted to optimize the efficacy of PCM for passive cooling. Finally, PCM applied together with solar reflective paint and thermal insulation paint was investigated to explore the potential synergy between them.

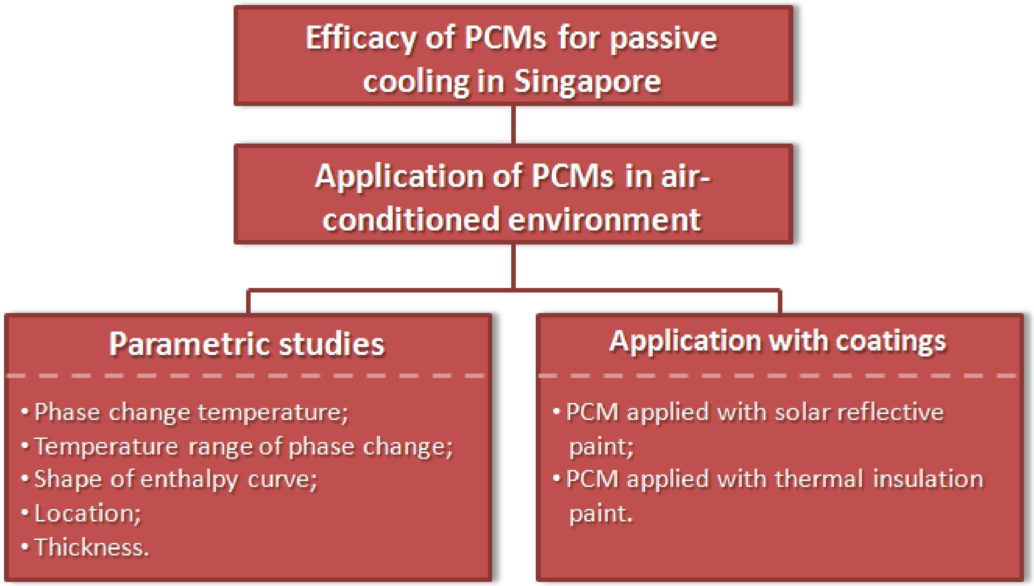

Fig. 1.3. Scope and objective of current research

It is expected that this study can provide informative knowledge and guideline to the design and application of PCMs in tropical climate.

1.4 Layout of the thesis

The thesis consists of four chapters. Chapter 1 is an introduction to background, knowledge gap, goals, and methodology of this research. Chapter 2 covers detailed literature review on properties and classification of PCM, PCM's application to space cooling and PCM's simulation by EnergyPlus. In Chapters 3, the simulation results on the efficacy of PCM for passive cooling in Singapore are showed, including the validation of PCM module in EnergyPlus, the bench mark study and the parametric studies. Chapter 4 shows the performance of PCM applied with solar reflective paint and thermal insulation paint, respectively. Chapter 5 gives conclusions of this study and proposed works for future study.

Chapter 2 LITERATURE REVIEW

2.1 Overview

In Chapter 1, a few literatures relevant to the study were introduced for the purpose to clarify the research motivation and to identify the knowledge gap. In this chapter, a more comprehensive literature review will be provided to give readers an explicit overview of previous researches on the PCM's applications to building envelope, which focus on space cooling, and the simulations by the whole building simulation software, EnergyPlus.

Properties and classification of PCM were introduced first. After that, state-of-the-art researches and applications of PCM in space cooling were reviewed. Results and problems were introduced for each study and the advantages and disadvantages of applying PCM were summarized. In the last part, the simulations of PCM using EnergyPlus were introduced including the mechanism and the validations of PCM module in EnergyPlus.

2.2 Properties and classification of PCM

Thermal energy can be stored in PCMs as latent heat during the phase transition process. Compared with another thermal energy storage method - sensible heat storage, which is storing heat by changing temperature, latent heat storage has much higher heat storage density. Comparative studies have shown that volume of storage mediate can be significant reduced by using PCM compared with sensible heat storage (Morrison and Abdel-Khalik 1978, Farid, Khudhair et al. 2004).

In latent heat storage applications, solid-liquid transition is mainly used due to the small volume variation during phase change process. Heat is stored and released in PCM through melting and solidification, while its temperature remains constant at the phase change temperature (Fig. 2.1). Considering this property, a variety of PCMs have been applied to stabilize temperature as “temperature bufferings”. There are many products of PCMs are available on the market for different applications, such as the temperature stabilization in transport containers, in peoples clothing, and in buildings (Mehling and Cabeza 2008).

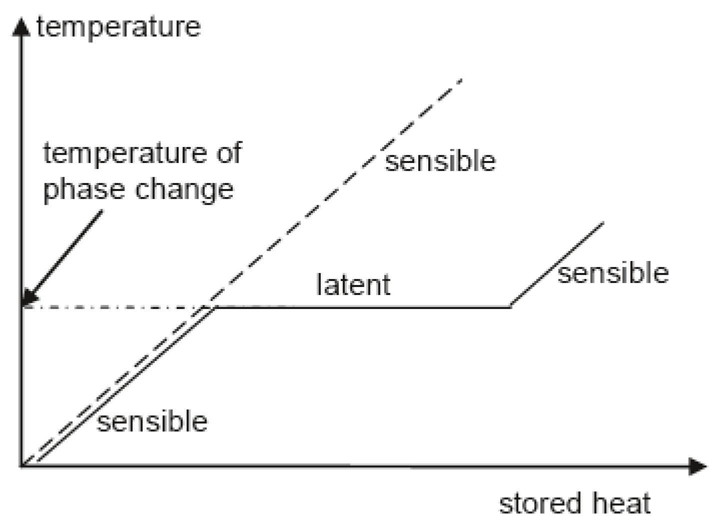

Fig. 2.1. Heat storage as latent heat for the case of solid-liquid phase change (Mehling and Cabeza 2008)

Generally, PCM to be used for thermal energy storage should have high heat of fusion, high thermal conductivity, high specific heat and density, long-term reliability during repeated cycling, low volume change during phase transition. Additionally, it should be noncorrosive, nontoxic, not flammable, and exhibit little or no supercooling (Ghoneim, Klein et al. 1991).

PCMs are classified as organic, inorganic and eutectic materials. Organic materials are divided into fatty acids, paraffin and non-paraffin. Inorganic materials are further described as salt hydrate and metallics. A eutectic is a minimum-melting composition of two or more organic or inorganic PCMs. The hydrated salts, paraffin waxes, fatty acids and eutectics of organic and inorganic compounds have been widely used and studied during the last 30 years (Osterman, Tyagi et al. 2012). Inorganic PCMs are more likely to have supercooling and phase segregation during transitional processes. On the other hand, organic PCMs show little supercooling or segregation and are available over a large temperature range. However, organic materials are flammable and have low conductivity (Zhang, Zhou et al. 2007).

2.3 Applications of PCM to building envelope

2.3.1 Space cooling

With the increased demands on electricity for cooling and air-conditioning in buildings worldwide, researchers are now paying more attention to the applications of PCM to space cooling. As a latent heat storage media, PCMs solidify when cooling resources are available and melt when cooling is needed. The advantages of PCMs as a heat storage media are two-fold. The heat capacity of PCM is order-of-magnitude higher than normal building material while the melting and freezing cycles are almost isothermal (Feustel, de Almeida et al. 1992). PCMs have been successfully incorporated into wall materials such as gypsum wallboard, plaster and concrete to enhance the thermal energy storage capacity of buildings with particular interest in cooling load reduction and peak load shifting. Many studies have been done to investigate the contribution of PCMs to the space cooling both experimentally and numerically.

Shilei et al. (2007) experimentally studied PCM-based wallboards that could reduce cooling load in buildings. PCM wallboard was used as building lining in a fully insulated room with air-conditioning. The results showed that the redundant heat in the room can be effectively absorbed by using PCM wallboard and the energy consumed for cooling can be reduced when compared with the conventional wallboard. A PCM based wallboard was also experimentally investigated to test the thermal behavior of light weight building internal partition wall by Kuznik et al. (2008). The experimental study was carried out in a full-scale test room where the ambient environment (temperature and solar radiation) were controlled to simulate a representative summer day. It was shown that the fluctuation of indoor air temperature and interior wall surface temperature was reduced by 4.7°C and 3.5°C respectively when PCM wallboard was used. In addition, a peak shift of 40 minutes on the interior wall surface temperature was observed. It was concluded that the PCMs can reduce the overheating effect in the day and release the heat to the room when it is cool at night to enhance the thermal comfort.

A numerical study was conducted to investigate the thermal response of a brick wall filled with PCM by Zhang et al. (2011). They evaluated the inside wall surface temperature of brick wall filled with PCM and compared it with a solid brick wall. This study showed that the use of PCM in the brick walls can decrease the input and output of heat transfer amount to the room space and decrease the cooling load to maintain a constant indoor temperature due to the enormous increase of specific heat capacity after adding PCMs.

A thermal building simulation program was used to evaluate the latent heat storage performance of PCM-treated wallboard in the hot summer in California (Corina and Helmut 1996). The result showed that the PCM-treated wallboard is able to store large amount of energy, to prevent heat penetration into indoor space and to reduce indoor air temperature during the day when compared with conventional wallboard. However, it was observed that the PCM-treated wallboard was not able to fully discharge over night because the indoor air temperature was higher than the melting temperature of PCM resulting in inefficient thermal storage in the next cycle. Similar situation was also observed in Castell's and Voelker's experiments (Voelker, Kornadt et al. 2008, Castell, Martorell et al. 2010), respectively. Night ventilation (either natural or mechanical) to assist discharge of PCM was recommended by these researchers. Other cooling strategies such as hydronic loop to facilitate the thermal discharge of PCM have to be investigated.

Carbonari et al. (2006) analyzed the thermal performance of sandwich panels containing PCMs for prefabricated walls in hot summer both experimentally and numerically. The result of the study showed that PCMs can be used as an intermediate wall layer to enhance the thermal behavior of light enclosures by absorbing incoming heat. It was also highlighted that the thermal performance depends on the climate in which PCMs operate and on the need to discharge the PCMs' heat for solidification which generally occurs during the night.

One study on PCM applied to buildings in tropics was conducted in Chennai, India (Pasupathy and Velraj 2008). A double layer of PCM with different phase change temperatures was designed to apply on the roof to enhance the thermal comfort in July. It was numerically found that 6.5 cm thick double layer PCM was needed totally to maintain the indoor temperature within comfort zone, which is not cost efficient.

According the literature review on the PCM's applications in building envelope to space cooling, the benefits of using PCM is concluded as follows:

- the ability to reduce heat flux transmitted into the building by latent heat storage;
- the ability to shift energy consumption from peak load to off-peak load period to get a better match of electricity demand and supply;
- the ability to attenuate the indoor temperature fluctuation due to heat storage and discharge at almost isothermal condition.

The main problem for using PCM for space cooling was observed by many researchers, that is PCM may not discharge heat when the ambient temperature is still too high at night especially when PCM is placed at interior surface. It may lead to inefficient heat storage in the next cycle. Efficient night ventilation is recommended to counteract this effect. In tropical climate, however, other issues may rise when the night ventilation is utilized. For example, dehumidification of the air may be necessary.

In addition, the release of heat at night may cause thermal discomfort or increase cooling load. In this scenario, the release of heat stored by PCM towards external environment is preferred. A thick insulation added to the inner side of PCM layer is a potential way to prevent the heat flux coming in (Carbonari, De Grassi et al. 2006).

2.3.2 Selection of phase change temperature of PCM

The selection of the phase change temperature is one of the most important parameters for the successful applications of PCM for both space cooling and heating. Many studies have been conducted to investigate the optimal phase change temperature of PCM.

Peippo et al. (1991) numerically analyzed a PCM wall in a well-insulated passive solar house based on the weather data of Helsinki, Finland and Madison, Wisconsin. PCM panels were attached to the inside surface of the room to receive direct heat gain. Heat absorbed during the daytime by the panel was discharged to the room when PCM solidified at night thus enabling more effective use of the daytime solar gains over the whole day. The simulation results indicated that the maximum energy delivered by the PCM during night occurs when the melting temperature of PCM was 1-3°C above the average room temperature in both climates.

A one-dimensional transient heat transfer model was developed to simulate the influence of PCM in external building walls under the climate of Spain (Izquierdo-Barrientos, Belmonte et al. 2012). The simulation results did not show any clear optimum phase change temperature that minimizes the heat gains through the wall in summer or lost in winter. Nonetheless, according to the results, it is still highlighted that the selection of phase change temperature of PCM depends on the orientation of the external walls, the location of the PCM layer in the wall and the period of the year during which the PCM operates. Besides all, the climate in which the building is located is a determining factor of the PCM's characteristics.

Ascione et al. (2014) numerically studied the performance of PCM used on the inner surfaces of external building envelope in the cooling season. Five Mediterranean climates have been considered in the simulation. The results showed that the optimal melting temperature varies with different climate and PCM thickness. It is recommended that the selection of phase change temperature of PCM should base on climatic condition, internal load, building utilization and structural design.

Neeper (2000) examined the thermal dynamics of a PCM gypsum wallboard applied to interior partition walls and external walls. For interior walls, both experimental and numerical analyses showed that the optimum performance occurs when the phase change temperature of PCM equals to the average wall temperature. For exterior walls, the optimum performance occurs when the phase change temperature of PCM is close to the average wall temperature which depends on the outdoor temperature and the thermal resistance of the wall.

In summary, there is no ‘the’ best phase change temperature of PCM that can apply to all buildings. The optimum phase change temperature of PCM depends on many factors including climate, indoor environment, thermal properties of the walls, PCM location (interior or exterior), thickness of PCM layer, and heat of fusion of PCM.

2.4 Simulation of PCM using EnergyPlus

2.4.1 Mechanism of PCM module in EnergyPlus

Many whole building energy simulation programs are available nowadays to assist designers, researchers and engineers evaluating new technologies and innovative ideas that can potentially improve the energy and thermal performance of buildings. Among them, only a few (i.e. EnergyPlus, TRNSYS, ESP-r, and BSim) are capable to simulate PCM layers (Al-Saadi and Zhai 2013).

EnergyPlus is one of the most commonly used software for the whole building energy simulation. The one-dimensional conduction finite difference (CondFD) solution was employed as the heat balance algorithm in EnergyPlus to simulate the PCM due to its capability to simulate material with varied properties, like enthalpy and thermal conductivity. The CondFD solution was first employed in to the EnergyPlus Version 2.0 in 2007. The algorithm uses a semi-implicit finite difference scheme based on the heat capacity method with an auxiliary enthalpy–temperature dataset to account for latent heat evolution (Curtis 2007). In the newer version 7.0, a fully implicit scheme, which is capable to simulate smaller nodal space and steadily decay to convergence, has also been added into the program (Tabares-Velasco, Christensen et al. 2012).

Version 8.1 with fully implicit scheme CondFD algorithm was used in this study. The model equation for this scheme is shown in the following equation.

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left(k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \right)$$

where,

T = node temperature

i = node being modeled

i+1 = adjacent node to interior of construction

i-1 = adjacent node to exterior of construction

j+1 = new time step

j = previous time step

Δt = calculation time step

Δx = finite difference layer thickness (always less than construction layer thickness)

C_p= specific heat of material

k_W= thermal conductivity for interface between i node and i+1 node

k_E= thermal conductivity for interface between i node and i-1 node

ρ= density of material

PCM has variable specific heat (C_p) and the value gets updated for each iteration by incorporating the following equation.

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

where "h" is the specific enthalpy of the material, which is the user defined input as a function of the temperature.

The iteration scheme assures that the correct C_p is used in each time step based on the user defined enthalpy-temperature function (US DOE, 2013).

2.4.2 Validation of the PCM module in EnergyPlus

Experimental validations have been carried out by many researchers to evaluate the accuracy of the PCM module in the EnergyPlus.

A fully instrumented wooden shed insulated with PCM sheets was tested in Phoenix, Arizona for a year (Muruganantham 2010). HVAC system was used and the energy consumption was monitored. EnergyPlus Ver.5 was used to simulate the effects of PCM and to compare with the test data. It was found that the simulated energy consumption values were lower (almost half) during the winter months and were slightly higher during the summer months. The simulated results in EnergyPlus Ver.5 showed inconsistency with the measured results. However, some input (i.e. performance curve of the air-conditioning, infiltration, and thermal properties of the envelope materials) in the simulation is not the exact value obtained from the experiment, which also may result in the failure of validation.

In Castell's experiment (Castell, Medrano et al. 2009), it is found that the simulated results in EnergyPlus did not show good agreement with the experimental results when PCM was implemented in concrete cubicles. The study concluded that the simulation results did not reflect the thermal improvement of PCM observed in the test cells. They indicated that weather data and other parameters such as infiltration should be modified in the simulation to further improve the accuracy of the predicted results.

Under the climatic conditions of Auckland, New-Zealand, an experimental study using PCM in gypsum board was compared to the simulation results (Augustin, Sam et al. 2011). Historical weather data as well as measured weather data were used in the EnergyPlus simulation. Although the simulation captured the overall trend of the indoor air temperature when measured weather data was used, the predicted indoor air temperature was still quite different than the measured results. The study highlighted that the simulation results might deviate from the actual measurement due to many parameters including air infiltration which was not captured properly in the EnergyPlus simulation.

An early successful validation of the CondFD solution algorithm used for PCM modeling was reported by Zhuang et al. (2010). The difference between the simulated and measured results was reported to be in the range of 0.71% and 12.41%. It was concluded that the most important factors to reduce the discrepancies between the simulated and the tested results are weather data and thermal properties of materials.

Other successful validations of PCM module in EnergyPlus was reported by Som et al. (2011). The study reported that simulated daily average heat flux through walls was within 9% of the field measurements. In addition, simulated temperature distribution of envelope compared fairly well with the measured data although some delayed response was observed. However, EnergyPlus given unreasonable results for heat fluxes and temperature distributions on the floor of attic of the experimental house.

The EnergyPlus developer team has also performed rigorous validation and verification studies for general heat transfer calculations as well as the CondFD solution algorithm (Tabares-Velasco and Griffith 2011, Tabares-Velasco, Christensen et al. 2012, Tabares-Velasco and Air-Conditioning Engineers 2012). The studies concluded that versions prior Ver.7 contain two bugs and will be fixed subsequently in a later version. A few guidelines for using the PCM module in the EnergyPlus are also recommended in these studies:

- Time steps should be equal to or shorter than three minutes;
- Accuracy issues can 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.

Chapter 3 EFFICACY OF PCM FOR PASSIVE COOLING IN SINGAPORE

3.1 Overview

EnergyPlus is one of the most commonly used software for whole building energy simulation. The fundamental of the PCM simulation module was introduced in chapter 2. In this chapter, simulation results on efficacy of PCM for passive cooling of buildings in Singapore were reported. Section 3.2 reports the validation of the PCM module in the EnergyPlus (Ver. 8.1). The validated model was then used to study the efficacy of PCM in a temperature-controlled room under the climatic condition of Singapore. Section 3.3 described the model for bench mark and parametric studies, followed by the results and discussion in Section 3.4.

3.2 Validation of the PCM module in EnergyPlus

In order to verify the accuracy of the PCM module in EnergyPlus, a numerical model was constructed based on a published experiment (Kuznik, Virgone et al. 2008). The experiment was conducted in a well-controlled environment which minimizes the uncertainty of many environmental factors.

The isometric diagram of test room in the experiment is shown in Fig. 3.1. The south facade was made of glass which exposed to a climatic chamber with temperature swings from 15~30°C as shown in Fig. 3.2. All other exterior surfaces of walls, ceiling and floor were kept at a constant temperature of 25°C. A solar simulator was used to provide radiation to the south façade and the radiation density on the exterior surface of the south façade is shown in Fig. 3.2.

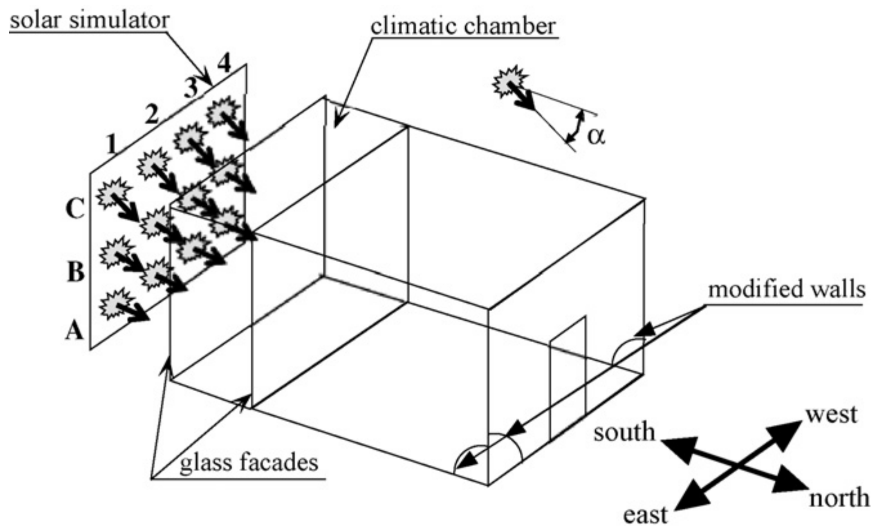

Fig. 3.1. Isometric diagram of the test room with dimension of 3.1×3.1×2.5 m (height) (Kuznik, Virgone et al. 2008)

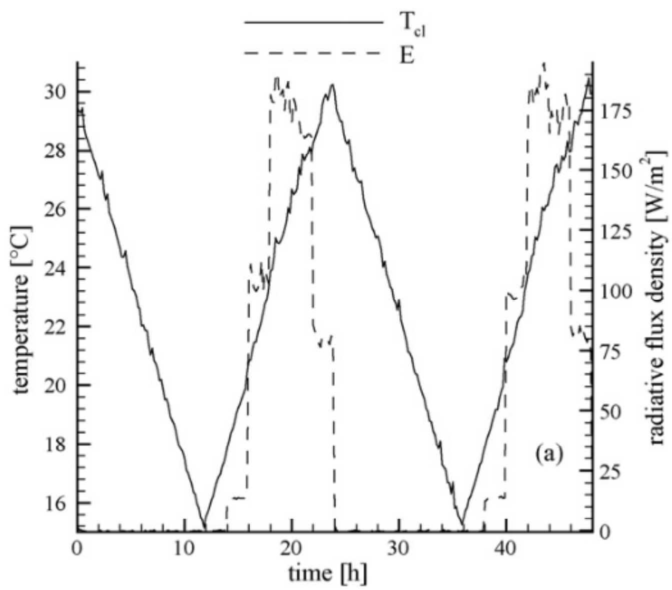

Fig. 3.2. Experimental climatic chamber temperature Tcl and radiative flux density E during the experiments (Kuznik, Virgone et al. 2008)

Experiments were carried out for both walls with and without PCM. The composition of the east, the west and the north wall is shown in Fig. 3.3. A 5 mm PCM layer was added to the walls near the interior surface for wall with PCM. The indoor air temperatures were monitored for 2 days.

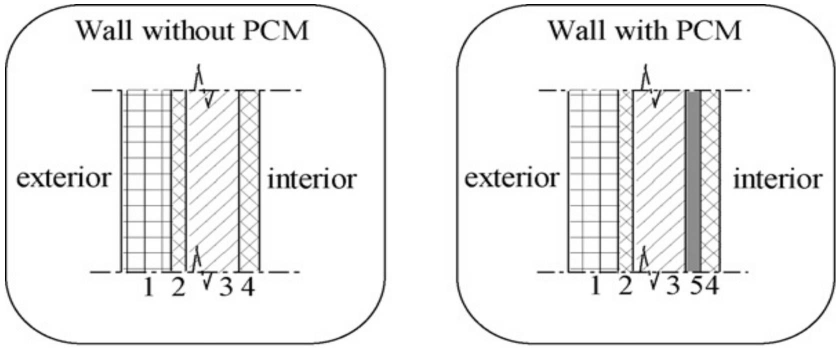

Fig. 3.3. Walls compositions with and without PCM:(1) 50 mm wood plate, (2) 10 mm plaster, (3) 50 mm polystyrene, (4) 13 mm plaster and (5)5 mm PCM (Kuznik, Virgone et al. 2008)

Based on the experiment, a numerical model with the same geometry, boundary conditions, and environmental exposures (according to Fig. 3.2) was constructed in EnergyPlus. Fig. 3.4 shows the measured and the simulated results and Table 3.1 summarizes the maximum and the minimum indoor air temperature of the measured and the simulated results.

Table 3.1. The maximum and the minimum indoor air temperature (T) of the measured and the simulated results

	T without PCM		T with PCM	
	Max T	Min T	Max T	Min T
Simulated results [°C]	34.0	18.5	29.6	21.0
Measured results [°C]	35.9	18.9	32.8	19.8
Temperature Difference [°C]	1.9	0.4	3.2	1.2
Relative difference	5%	2%	10%	6%

As can be seen, the simulated results show good agreement with the measured results. Table 3.1 shows the relative difference in the indoor air temperature is within 2-10% between the simulated and the measured results. In Fig. 3.4, it is observed that a reduction of 3.1°C in the peak indoor air temperature by PCM was recorded in the experiment while a 4.4°C drop is predicted in the simulation. Some discrepancies between the experiment and the simulation are observed on the valley of the curves, that is, the temperature increase by adding the PCM is much larger in the simulated results. It reveals that the simulation overestimates the heat released during the cooling night. This may be attributed to the limitation of the PCM module in EnergyPlus which is unable to consider the hysteresis effect of PCM as only one enthalpy-temperature function can be specified in the program (enthalpy-temperature information for heating is specified in this model). This is consistent with the simulation results from Tabares-Velasco et al.(2012).

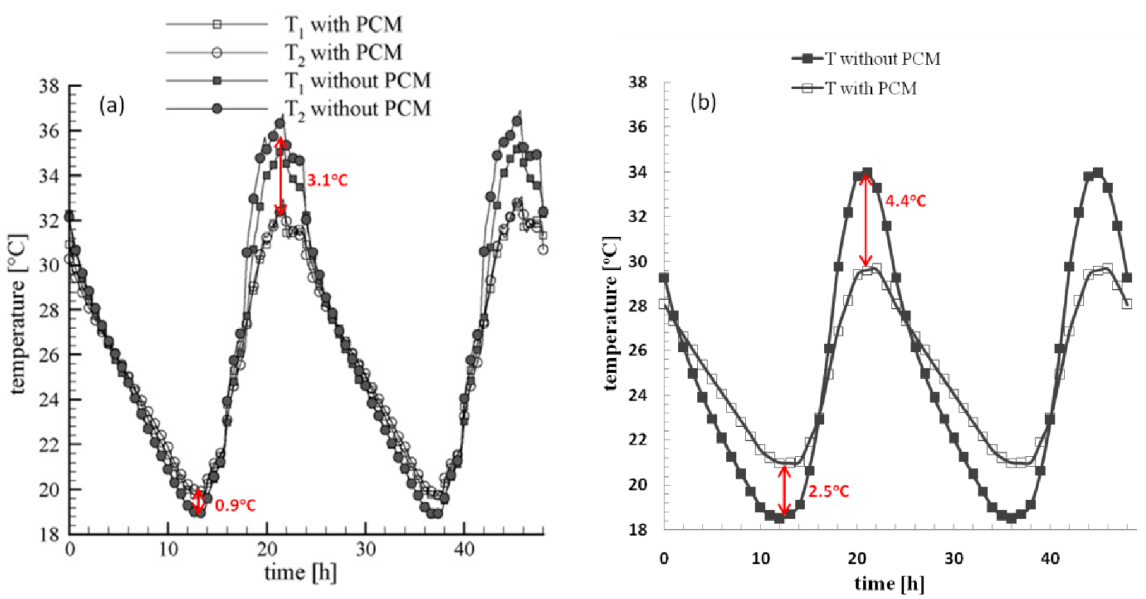

Fig. 3.4. (a) Measured indoor air temperature from the published experiment. T1 was measured at the height of 0.85 m and T2 is measured at the height of 1.70 m (Kuznik, Virgone et al. 2008), and (b) simulated indoor air temperature in EnergyPlus

Conclusively, the simulation results from EnergyPlus show good accordance with the experimental results. This enables the use of EnergyPlus to study the efficacy of PCM for passive cooling of buildings. The limitation in capturing the hysteresis effect of PCM, however, may cause inaccuracy when PCM with strong hysteresis is used.

3.3 Efficacy of PCM for passive cooling in Singapore

3.3.1 Bench mark study

The validated model in Section 3.2 was then modified to study the efficacy of PCM for passive cooling in Singapore as shown in Fig. 3.5. SkechUp, a 3-D modeling program, was engaged to construct the geometry of the model. This simplified cubic model was built in this study for the purpose of easy interpretation and analysis on the thermal behavior of the building facades with PCM. The dimension of the model is 3×3×2.8 m (height). The vertical walls, floor and ceiling are made of normal concrete with thickness of 150 mm, representing the construction of normal office buildings. The properties of the concrete are shown in Table 3.2 (BCA 2008).

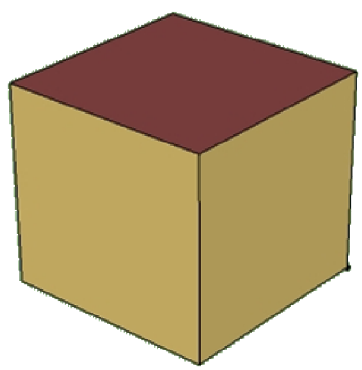

Fig. 3.5. Isometric drawing of the model in SkechUp

The exterior surface temperatures of the floor and the ceiling are kept constant at 25°C. All the other vertical surfaces are exposed to the outdoor environment. The weather data used in the simulation is the International Weather for Energy Calculations (IWEC) data for Singapore obtained from website of U.S. Department of Energy (U.S.DOE). Since the climate in Singapore is rather stable all year round, a simulation period of one day (30th July) is chosen for the purpose of parametric study on the efficacy of PCM. The global horizontal radiation and the air dry bulb temperature of 30th July are showed in Fig. 3.6.

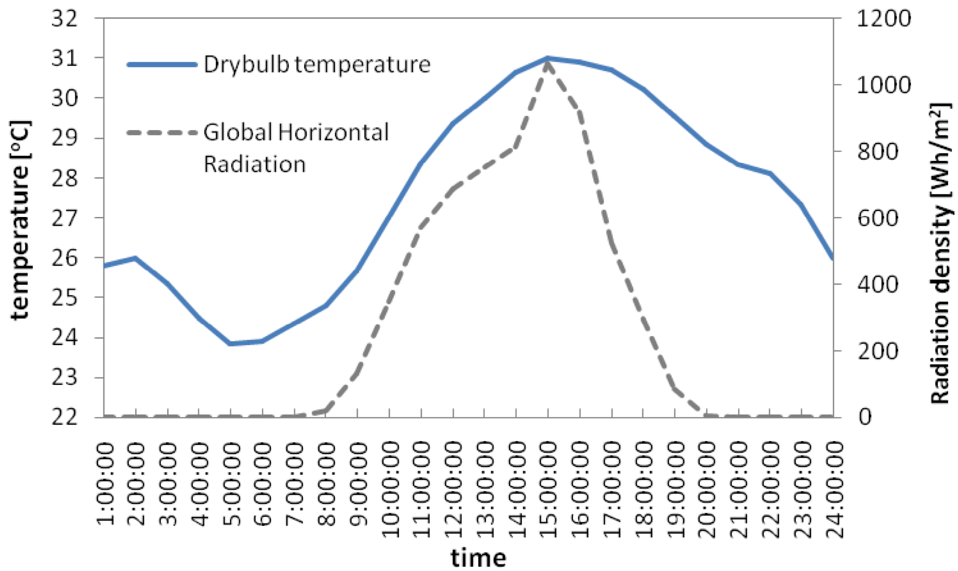

Fig. 3.6. Radiation density and air temperature of simulation period

Table 3.2. Physical property of construction material

Physical property	Concrete	PCM
Conductivity [W/m·K]	1.442	0.15-0.35
Density [kg/m^3]	2400	814
Specific heat capacity [J/kg·K]	750	2150

The efficacy of PCM for passive cooling is studied in a temperature-controlled condition. The ideal load HVAC system is employed in the model, which removes the heat at 100% efficiency to supply conditioned air to the zone that meets the load requirements. The set-point of the indoor air temperature is 25°C, commonly adopted in the commercial air-conditioned buildings in Singapore. The room is fully enclosed and energy consumption for cooling is calculated in the simulation.

The room with and without PCM is simulated. The paraffin-based (n-Octadecane) PCM is adopted in this study with physical properties shown in Table 3.2. The thickness of the PCM layer is 10 mm and it is placed on the outside surfaces of all the vertical walls. The profiles of the walls with and without PCM are showed in Fig. 3.7. As shown in the Fig.3.7, the outside surface of the PCM layer, the outside and inside surfaces of the concrete layer are defined as surface a, b and c, respectively.

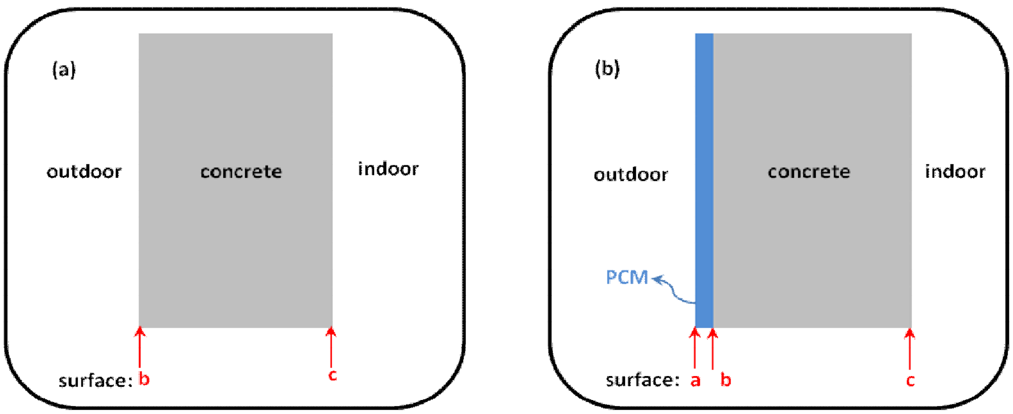

Fig. 3.7. (a) Profile of the wall without PCM, (b) Profile of the wall with PCM on the outside surface

Table 3.3. Enthalpy-temperature input in tabular form

Temperature[°C]	Enthalpy[J/kg]
0	0
28	60200
28.1	275037.5
50	322122.5

The phase change temperature of the PCM is 28°C in the bench mark study, close to the average diurnal temperature in Singapore. PCM with a very small phase change temperature range of 0.1°C (28-28.1°C) is used to represent an idealized PCM that changes phase instantaneously and completely once the phase change temperature is reached. The specified enthalpy profile of the idealized PCM is shown in Fig. 3.8 and is discretized to be incorporated into EnergyPlus. Table 3.3 shows the enthalpy-temperature input of the PCM in tabular form. The software linearly interpolates the unidentified points in the given range.

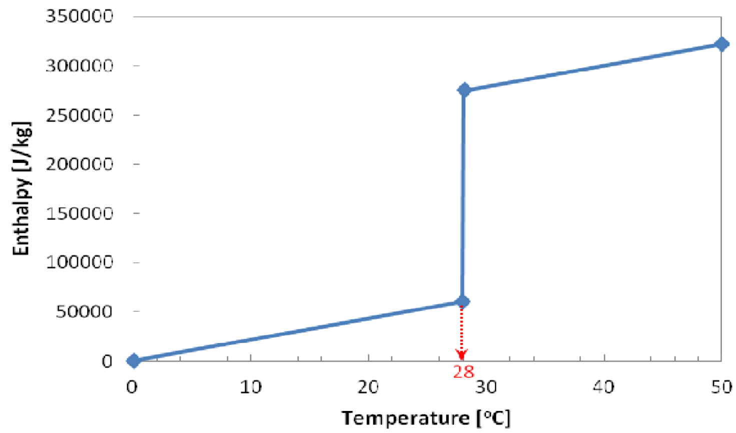

Fig. 3.8. Enthalpy profile of the PCM in the bench mark study

According to Tabares-Velasco et al. (2012), the time step less than or equal to three minutes and the node space equal to 1/3 of the default value in EnergyPlus are recommended. In addition, the changes on thermal conductivity of PCM should be considered to increase the accuracy of the simulation. In this study, the time step is one minute and the node space is modified into 1/3 of the default value. The thermal conductivity of PCM is 0.35 W/m·K for the solid phase and 0.15 W/m·K for the liquid phase (Mehling and Cabeza 2008). The value of the thermal conductivity is interpolated during the mushy state (the mixture of the solid and the liquid phases).

3.3.2 Parametric studies

After the bench mark study, important parameters including phase change temperature, temperature range of phase change, shape of enthalpy curve, location and thickness of PCM are studied to optimize the efficacy of PCM for passive cooling.

3.3.2.1 Phase change temperature

The phase change temperature of the PCM is varied from 22°C to 32°C and phase change range is remained the same at 0.1°C. The PCM with a specific phase change temperature is incorporated into the model by shifting the latent heat part of the enthalpy profile in the bench mark to the certain phase change temperature. It is aimed to investigate the effect of phase change temperature of PCM on passive cooling under the climatic condition of Singapore.

3.3.2.2 Temperature range of phase change and shape of enthalpy curve

The simplified linear enthalpy profile with phase change range of 0.1°C is adopted in the bench mark study for the easy interpretation of the results. In the realistic case, however, the phase change occurs in a temperature range of several Celsius degrees and the enthalpy profile is non-linear.

An example of heat capacity profile and enthalpy profile of the PCM employed in the realistic case is shown in Fig. 3.9. The heat capacity and temperature profile of the PCM is obtained from the Differential Scanning Calorimetry (DSC) test. The enthalpy and temperature profile is then derived by integrating the area of it.

The following cases are studied to investigate the effect of the temperature range of phase change and shape of enthalpy curve of PCM:

Case 1: PCM with phase change range of 0.1°C, linear enthalpy profile and different phase change temperature varied from 22°C to 32°C is applied (studied in Section 3.3.2.1).

Case 2: PCM with phase change range of 4°C, linear enthalpy profile and different phase change temperature varied from 22°C to 32°C is applied.

Case 3: PCM with phase change range of 4°C, non-linear enthalpy profile and different phase change temperature varied from 22°C to 32°C is applied.

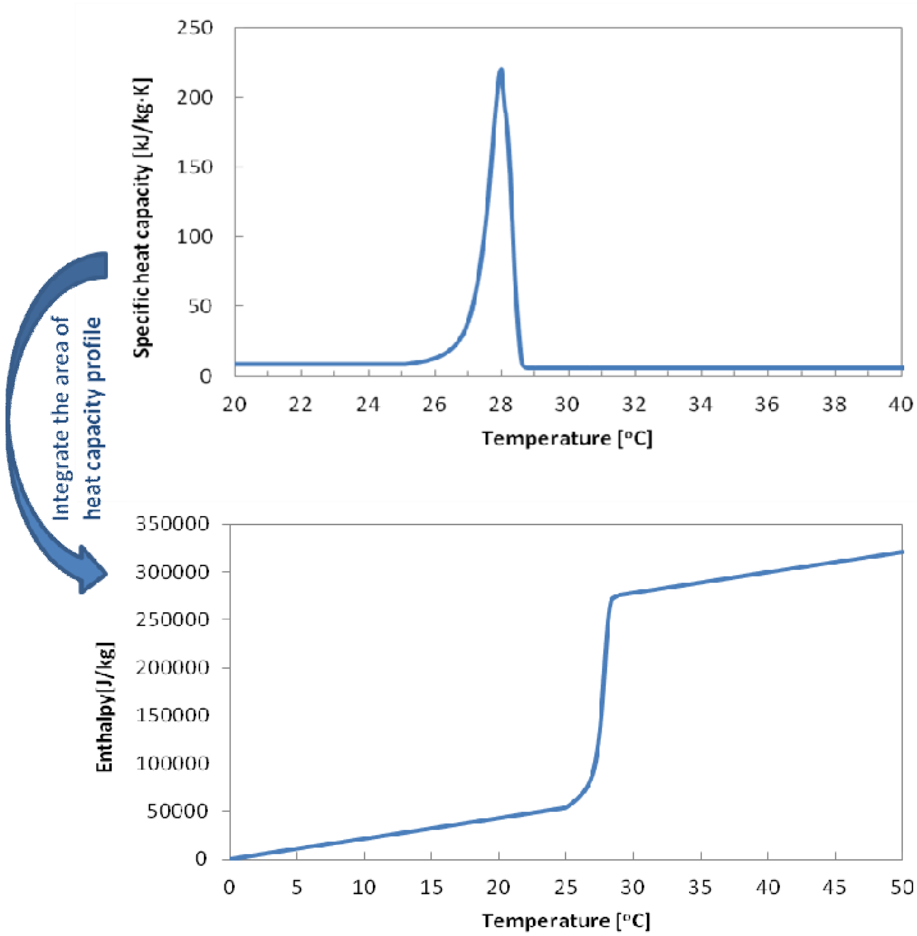

Fig. 3.9. (a) heat capacity and temperature profile (b) enthalpy and temperature profile

The enthalpy profiles and heat capacity profiles of cases 1 to 3 when phase change temperature is 28°C are shown in Fig. 3.10 and Fig. 3.11, respectively. For the case 3, as can be seen in Fig. 3.11, melting starts at 25°C, peaks at 28°C and completes at 29°C. The phase change temperature of PCM in case 3 is defined as the temperature of the peak heat capacity. Table 3.5 shows the tabular form of enthalpy-temperature input of PCM with phase change temperature of 28°C in case 3. In the case 2, the heat capacity keeps constant during the phase change which starts at 25°C and completes at 29°C. To facilitate the comparison between each case, the phase change temperature of PCM in case 2 is defined as 3°C higher than the starting point of melting. The enthalpy-temperature input of PCM with phase change temperature 28°C in case 2 in tabular form is shown in Table 3.4. The PCM with other phase change temperature in the cases 1 to 3 is incorporated into the model by shifting the latent heat part of the enthalpy profile to the required phase change range.

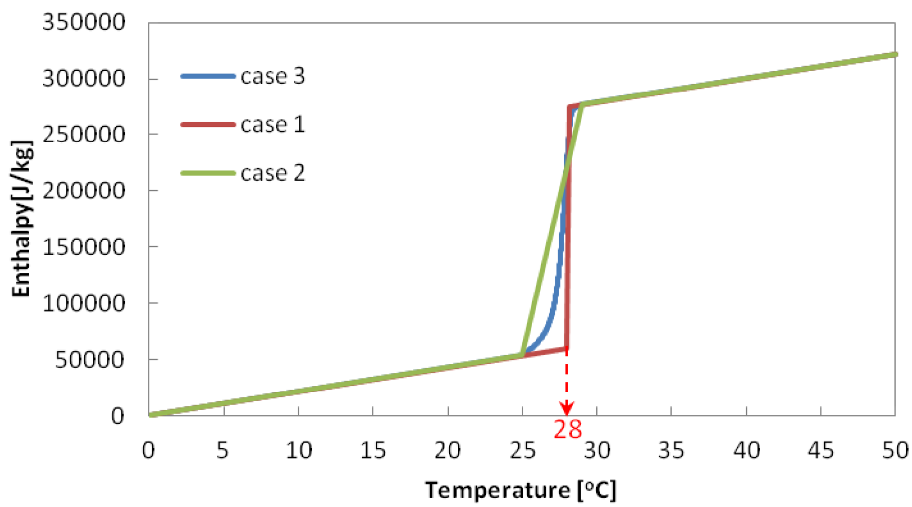

Fig. 3.10. Enthalpy and temperature profile of cases 1 to 3

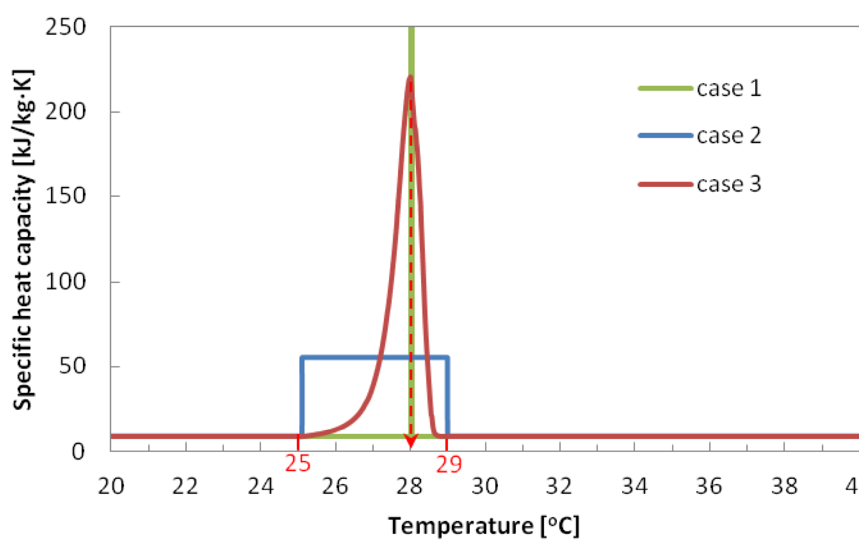

Fig. 3.11. Heat capacity and temperature profile of cases 1 to 3

Table 3.4. Enthalpy-temperature input in tabular form of case 2 (phase change temperature 28°C)

Temperature[°C]	Enthalpy[J/kg]
0.0	0.0
25.0	54102.5
29.0	277314.9
50.0	322122.5

Table 3.5. Enthalpy-temperature input in tabular form of case 3 (phase change temperature 28°C)

Temperature[°C]	Enthalpy[J/kg]	Temperature[°C]	Enthalpy[J/kg]
0.0	0	27.5	129019.9
25.0	54102.5	28.0	223022
26.0	65004.8	28.2	256816.4
26.5	73731.2	28.4	271818.4
26.8	81697.8	29.0	277314.9
27.0	89418.4	50.0	322122.5
27.2	100689.1		

3.3.2.3 Location

The location of the PCM is altered to the inside surface of the vertical walls as shown in Fig. 3.12, to study the effect of location on the efficacy of PCM. The inside surface of the PCM layer is defined as surface d as shown in the figure.

The idealized PCM in the bench mark study is utilized in all the following studies. In addition, the optimal phase change temperature of the PCM on the inside surface is studied by varying the phase change temperature from 22°C to 32°C.

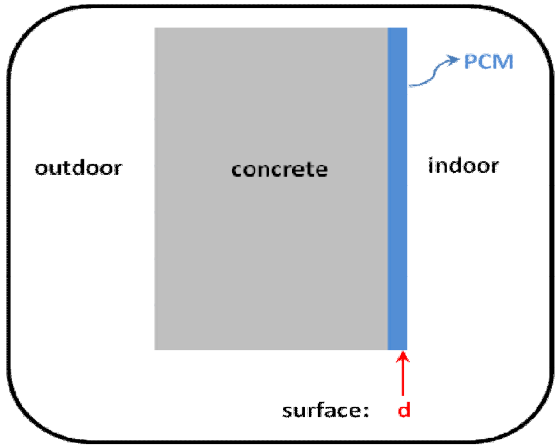

Fig. 3.12. Profile of the wall with PCM on the inside surface

3.3.2.4 Thickness

The amount of the PCM is another critical factor that influences the performance of PCM. PCM with varied thickness from 3 mm to 100 mm is simulated for PCM both applied to the outside and inside surfaces of the vertical walls to study the impact of the amount of PCM.

3.4 Results and discussion

3.4.1 Benchmark study

The energy consumption of the HVAC system and the energy saving rate by adding the PCM are summarised in Table 3.6. The “solid PCM” represents the imaginary material with the same properties as the PCM in solid phase but without the ability to change phase. The purpose of using this imaginary material as a reference is to illustrate the impact of phase change of the PCM. The energy saving rate is defined in the following equation.

$$\text{Energy saving rate} = \left(1 - \frac{E_{PCM}}{E_{No\_PCM}}\right) \times 100\%$$

where E_{No_PCM} and E_{PCM} are the energy consumption of the HVAC when no PCM and a specific kind of PCM is added respectively.

Table 3.6. Energy consumption and energy saving rate

	Energy consumption [kWh]	Energy saving rate
Without PCM	6.83	/
With "solid PCM"	6.52	4.5%
With PCM (phase change temperature 28°C)	4.05	40.7%

It is observed that the energy saving rate is only 4.5% when a 10 mm thick layer of "solid PCM" is added, attributed to the additional thermal resistance and thermal mass of the wall by incorporating the PCM but without phase change process. The energy saving rate of 40.7% is achieved by adding the same thickness of the PCM with the phase change temperature of 28°C. It reveals that the contribution of the "solid PCM" on the energy savings is far less than that of the phase change of the PCM. The latent heat of the PCM during the phase transition plays a significant role on reducing the energy consumptions.

The temperature profiles of the surface b and c as showed in Fig. 3.7 are investigated (Fig. 3.13 and Fig. 3.14) to understand the influence of PCM on the energy savings. The solid lines and the dashed lines in the figures represent the temperature profiles of the vertical surfaces in different orientations with or without the addition of a PCM layer.

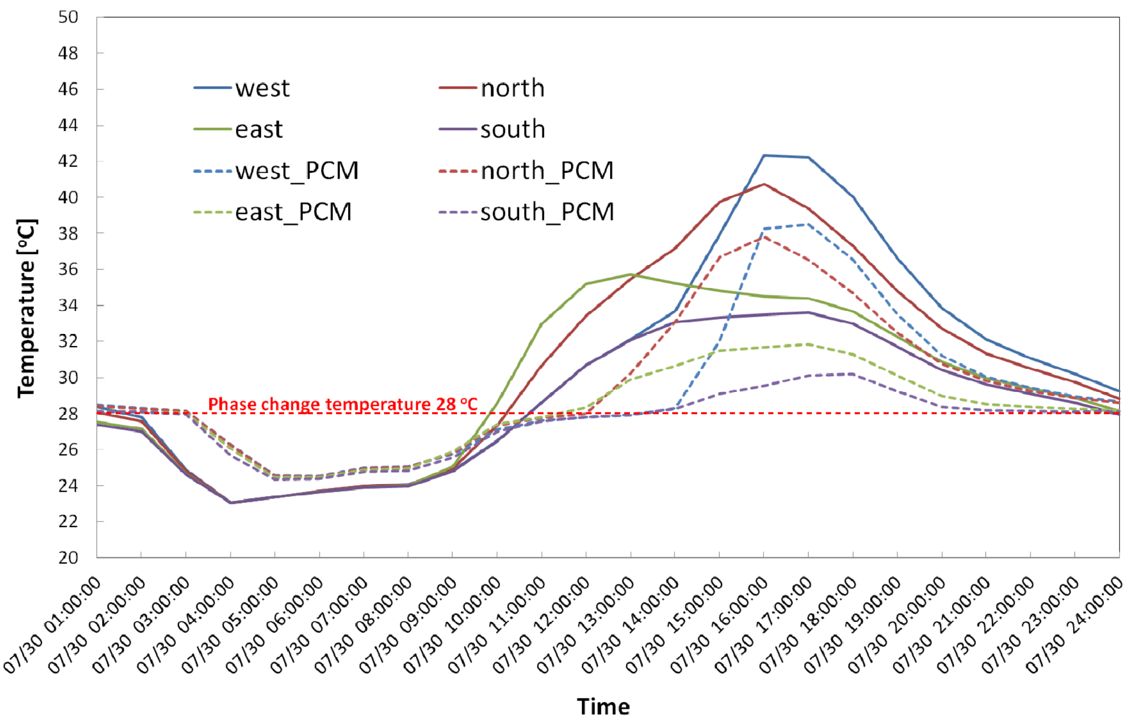

Fig. 3.13. Temperature of the outside surface of the concrete layer (surface b)

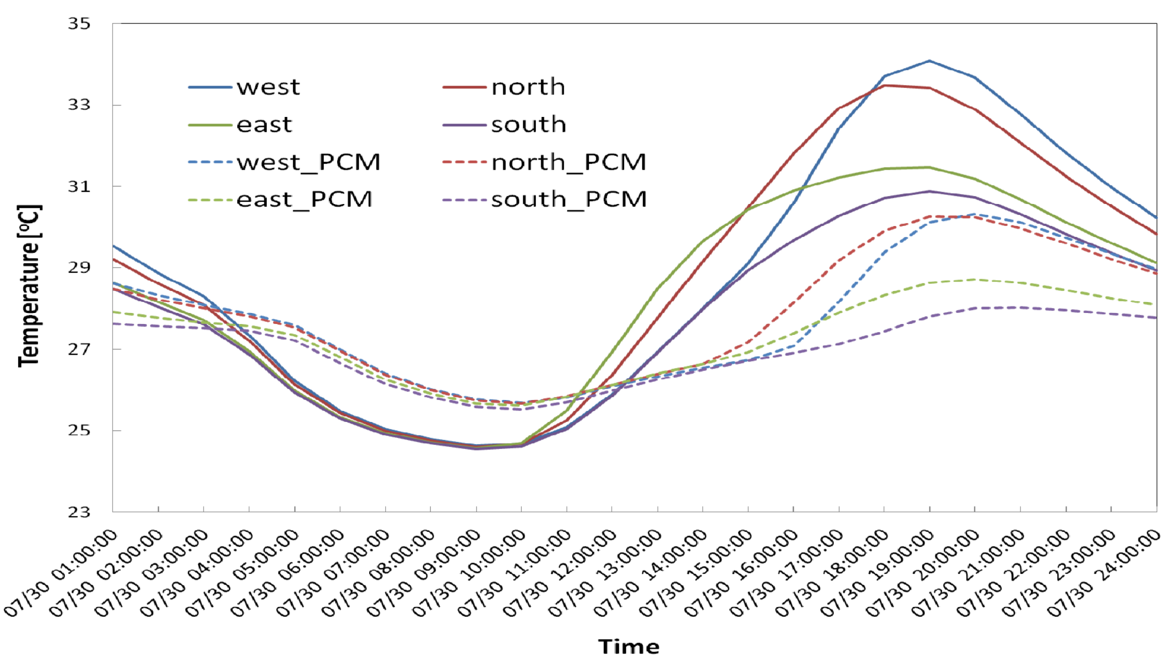

Fig. 3.14. Temperature of inside surface of the concrete layer (surface c)

As shown in Fig. 3.13, temperature variations on the outside surfaces of the concrete layer are large enough for the PCM to go through the full melting-freezing cycle. The large temperature variations on the outside surface result from the high intensity of solar radiation in the daytime that increases the surface temperature sharply even though the diurnal temperature range is very small, only 5-7◦C in Singapore. It is also observed that the fluctuations of the surface temperatures are attenuated by adding the PCM. The peak temperatures are reduced by 3-4°C while the temperatures are increased around 1.4°C on the valley of the curves, attributed to the "buffering effect" of the PCM, i.e., heat is absorbed by the PCM during the day and released when ambient cools down.

Another interesting observation in Fig. 3.13 is that the surface temperature profiles stay stable around 28°C, which is the phase change temperature of the PCM, for a long period of more than 8 hours after PCM is added. This is because during the phase transition around 28°C, the PCM can absorb and release the heat at almost isothermal condition due to its high latent heat of fusion.

Table 3.7. Average temperature of the inside surface [°C]

	West	North	East	South
without PCM	28.8	28.8	28.3	27.8
with PCM	27.8	27.8	27.3	27.0
temperature reduced	1.0	1.0	1.0	0.8

In Fig. 3.14, the fluctuations of the inside surface temperatures are reduced accordingly to the temperature variations on the outside surfaces by adding the PCM. The incoming heat is reduced during the day due to the lower surface temperatures by adding the PCM, while the heat released from the PCM when the ambient cools down elevates the surface temperatures resulting in larger energy consumption.

Consequently, the PCM achieves cooling energy savings during the day but increases the cooling energy load at night. However, it is observed that the temperature increased on the valley is relatively less than the temperature reduction of the peak and the average temperatures of the inside surfaces are reduced by adding the PCM as shown in Table 3.7, because much of the heat stored in the PCM is released to the outdoor environment at night when PCM placed outside due to the high thermal resistance of the concrete wall. Therefore, the energy savings are achieved by the PCM for a whole day under the climatic condition of Singapore because the energy savings in daytime typically outweigh the energy penalties at night.

3.4.2 Parametric studies

3.4.2.1 Phase change temperature

The energy consumption and the energy saving rate are shown in the Fig. 3.15 by adding the PCM with different phase change temperatures. Fig. 3.16 and Fig. 3.17 show the temperature profiles of the outside and inside surface of the PCM layer (surface a and b) on the west wall, respectively. The results and the analysis are similar for the PCM on the other orientations.

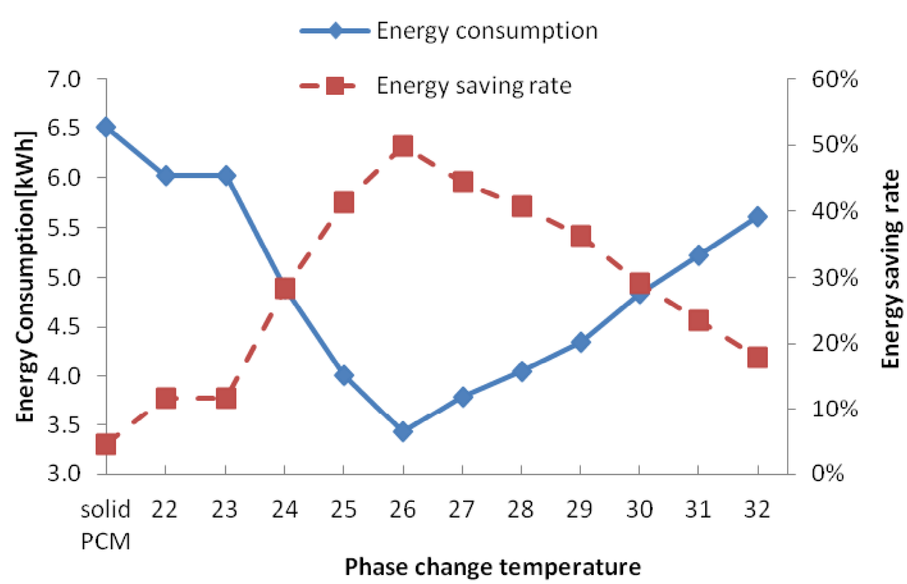

Fig. 3.15. Energy consumption and energy saving rate by adding PCM

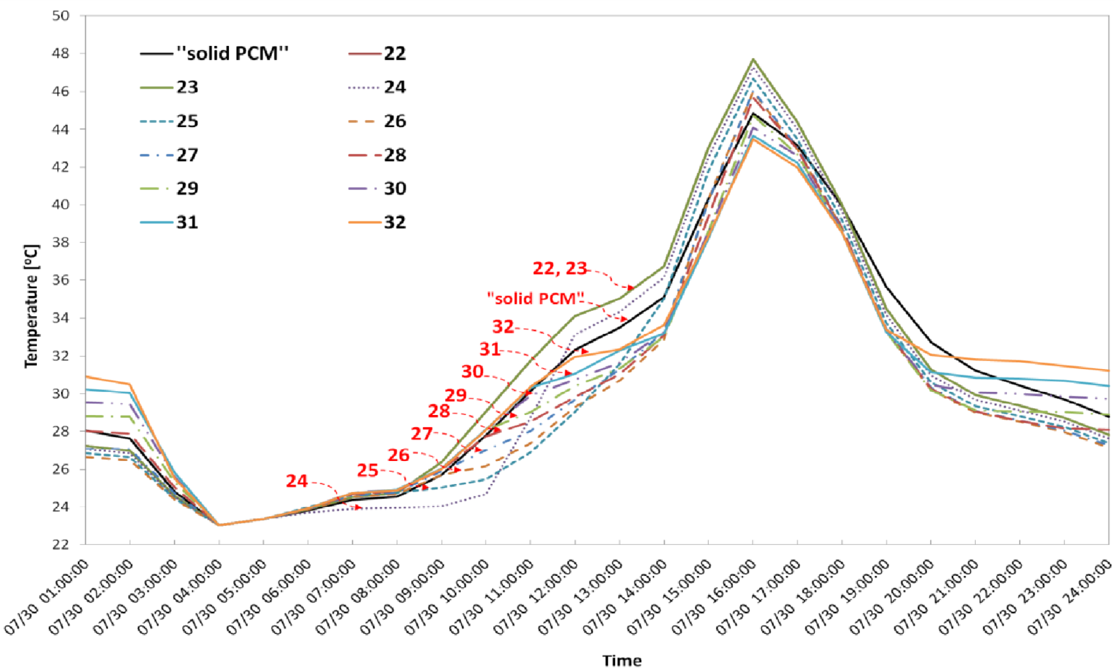

Fig. 3.16. Temperature of the outside surface of the PCM layer (surface a)

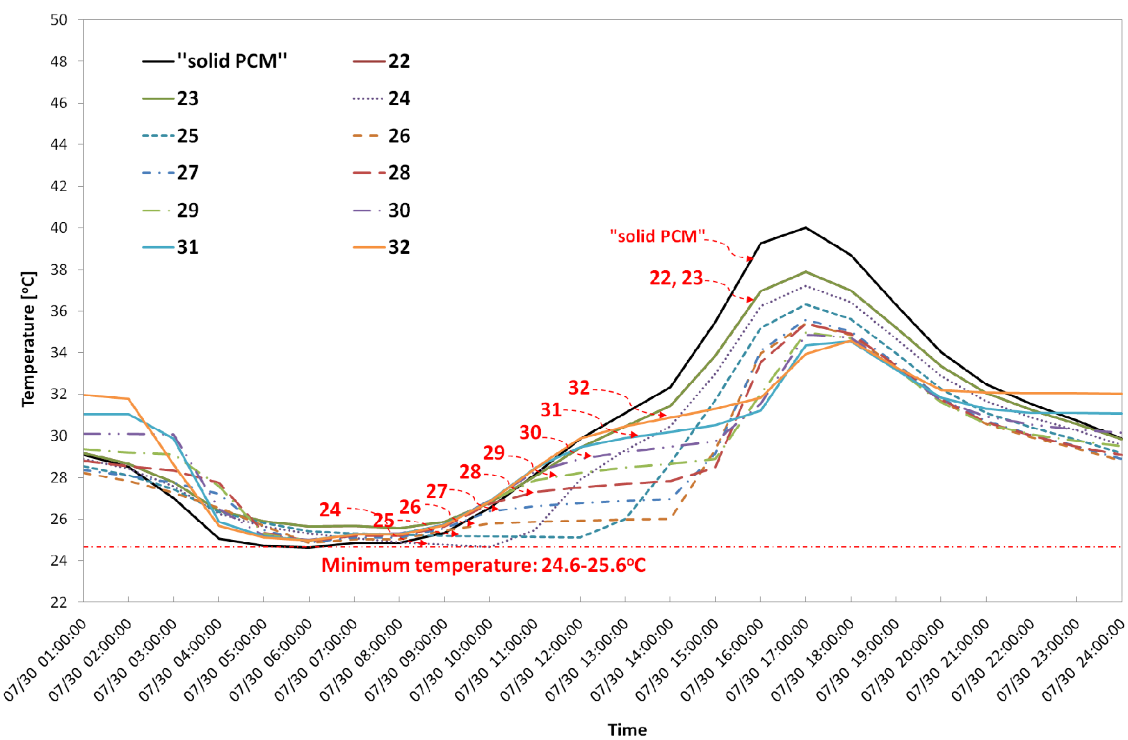

Fig. 3.17. Temperature of the inside surface of the PCM layer (surface b)

As can be seen from Fig. 3.15, energy saving rate increases with increasing phase change temperature and peaks at 26°C. After that, energy saving rate decreases with continuous increase of phase change temperature. The least energy saving is observed when PCM with phase change temperature of 23°C and below is used. This is attributed to the fact that the minimum temperature in the PCM layer as shown in Fig. 3.16 (outside surface) and 3.17 (inside surface) is higher than the phase change temperature. Therefore, PCM with phase change temperature below 23°C cannot solidify and always stays in the liquid state. As a result, the latent heat during phase change is not utilized for energy savings. A small increase in energy savings from the "solid PCM" to the PCM with phase change temperature of 22°C is due to the lower thermal conductivity of the PCM in liquid state, resulting in higher thermal resistance when PCM with phase change temperature of 22°C or 23°C is applied.

When PCM with a phase change temperature between the minimum temperature of the most outer PCM layer (23.0, Fig. 3.16) and the most inner PCM layer (25.6°C, Fig. 3.17) is used, partial phase change in the PCM layer is expected, i.e. PCM located near to the inner layer may stay in liquid without going through phase change in a day cycle. A higher phase change temperature enables more PCM to go through the melting-solidifying cycle in the layer therefore enhancing the efficiency of the PCM layer. As a result, energy saving increases with increasing phase change temperature from 23°C to 26°C as shown in Fig. 3.15.

To illustrate this point and to reveal the temperature gradient in the PCM layer, six equal spacing sections are defined in the PCM layer as shown in Fig. 3.18. Fig. 3.19-3.21 show the daily temperatures profile of the six sections in the PCM layer with phase change temperature from 24°C to 26 °C, respectively. As can be seen, the most outer PCM layer exhibits the largest temperature variation with the highest maximum temperature and the lowest minimum temperature in the PCM layer. The minimum temperature of each section increases from the most outer section to the most inner section as discussed above.

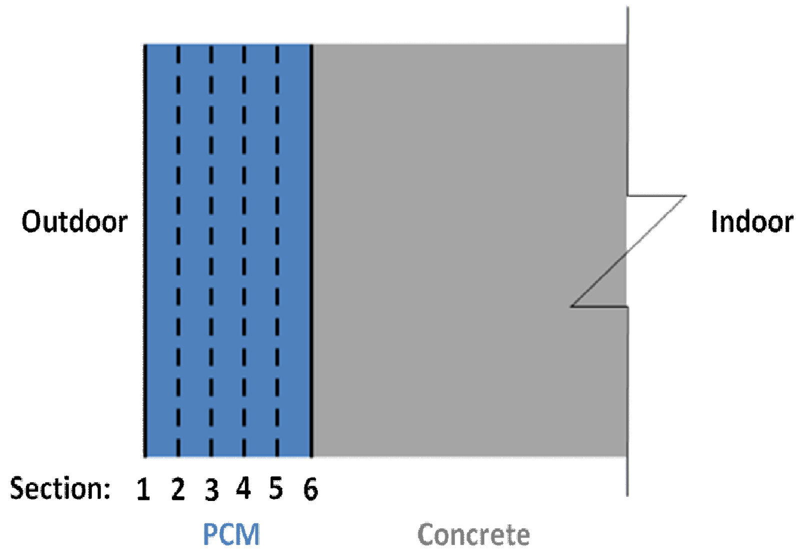

Fig. 3.18. Section depiction of the PCM layer

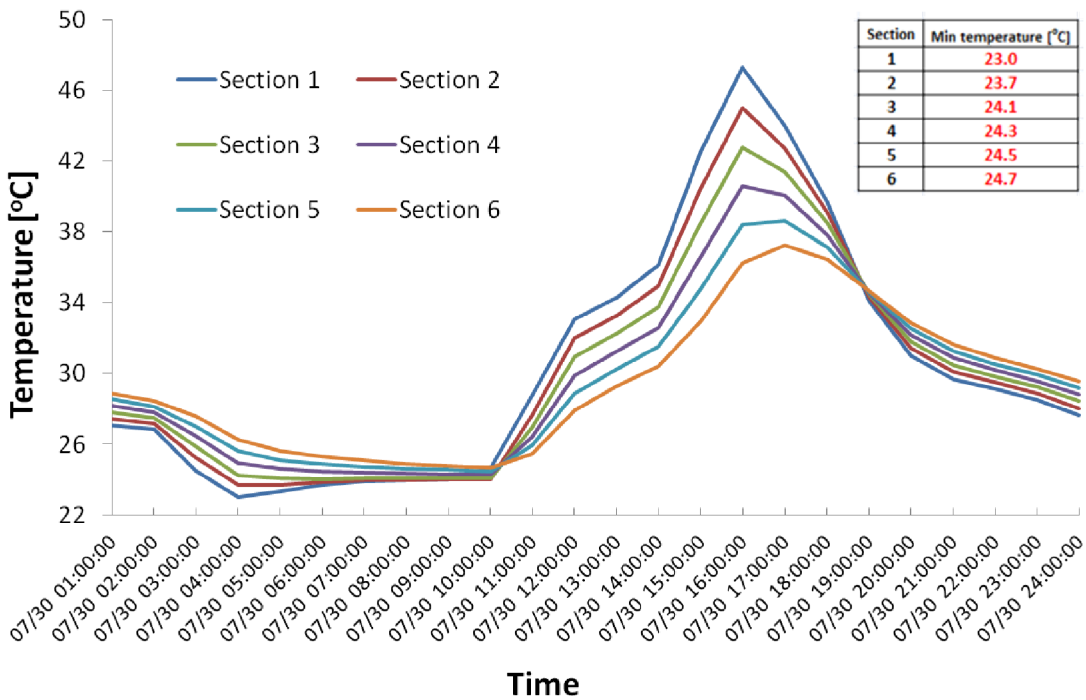

Fig. 3.19. Temperature of the sections in PCM layer (phase change temperature 24°C)

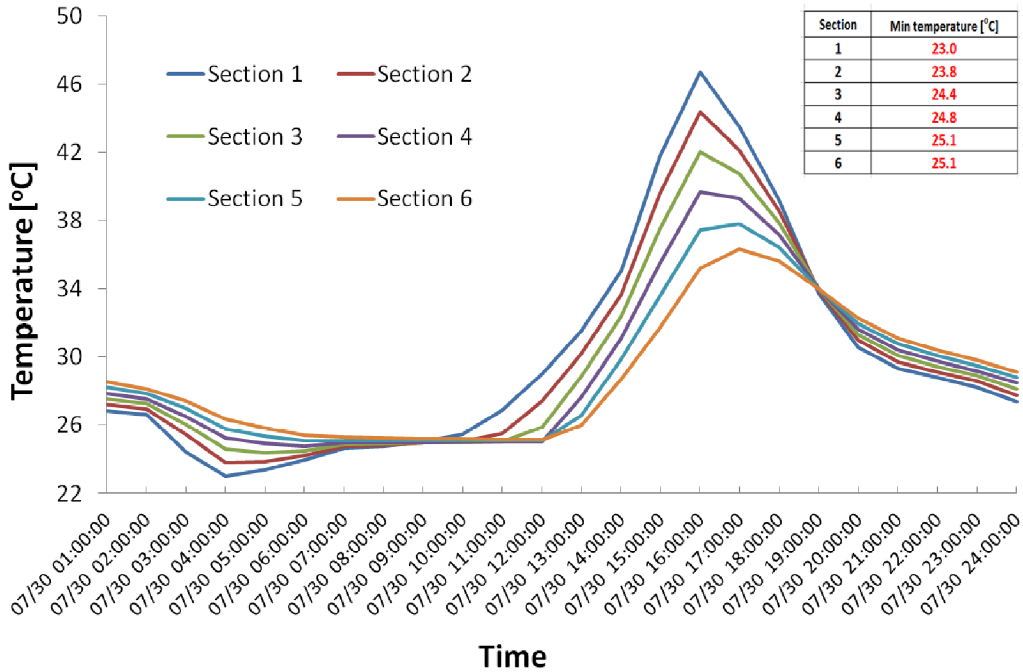

Fig. 3.20. Temperature of the sections in PCM layer (phase change temperature 25°C)

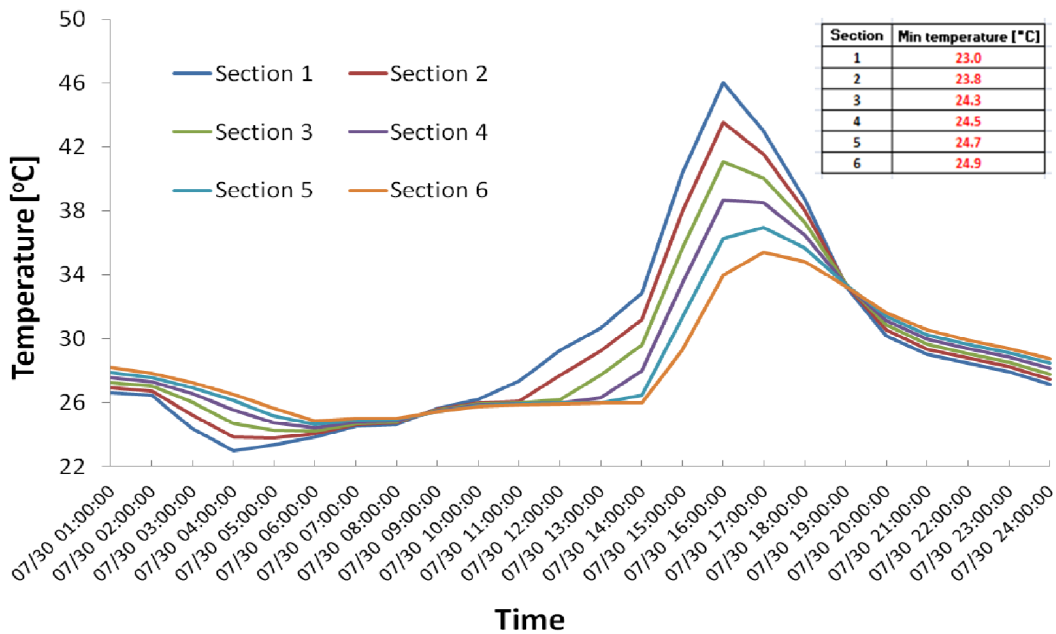

Fig. 3.21. Temperature of the sections in PCM layer (phase change temperature 26°C)

When PCM with a phase change temperature of 24°C is used as illustrated in Fig. 3.19, only PCM in section 1 and 2 can successfully release the heat and go through the solidifying cycle in the night. The majority of the PCM layer stays in liquid and is not utilized and therefore ending up with low energy saving. Similarly, PCM with a phase change temperature of 25°C is also partially utilized as shown in Fig. 3.20. However, larger proportion of the PCM can solidify compared with the 24°C PCM, which leads to higher energy savings. Fig. 3.21, on the other hand, shows the daily temperature profile of the PCM layer when PCM with a phase change temperature of 26°C is used. It is observed the minimum temperatures of all six sections are below the phase change temperature of the PCM, i.e. 26°C. This suggests the whole PCM layer can go through the melting and solidifying cycle and the latent heat of PCM is fully employed to contribute to the high energy savings as shown in Fig. 3.15.

When PCM with an even higher phase change temperature above 26°C is employed, the PCM layer is still able to go through the melting-solidifying cycle and the latent heat of the whole PCM layer is still fully utilized as long as the phase change temperature is not higher than the maximum temperature in the most inner layer (~38°C in this case). However, it is interesting to show that the energy saving is actually reduced with further increase of the phase change temperature.

Fig. 3.22 shows the daily temperature profile of the most inner surface of the concrete layer (surface c in Fig. 3.7b). As can be seen, use of PCM with phase change temperature of 26°C provides the lowest temperature gain of the inner surface of the concrete layer in a day and reduces the temperature gradient between the wall and the indoor air resulting in less heat transferred into the room which contributes to the highest energy saving. This may be understood by the following:

1. For phase change temperature below 26°C, only partial phase change is expected in the PCM layer as discussed above. As can be seen in Fig. 3.22, the period of temperature stabilization is obviously shorter for PCM with phase change temperature below 26°C because the latent heat of the PCM layer is only partially utilized.

2. The temperature of the PCM layer is stabilized around its phase change temperature because phase change occurs at almost isothermal condition. While all PCMs with phase change temperature above 26°C allow the full utilization of the PCM layer, another important factor contributes to cooling energy saving is to use PCM with lower phase change temperature that keeps the surface temperature low for a long time.

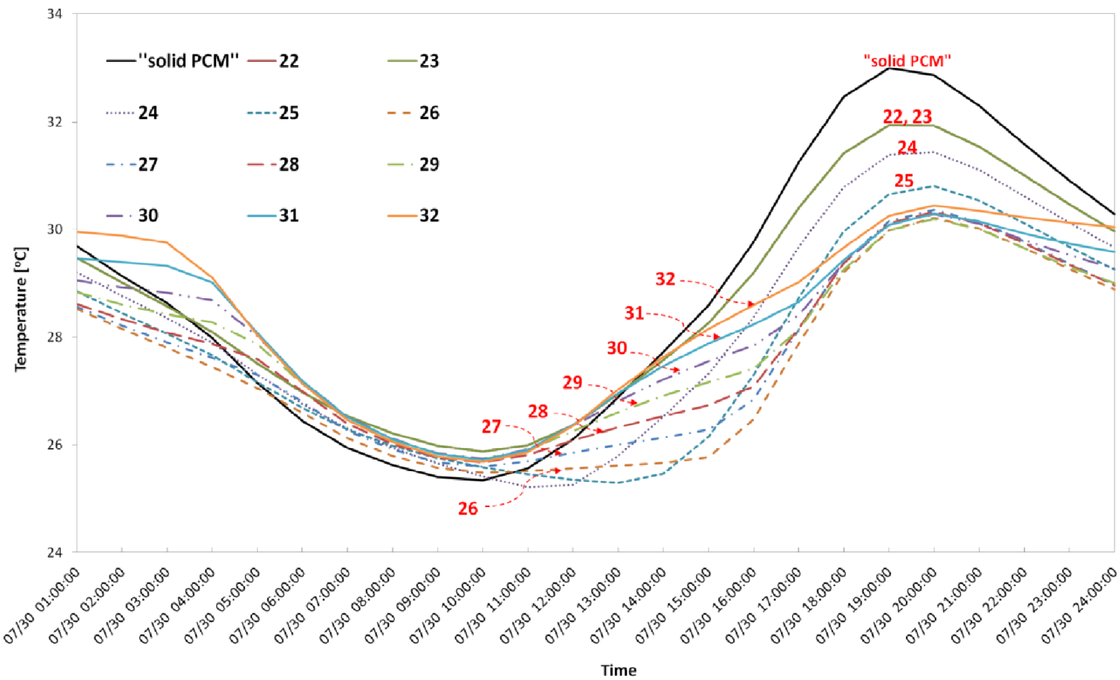

Fig. 3.22. Temperature of the inside surface of the concrete layer (surface c)

Additional observation in Fig. 3.22 is summarized below. The peak temperature is largely reduced when the phase change temperature increases from 22°C to 25°C and tends to be relatively stable when the phase change temperature reaches 26°C. This is due to the latent heat storage of the PCM is partially used when the phase change temperature is below 26°C and the amount of the PCM going through phase change increases as the phase change temperature rises. Consequently, the peak temperature decreases due to the increasing energy storage by the PCM in daytime when phase change temperature increases from 22°C to 25°C. At a phase change temperature 26°C and above, the whole layer of the PCM can be fully utilized and the heat absorbed by the PCM remains the same, so that the temperature increase in the daytime is similar for PCM with phase change temperature 26°C and above. In addition, the difference of the temperatures on the valley of the curves is relatively small comparing to that of the peak temperatures. This may be attributed to the fact the PCM is placed in the outside of the wall. Instead of penetrating to the concrete, the heat may be easily transferred to the ambient environment due to lower thermal resistance to the outdoor air.

Above discussion suggests that when PCM is placed on the outside surface, proper selection of PCM with suitable phase change temperature for building cooling load reduction in tropical climate is critical. The PCM should have a low phase change temperature but high enough to enable fully utilization of the PCM layer.

3.4.2.2 Temperature range of phase change and shape of enthalpy curve

Previous study assumes idealized phase change behavior in which phase change occurs in a very narrow temperature range of 0.1°C. In reality, phase change can occur in a wide temperature range and the enthalpy may changes non-linearly with temperature as shown in Fig. 3.10. Fig. 3.23 shows the effects of phase change range and shape of enthalpy curve on energy consumption and the energy saving rate for PCMs with different phase change temperature. Cases 1 to 3 as introduced in Section 3.3.2.2 are used to represent three different PCMs.

- Case 1 (0.1°C, linear): Idealized PCM with a narrow phase change temperature range of 0.1°C and a linear enthalpy-temperature curve.
- Case 2 (4°C, linear): PCM with a wider phase change temperature range of 4°C and linear enthalpy-temperature curve.
- Case 3 (4°C, non-linear): Practical PCM with a wider phase change temperature range of 4°C and a non-linear enthalpy-temperature curve.

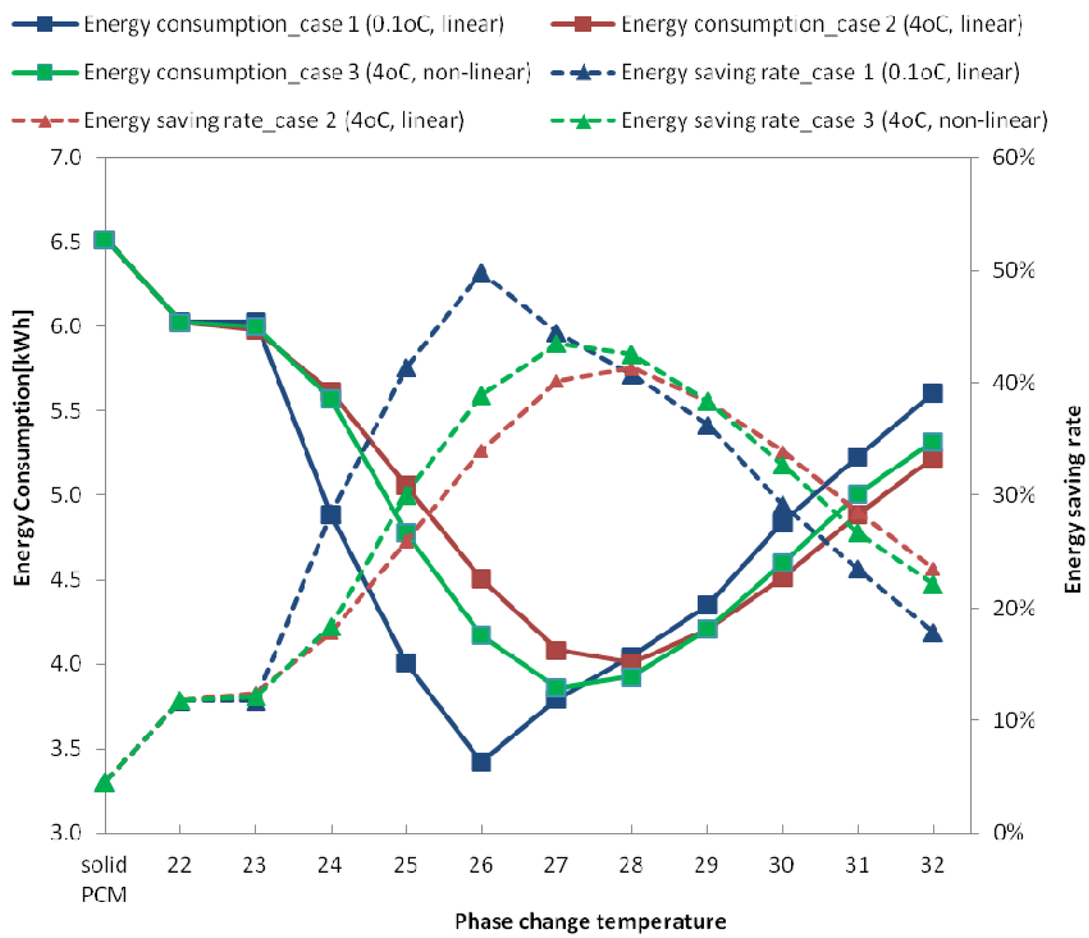

Fig. 3.23. Energy consumption and energy saving rate of case 1-3

General trend of the curves of cases 1 to 3 remains similar with reduced energy saving of around 5% and shift of the optimum phase change temperature to a higher level. In Case 2, it shows that the optimal phase change temperature is 28°C. According to the discussion in the last section, the phase change temperature should be selected to guarantee the latent heat of the PCM can be fully utilized. As a phase change range of 4°C is incorporated into the Case 2 PCM, the starting point of the melting process, 3°C lower than the defined phase change temperature, should be higher than the minimum temperature of the most inner PCM layer. As shown in Fig. 3.24, the minimum temperature of the most inner PCM layer ranges from 25°C to 25.6°C which suggests a phase change temperature higher than 28 °C or 29°C allows full utilization of the PCM layer.

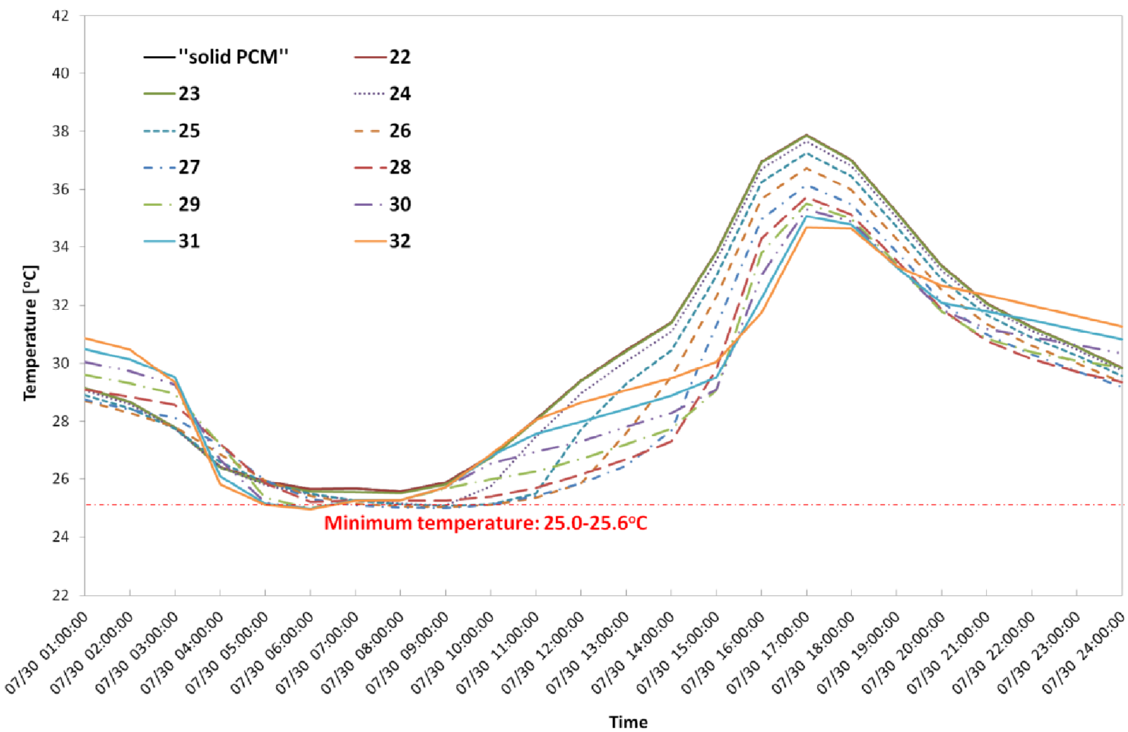

Fig. 3.24. Temperature of the most inner surface of the PCM layer in Case 2

Detailed analyses shows that PCM with phase change temperature of 28°C is not able to allow the whole layer to go through the solidifying phase as the minimum temperature of the most inner PCM layer is 0.2°C higher than the starting melting point of 25°C. Although 29°C PCM allows fully utilization of the latent heat, the optimal phase change temperature in Case 2 is still 28°C. This is attributed to the contribution of keeping lower surface temperature by using the 28°C PCM which compensates the negative impact of a small portion of un-utilized 28°C PCM layer.

In Case 3 when nonlinear enthalpy was considered, the optimum phase change temperature shifts to 27°C instead. Similar to Case 2, the minimum temperature of the most inner 27°C PCM layer is 25.3°C which is 1.3°C higher than the starting melting temperature (24°C) of the 27°C PCM. As a result, latent heat in the range of 24-25.3°C is not utilized in the PCM layer. This is mainly attributed to the non-linearity of the Case 3 PCM as shown in Fig. 3.11. Since the heat capacity of this range only accounts for about 8% of the total latent heat, the benefits of temperature stabilization at a lower level by choosing lower phase change temperature (27°C in this case) outweigh the disadvantages of a small portion of un-utilized latent heat.

Another observation is that the slope of the curves in Cases 2 and 3 is gentler than that in Case 1 which indicates the energy consumption/saving is less sensitive to the phase change temperature, i.e. higher tolerance to ambient climate change and improper selection of phase change temperature. This is attributed to wider phase change temperature range in Cases 2 and 3, which improves the adaptive capacity of the PCM to the temperature variation. However, larger phase change temperature range may compromise the optimal performance of PCM, e.g. 5% reduction in peak energy saving in Case 2 as compared to that in Case 1. This is mainly due to higher optimum phase change temperatures in Cases 2 and 3 result in higher wall temperature which increases energy usage.

Conclusively, the temperature range of phase change and the shape of the enthalpy-temperature curve influence the selection of the optimal phase change temperature. The larger phase change temperature range improves the adaptive capacity of the PCM to the temperature variations, but may compromise the best energy savings that the PCM can achieve.

In addition, according to the results in Section 3.4.2.1 and 3.4.2.2, the general principles to select the optimal phase change temperature of the PCM on the outside surface of the wall in the climatic condition of Singapore are provided as the followings:

- The starting point of the melting process should be close to the minimum temperature of the most inner surface of the PCM;
- Once the first principle is satisfied, the lowest phase change temperature should be selected.

- In case a PCM with wider temperature range of phase change and non-linearity of the enthalpy-temperature curve is used, a slightly higher phase change temperature is expected to achieve the optimum performance.

3.4.2.3 Location

The effects of PCMs' location on energy consumption and the energy saving rate as a function of phase change temperature are shown in Fig. 3.25. The idealized PCM in the case 1 is utilized. The PCM layer is placed either on the inside or on the outside surface of all vertical walls.

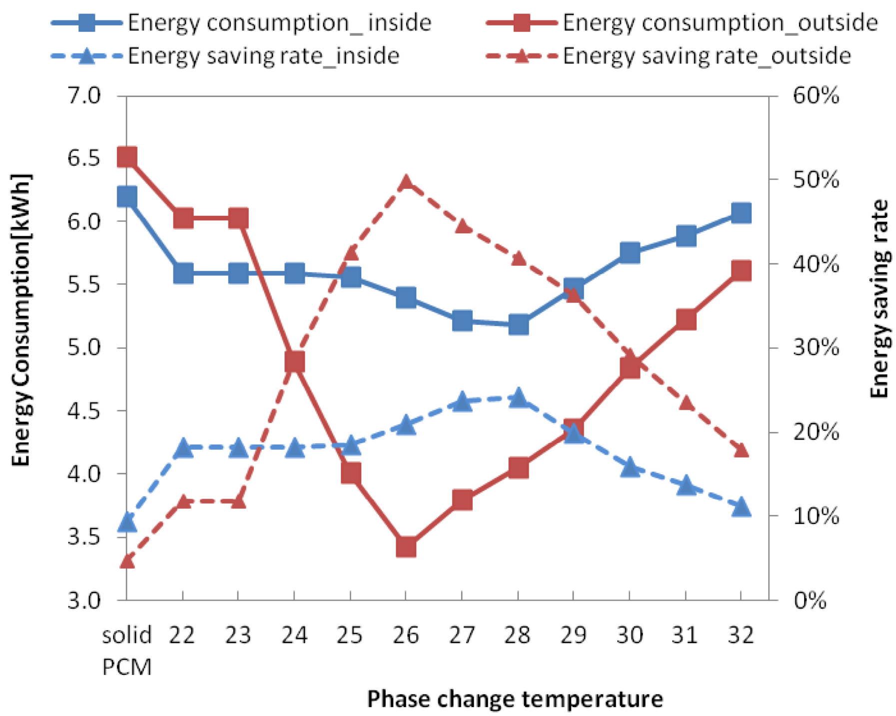

Fig. 3.25. Energy consumption and energy saving rate of PCM placed on the inside or outside surface of all vertical walls

It is observed that PCM placed on the outside surface registers lower energy consumption and higher energy saving and the optimum phase change temperature is different when PCM is placed on the inside surface as compared to the outside surface. It shows that the highest energy saving rate is 24% when the PCM is put on the inside surface, less than the value of 50% when PCM is placed outside. This is because the heat discharged from the PCM at night is prone to transfer to the room rather than to the outdoor environment when PCM put inside due to the high thermal resistance of the walls. The energy penalties at night are higher than that of the PCM put outside. This is confirmed by the temperature profiles of the inside surface of the wall as shown in Fig. 3.26, taking the west wall as an example.

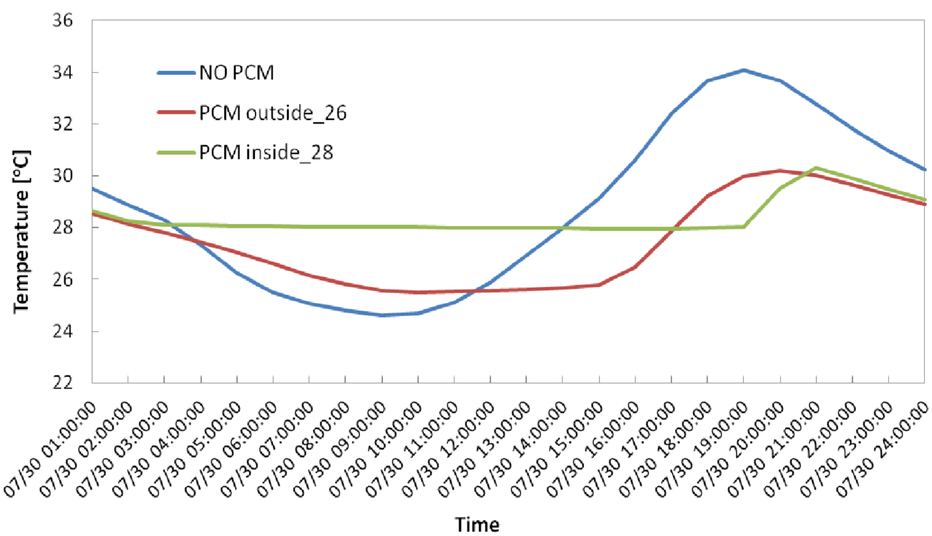

Fig. 3.26. Temperature profiles of the interior surface of the west wall

The cases that PCM with optimal phase change temperature when put inside (28°C) and outside (26°C) are compared with the case with no PCM. It is observed that the peak temperatures are largely reduced in both cases after the adoption of PCM, but when PCM put inside the temperature increased on the valley of the curve is much larger than that when PCM put outside resulting in higher energy penalties at night. It is therefore recommended that PCM should be placed on the outside surface of the vertical walls when PCM is used for passive cooling of buildings in Singapore.

In addition, Fig. 3.25 shows that the optimal phase change temperature is 28°C when PCM put on the inside surface of the walls, which is close to the average temperature of the inside surfaces of the vertical walls when PCM added as shown in Table 3.8, which is consistent with the simulation results from Neeper (2000). Table 3.8 reveals that the average surface temperatures are within 27.5-28.6°C due to the different solar radiation density on the different orientations. For each orientation, the average surface temperatures remain stable when the phase change temperature varies, while the temperature profiles are quite different as shown in Fig. 3.27 (taking the west wall as an example). It shows that the temperature profile of the inside surface is modified by adding the PCM even though the average temperature remains almost the same and the least fluctuation is achieved by adding PCM with the phase change temperature of 28°C.

Table 3.8. Average temperature of the inside surfaces of the vertical walls

Phase change temperature [°C]	Orientations			
	West	North	East	South
22	28.3	28.3	27.9	27.5
23	28.3	28.3	27.9	27.5
24	28.3	28.3	27.9	27.5
25	28.3	28.3	27.9	27.5
26	28.3	28.3	27.9	27.5
27	28.3	28.3	27.9	27.5
28	28.4	28.4	27.9	27.6
29	28.5	28.5	28.0	27.6
30	28.6	28.5	28.0	27.6
31	28.4	28.5	28.1	27.6
32	28.5	28.5	28.1	27.6

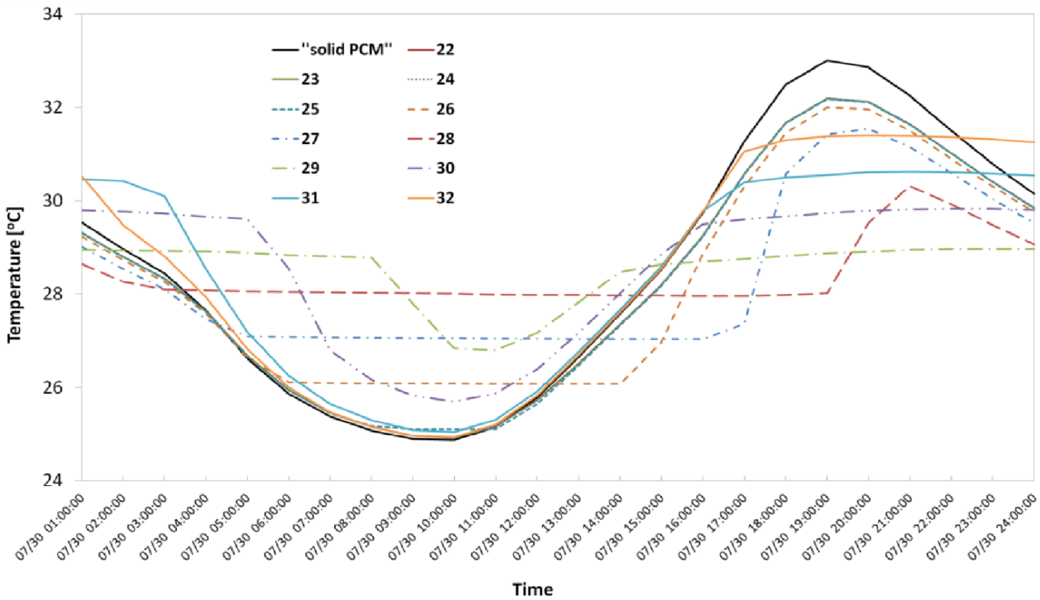

Fig. 3.27. Temperature profiles of the inside surface of the west wall (surface d) when PCM put on the inside surface

The cooling load resulting from the incoming heat transferred from the inside surface of the walls to the indoor air, is dominated by the heat convection. In EnergyPlus the interior convection flux is calculated using the heat transfer coefficients as follows.

$$q''_{conv} = h_c\left(T_s - T_a\right)$$

where, q''_{conv} *= convective heat flux to zone air.*

T_s *= inside surface temperature*

T_a *= indoor air temperature*

h_c*= inside convection coefficients.*

The default model of the inside surface convection algorithm, named TARP, is selected to calculate the inside convection coefficients (h_c). The convection model "TARP" correlates the convective heat transfer coefficient to the surface orientation and the difference between the surface and zone air temperatures (where ΔT = Surface Temperature - Air Temperature), derived from ASHRAE literature by Walton (1983).

Only natural convection is considered in this inside surface convection algorithm. The following correlation is used for a vertical surface.

$$h_c = 1.31|\Delta T|^{\frac{1}{3}}$$

Then the interior convection flux is expressed as:

$$q''_{conv} = 1.31 \cdot \Delta T^{\frac{4}{3}}.$$

where ΔT is positive due to the higher surface temperature than indoor air temperature. Therefore the modifications on the inside surface temperature profiles by PCM result in the difference of the convection heat from the inside surface to the zone air as shown in Fig. 3.28. The negative value indicates heat is transferred from the surface to the air. The lowest convection heat is added to the indoor air as PCM with phase change temperature of 28°C applied, giving the largest energy savings of the HVAC. This is attributed to that convection heat transfer is very sensitive to the temperature gradient ΔT to the power of 4/3. A steady temperature fluctuation on the wall temperature and therefore a stable ΔT result in lower energy consumption when 28°C PCM is used in the inside wall surface.

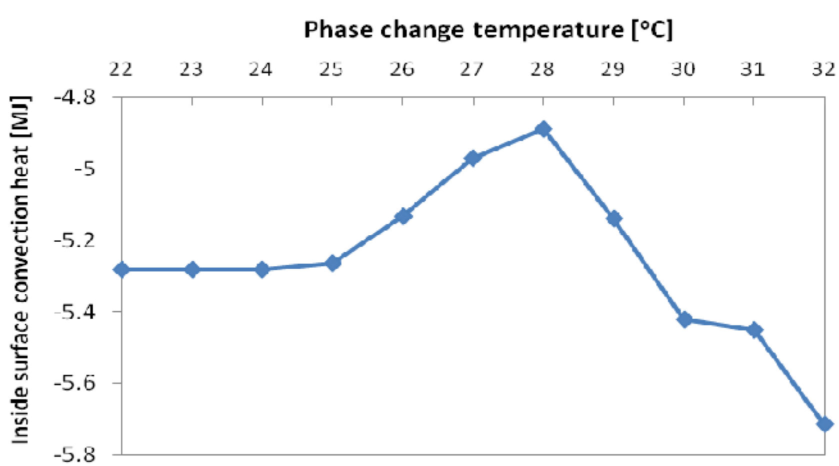

Fig. 3.28. Convection heat from inside surface to indoor air

3.4.2.4 Thickness

Fig. 3.29 and Fig. 3.30 show the effects of PCM layer thickness on the energy saving rates as a function of phase change temperature when PCM is used on the outside or on the inside surface, respectively.

For PCM applied on the outside surface of the walls as shown in Fig. 3.29 and Table 3.9, it reveals that the energy saving rates increase as the thicker PCM is added due to larger amount of incoming heat absorbed by the PCM. It is noticed that the largest energy saving is achieved around phase change temperature of 26°C when the thickness of PCM layer is less than 50 mm. This is because the minimum temperature of the most inner PCM layer is slightly changed as the thickness of PCM increases from 3 mm to 50mm. As the thickness keeps increasing, the minimum temperature of the most inner PCM layer is decreased and therefore the optimal phase change temperature allowing fully utilization of the latent heat is also reduced.

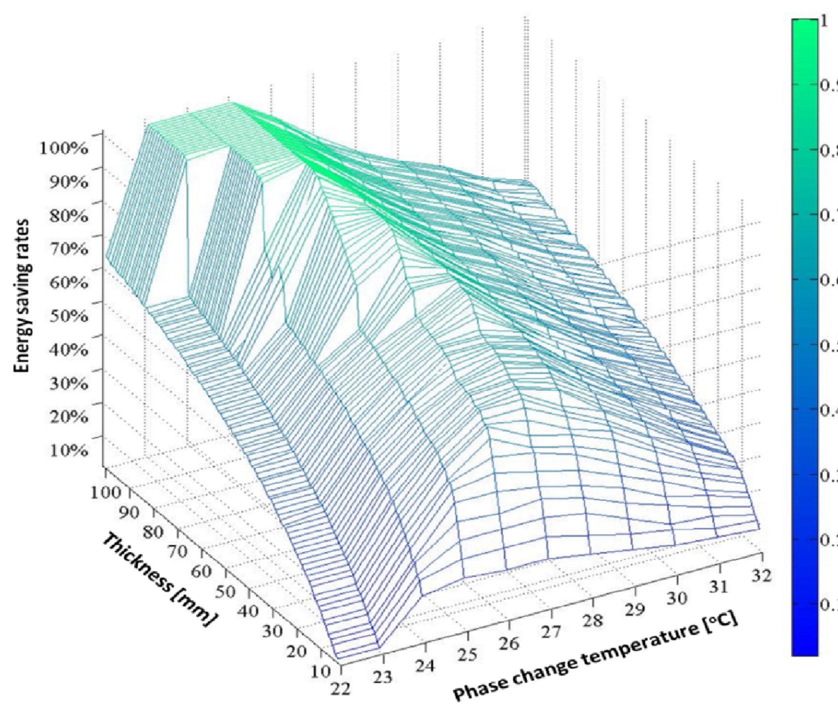

Fig. 3.29. Energy saving rates of PCM located outside as a function of phase change temperature and thickness

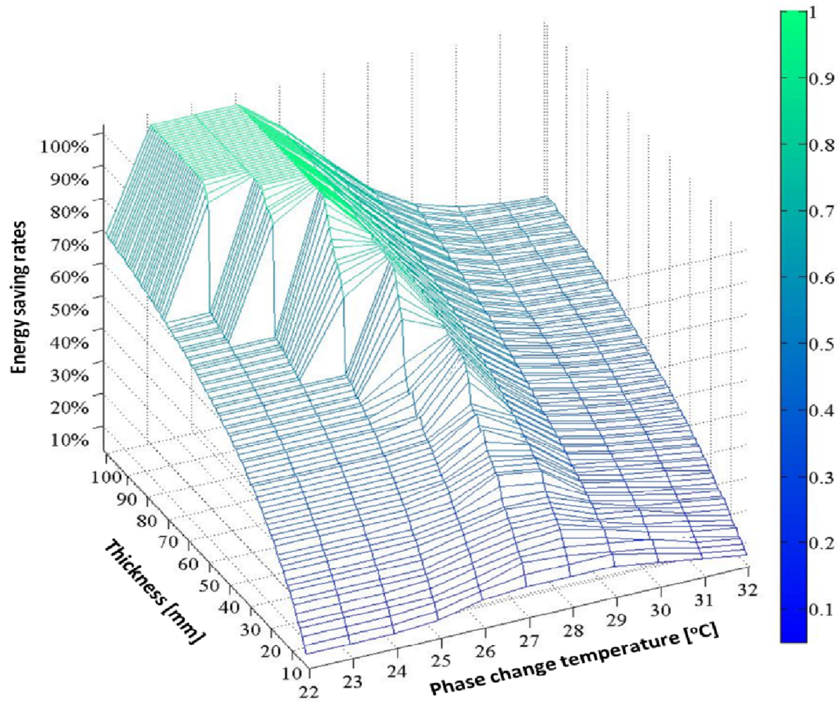

Fig. 3.30. Energy saving rates of PCM located inside as a function of phase change temperature and thickness

For the PCM applied on the inside surface of the walls as shown in Fig. 3.30 and Table 3.10, it is also noticed that the energy saving rate rises and the optimal phase change temperature becomes lower as the increase of the thickness. This is because the average temperature of the inside surface of the wall is reduced as the thickness of PCM increases as shown in Table 3.10, which directly decreases the convective heat added to the indoor air. In addition, the optimal phase change temperature in Table 3.10 shows good accordance with the average temperature of the inside surface of the walls (the optimum cases are highlighted) as shown in Table 3.11. It is confirmed that the optimal phase change temperature should be selected close to the average temperature of the inside surface of the wall when PCM placed inside.

Table 3.9. Energy saving rates of PCM located outside as a function of phase change temperature and thickness

Thickness [mm]	Phase change temperature [°C]										
	22	23	24	25	26	27	28	29	30	31	32
3	2%	2%	14%	16%	15%	15%	13%	11%	9%	8%	7%
4	3%	3%	18%	21%	21%	21%	18%	15%	13%	10%	9%
5	5%	5%	19%	26%	26%	26%	24%	19%	14%	13%	10%
6	6%	6%	22%	31%	30%	31%	28%	23%	19%	15%	12%
7	7%	7%	22%	36%	36%	34%	31%	27%	21%	18%	14%
8	9%	9%	25%	39%	41%	38%	35%	30%	25%	19%	15%
9	10%	10%	26%	41%	45%	43%	39%	33%	27%	22%	17%
10	12%	12%	28%	41%	50%	44%	41%	36%	29%	23%	18%
20	23%	23%	40%	50%	58%	60%	57%	47%	39%	32%	25%
30	32%	32%	47%	57%	65%	65%	61%	51%	43%	36%	29%
40	39%	39%	53%	62%	68%	74%	64%	56%	47%	40%	34%
50	45%	45%	57%	79%	87%	76%	66%	59%	50%	43%	39%
60	50%	50%	62%	93%	89%	78%	68%	62%	54%	47%	42%
70	54%	54%	97%	100%	90%	79%	70%	64%	56%	50%	45%
80	58%	58%	100%	100%	91%	80%	72%	66%	60%	53%	49%
90	61%	100%	100%	100%	91%	82%	73%	68%	62%	56%	50%
100	64%	100%	100%	100%	92%	83%	75%	69%	64%	57%	53%

Table 3.10. Energy saving rates of PCM located inside as a function of phase change temperature and thickness

Thickness [mm]	Phase change temperature [°C]										
	22	23	24	25	26	27	28	29	30	31	32
3	6%	6%	6%	7%	10%	11%	11%	11%	9%	7%	5%
4	8%	8%	8%	9%	12%	14%	14%	14%	11%	8%	6%
5	10%	10%	10%	11%	13%	17%	16%	14%	12%	9%	7%
6	12%	12%	12%	12%	15%	18%	18%	16%	14%	10%	8%
7	13%	13%	13%	14%	17%	19%	20%	17%	13%	11%	8%
8	15%	15%	15%	16%	18%	21%	22%	19%	15%	12%	10%
9	17%	17%	17%	17%	20%	22%	23%	19%	16%	13%	10%
10	18%	18%	18%	18%	21%	24%	24%	20%	16%	14%	11%
20	31%	31%	31%	31%	33%	38%	36%	26%	23%	21%	19%
30	40%	40%	40%	40%	41%	49%	42%	32%	29%	27%	25%
40	48%	48%	48%	48%	53%	63%	47%	36%	34%	31%	30%
50	53%	53%	53%	78%	84%	66%	51%	41%	38%	36%	35%
60	58%	58%	58%	100%	86%	69%	55%	45%	41%	40%	39%
70	61%	62%	100%	100%	87%	72%	58%	49%	44%	43%	42%
80	65%	100%	100%	100%	88%	74%	61%	52%	47%	46%	45%
90	67%	100%	100%	100%	89%	76%	63%	54%	50%	49%	48%
100	70%	100%	100%	100%	90%	77%	65%	57%	53%	51%	50%

Table 3.11. Average temperature of the inside surface when PCM put inside

Thickness [mm]	Phase change temperature [°C]										
	22	23	24	25	26	27	28	29	30	31	32
3	28	28	28	28	28	28	28	28	28	28	28
4	28	28	28	28	28	28	28	28	28	28	28
5	28	28	28	28	28	28	28	28	28	28	28
6	28	28	28	28	28	28	28	28	28	28	28
7	28	28	28	28	28	28	28	28	28	28	28
8	28	28	28	28	28	28	28	28	28	28	28
9	28	28	28	28	28	28	28	28	28	28	28
10	28	28	28	28	28	28	28	28	28	28	28
20	28	28	28	28	28	28	28	28	28	28	28
30	27	27	27	27	27	27	28	28	28	28	28
40	27	27	27	27	27	27	27	28	28	28	28
50	27	27	27	26	26	27	27	28	28	28	28
60	27	27	27	25	26	27	27	27	28	28	28
70	27	27	24	25	26	26	27	27	27	27	27
80	27	23	24	25	26	26	27	27	27	27	27
90	27	23	24	25	26	26	27	27	27	27	27
100	27	23	24	25	26	26	27	27	27	27	27

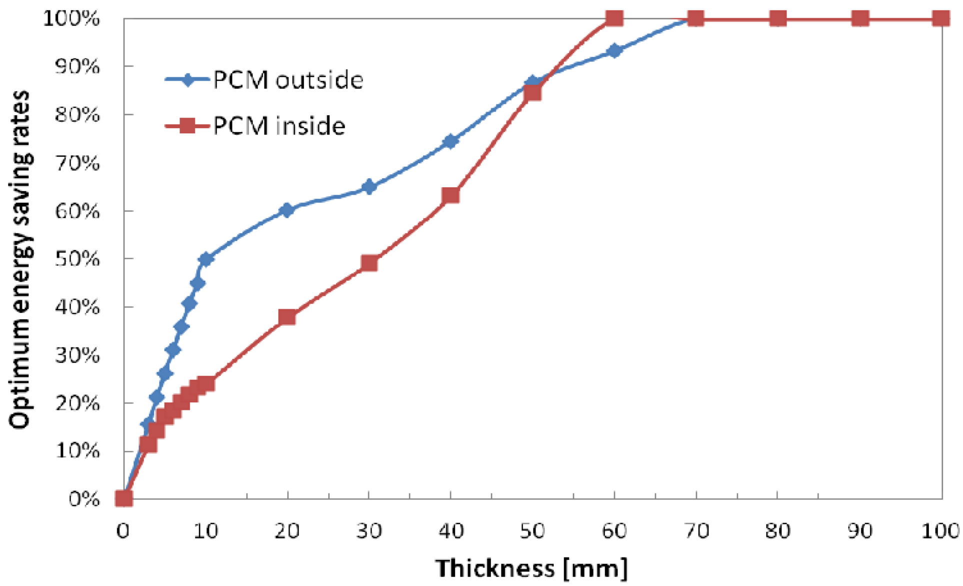

Fig. 3.31. Optimum energy saving rates of PCM as a function of thickness

Fig. 3.31 shows the optimum energy saving rates by adding PCM as a function of thickness. It reveals that higher energy saving is achieved when the same amount of PCM is placed on the outside surface as compared to on the inside surface of the wall. However, the difference on energy saving between the two scenarios reduces with increasing thickness. As the thickness of the PCM layer is more than 70 mm, both scenarios is able achieve 100% energy saving. This indicates that the amount of PCM is sufficient to absorb all incoming heat and keeps the wall temperature to below the set-point of the indoor air temperature (25°C). Therefore, no cooling load is induced by the incoming heat through building façades. In addition, it was observed that the curve of PCM outside exhibits steep increase when the PCM is thinner than 10 mm suggesting high efficiency and cost benefit of using thin PCM layer on the outside of building envelope.

Chapter 4 EFFICACY OF PCM APPLIED WITH COATINGS

4.1 Overview

Advanced coating system such as solar reflective paint, i.e. cool paint, and thermal insulation paint may be used together with PCM for passive cooling of buildings. In this chapter, potential synergy between PCM and these coatings was investigated respectively, as reported in Section 4.2 and 4.3. A summary was included in the last section.

4.2 Efficacy of PCM applied with solar reflective paint

Applying solar reflective paint on the building exterior can be an effective way to reduce the cooling loads of buildings in tropics. Solar reflective paint effectively reflects solar radiation and emits the absorbed heat away from the building due to its high reflectivity as well as high emissivity to prevent the building been heated up. However, solar reflective paint has negligible resistance to conductive heat transfer and cannot prevent conductive heat penetration into building. PCM with high latent heat capacity can be an ideal complementation to the deficiency of solar reflective paint. However, the use of PCM together with solar reflective paint may alter the selection of PCM to achieve the optimum performance. In this section, the effects of solar reflective coating on PCM performance were investigated.

4.2.1 Modelling of solar reflective paint

Due to small thickness of several tens to hundreds micron meters, the thermal resistance of solar reflective paint can be neglected. As such, the solar reflective coating was not simulated as an additional layer in EnergyPlus. Instead, only the exterior surface properties of the façade were modified in the simulation model to reflect the effects of solar reflective paint on the passive cooling.

Based on the model in the bench mark study, the inputs “Thermal Absorptance” and “Solar Absorptance” were modified in EnergyPlus to capture the high reflectivity and high emissivity of solar reflective paint. The first parameter represents the fraction of incident long wavelength radiation absorbed by the material. It is used to calculate the long wavelength radiant exchange between various surfaces, which is equal to the thermal emissivity. The second parameter represents the fraction of incident solar radiation, including the visible spectrum as well as infrared and ultraviolet wavelengths, absorbed by the material. It is used to calculate the amount of incident solar radiation absorbed by surfaces. Solar reflectivity is equal to 1 minus the value of Solar Absorptance (US.DOE 2013).

Table 4.1. Input for absorptance values in the model

	Thermal Absorptance	Solar Absorptance
E+ default value	0.9	0.7
Solar reflective paint	0.9	0.5

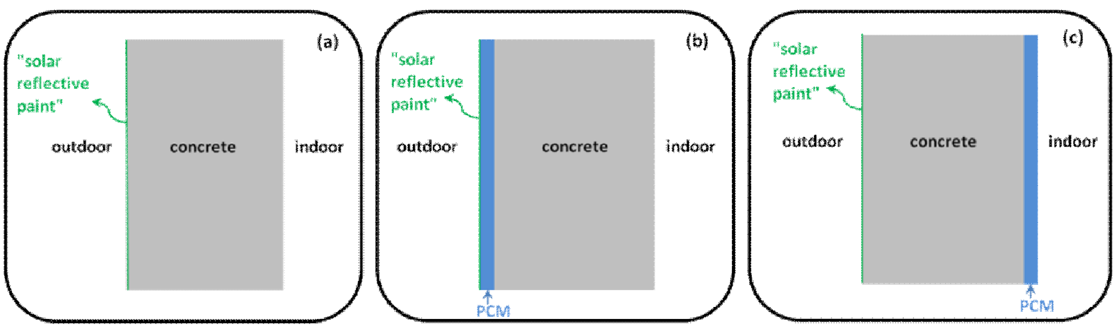

Fig. 4.1. Composition of the wall: (a) wall with solar reflective paint; (b) wall with solar reflective paint and PCM outside; (c) wall with solar reflective paint and PCM inside

Table 4.1 exhibits the input for absorption values in the model. In EnergyPlus, the default value of thermal absorptance (0.9) is close to the thermal emissivity of solar reflective paint. From the experimental results from Levinson (2009), it is found that for different colours, the solar reflectance of solar reflective paint is 0.15-0.37 higher than that of the standard paint with the same colour. Therefore, in the simulation model, a general increase of 0.2 on the solar reflectance was adopted to simulate the efficacy of solar reflective paint over the facades with the same colour as shown in Table 4.1. Absorption values of solar reflective paint were adopted on the exterior surfaces of the vertical walls and default values were used for the other surfaces.

In addition, the idealized PCM in the bench mark was incorporated in the model to study the efficacy of PCM applied together with solar reflective paint. PCM with varied phase change temperature within 22-32°C was placed on the outside and inside surface of the vertical walls respectively. The composition of the wall with solar reflective paint and PCM is shown in Fig. 4.1.

4.2.2 Results and discussion

The temperature profiles of the outside and the inside surface of the west wall are shown in Fig 4.2 and 4.3, respectively. Significant reductions of the outside surface temperature in daytime by adding solar reflective paint are observed and the lowest surface temperature remains the same, indicating the property of solar reflective paint that it keeps the surface cooler in daytime by reflecting larger amount of solar radiation but has limited effects at night. Fig 4.3 shows that the temperature of the inside surface is also reduced by adding the solar reflective paint and the average temperature is reduced from 28.8°C to 27.8°C.

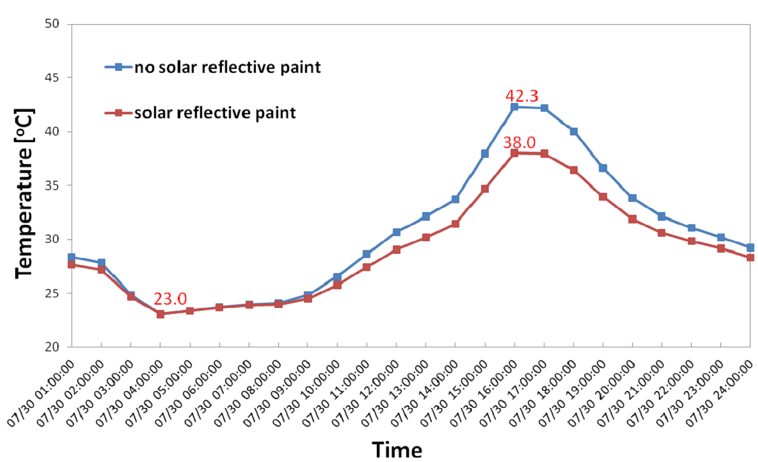

Fig. 4.2. Outside surface temperature of the west wall

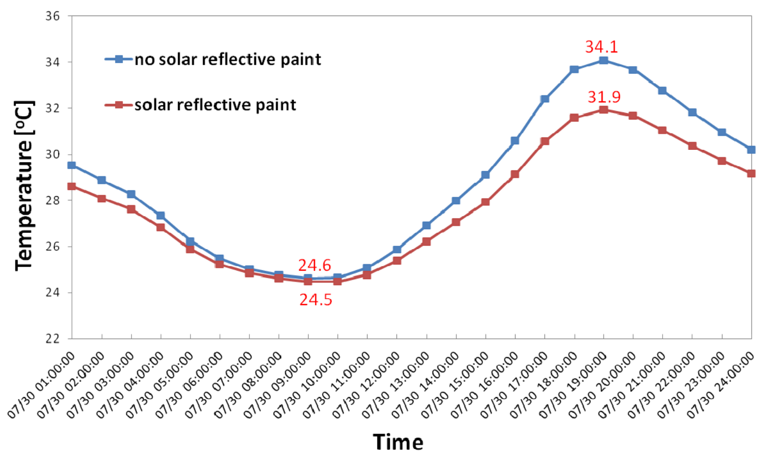

Fig. 4.3. Inside surface temperature of the west wall

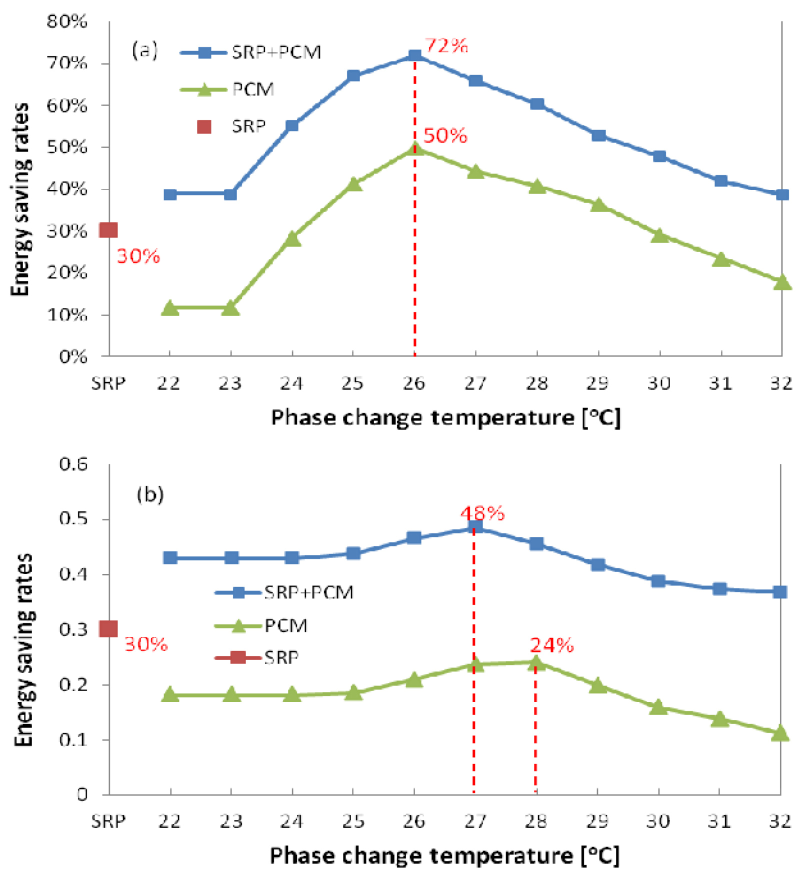

Fig. 4.4. Energy saving rates by adding solar reflective paint and PCM: (a) PCM put outside; (b) PCM put inside

Fig 4.4 shows the energy saving rates by adding the solar reflective paint (SRP) and PCM with different phase change temperature of 22-32°C. It shows that energy savings of 30% is achieved by adding the solar reflective paint alone (the isolated red square). The blue curve represents the energy saving rates of solar reflective paint and an additional layer of PCM and the green curve represents the results when PCM applied alone as studied in Chapter 3.

As shown in Fig. 4.4 (a), when PCM is applied on the outside surface of the wall, the largest energy saving rate is 72% by adding solar reflective paint combined with PCM and the optimal phase change temperature remains the same (26°C) compared with PCM applied alone. As we discussed previously, the optimal phase change temperature should be selected as the lowest phase change temperature that can make sure the latent heat of the PCM can be almost fully utilized, which highly depends on the minimum temperature that the PCM can go through. It is showed in Fig. 4.2 that the solar reflective paint has little impact on the minimum temperature of the wall at night. Therefore, the selection of optimal phase change temperature of PCM put outside is not affected by adding the solar reflective paint.

The results of solar reflective paint used with an additional layer of PCM put inside in Fig. 4.4 (b) reveal that the optimal phase change temperature is 1°C lower than the value when PCM used alone. This is because the average temperature of the inside surface of the wall is reduced by adding the solar reflective paint, which is around 27°C when PCM with different phase change temperature added as shown in Table 4.2. According to the principle that the optimal phase change temperature should be selected close to the average temperature of the inside surface of the wall, 27°C is selected as the optimal phase change temperature, which is lower than the optimal value when PCM applied alone.

Table 4.2. Average temperature of the inside surfaces of the vertical walls after adding solar reflective paint

Phase change temperature [°C]	Orientations			
	West	North	East	South
22	27	27	27	27
23	27	27	27	27
24	27	27	27	27
25	27	27	27	27
26	27	28	27	27
27	28	28	27	27
28	28	28	27	27
29	28	28	27	27
30	28	28	27	27
31	28	28	27	27
32	28	28	27	27

As shown in Fig. 4.4, the energy saving rates by using solar reflective paint alone is 30% and a further increase of 42% and 18% is achieved by adding a layer of PCM on the outside surface and inside surface respectively. It indicates that solar reflective paint can effectively reduce the cooling load by reflecting the solar radiation and the conducted heat then can be absorbed by the additional PCM layer to further improve the performance for passive cooling.

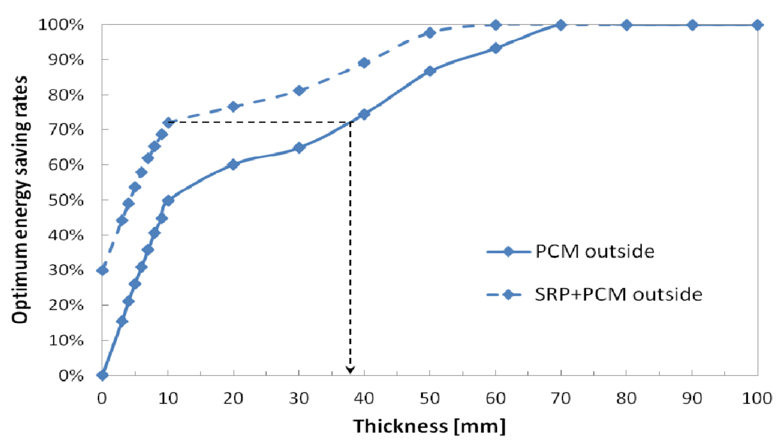

Fig. 4.5. Optimum energy saving rates of PCM placed outside with and without SRP as a function of thickness

In addition, in the tropical regions like Singapore, the high density of solar radiation significantly increases the cooling load of buildings, inducing a large amount of heat transferred into indoor environment. Only using the PCM to absorb the conducted heat in the building envelope is not cost efficient due to its relatively higher price than the normal construction materials. By using solar reflective paint on the building exterior as the "first protection" through its high reflectivity, the amount of the PCM could be largely reduced to achieve a certain amount of energy savings. Fig. 4.5 shows the optimum energy saving rates of PCM placed outside with and without SRP as a function of thickness. It shows that the thickness of PCM to achieve 100% energy saving is reduced by 10 mm after applying SRP on the building exterior, indicating that the SRP reduces the incoming heat through building facades by its high reflectivity. As shown in the figure, around 40 mm thick PCM is needed to achieve the same amount of energy savings of 10 mm thick PCM together with SRP. Therefore, considering the relatively high cost of PCM, it is more economically beneficial to apply PCM together with solar reflective paint.

4.3 Efficacy of PCM applied with thermal insulation paint

Applying thermal insulation paint to building surface provides additional thermal resistance to the building envelope due to its low thermal conductivity, which is around 0.07-0.2 W/m*K for the commercial insulation paints with different formulas (Kiil 2014). Such coating cannot provide the same degree of insulation as traditional insulation material (e.g., mineral wool or polystyrene foam) due to its thin thickness of a few millimeters, but has an advantage that it is easy to be applied to existing buildings for the purpose of energy-oriented refurbishments, especially for the concrete constructions in Singapore. The addition of PCM into to thermal insulation paint may greatly improve the heat capacity of the thin coating and reduce the cooling load by absorbing the incoming heat.

4.3.1 Modelling of thermal insulation paint with PCM

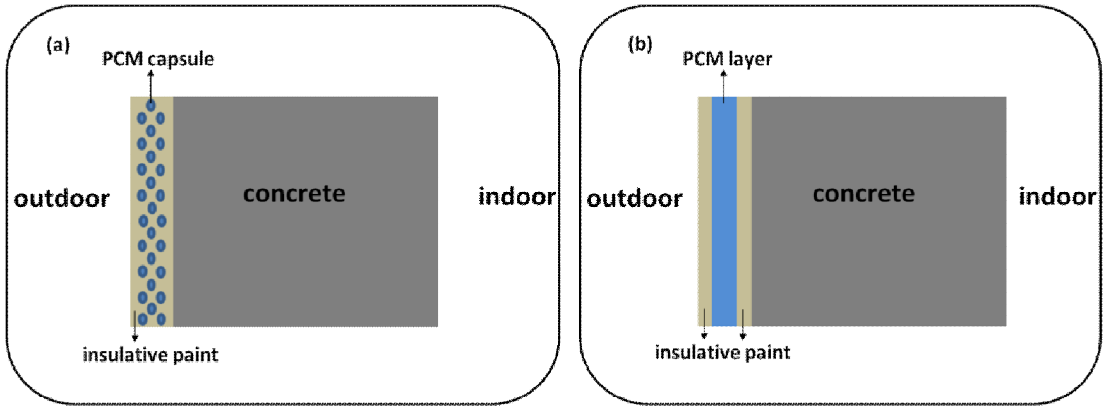

Fig. 4.6. (a) Profile of the vertical wall with insulation paint incorporating PCM micro-capsules; (b) Profile of the vertical wall with insulation paint layer and PCM layer simulated in the model

Fig. 4.6 (a) shows the insulation paint incorporating PCM micro-capsules applied to the outside surface of the vertical wall. Because only material with homogeneous layer is allowed in EnergyPlus, the PCM micro-capsules are simplified as a continuous layer in the model with a layer of insulation paint on each side as shown in Fig. 4.6 (b). The simulation model is based on the model in the bench mark study with the idealized PCM. The thickness of the PCM layer is 1.5 mm and the insulation paint layer on each side is 0.75 mm. The thermal conductivity of insulation paint is selected as 0.1 W/m*K.

4.3.2 Results and discussion

Fig. 4.7 shows the energy saving rates by adding insulation paint and PCM. The blue curve represents the energy saving rate of insulation paint incorporating PCM with varied phase change temperature as shown in Fig. 4.6 (b). It is found that the optimal phase change temperature when PCM and the insulation paint applied together remains the same (27°C) as that when PCM used alone on the outside surface of the wall because the thin layer of insulation paint does not have much influence on the minimum temperature that the PCM can go through.

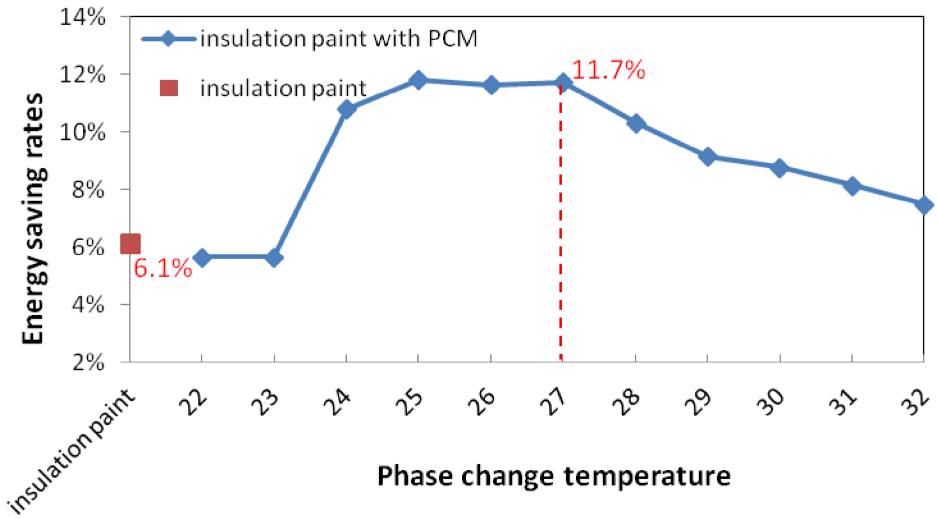

Fig. 4.7. Energy saving rates by adding insulation paint and PCM

Energy saving of 6.1% (the isolated red square) is achieved by adding the insulation paint alone with thickness of 3 mm due to the additional thermal resistance, which is much less than the energy saving rate by insulation paint incorporating PCM with phase change temperature 27°C (11.7%). It reveals that adding PCM into insulation paint significantly improve the performance of the insulation coating on energy savings.

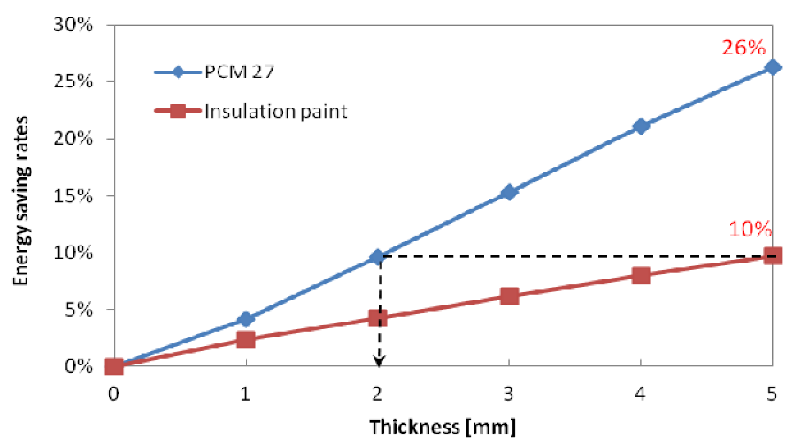

Fig. 4.8. Energy saving rates by adding PCM and insulation paint respectively with varied thickness

Fig. 4.8 shows the energy saving rate by the insulation paint alone and the PCM with optimal phase change temperature respectively with varied thickness ranged from 1-5mm. It is observed that PCM layer with thickness of 2 mm has the equivalent performance as the 5 mm thick insulation paint. The figure indicates that PCM has much higher efficiency on energy savings compared with the insulation paint with the same thickness due to its high latent heat. The limitation of the insulation paint for refurbishment of existing buildings is its thin thickness, which constrains the insulation effect of the coating on buildings. Therefore, adding PCM capsules into insulation paint could greatly improve the performance of the insulation coating to reduce the cooling loads.

4.4 Summary

Advanced coating system provides a promising approach for building energy-oriented refurbishment, because it can be easily applied to existing buildings, especially for concrete constructions. Solar reflective paint can effectively reduce cooling loads due to its high reflectivity but has negligible resistance to conductive heat. PCM with high latent heat capacity is an ideal complementation to the solar reflective paint to reduce the cooling loads by absorbing the conductive heat.

Another commonly used coating for cooling load reduction is the thermal insulation paint, which provides additional thermal resistance to building envelope due to its low thermal conductivity. However, the insulation effect on building is constrained by its thin thickness. PCM exhibits much higher efficiency in terms of reducing heat gain through envelope due to its high latent heat storage density. The addition of PCM into the thermal insulation paint significantly increases the efficiency of the coating for cooling load reduction.

Chapter 5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This study focused on the efficacy of PCM for passive cooling of buildings in tropical climate, Singapore for example. The first part concentrated on the parametric study to optimize the efficacy of PCM for passive cooling. The second part investigated the potential synergy to apply PCM with advanced building surface coatings, such as solar reflective paint and thermal insulation paint, to further improve the performance for cooling energy savings. The main objective of this study is to provide informative knowledge and guideline to the design and application of PCM in tropical climate for passive cooling.

The conclusions are made as follows:

1) PCM achieves cooling energy savings during the day but increases the cooling energy loads at night. However, generally, the energy savings are achieved for a whole day by PCM because it is found the energy savings in daytime typically outweigh the energy penalties at night.
2) The lowest phase change temperature that could guarantee the latent heat of PCM been fully utilized should be selected as the optimal phase change temperature when PCM applied to the outside surface of the exterior wall.
3) The optimal phase change temperature when PCM applied to the inside surface of the exterior wall, in the condition of no forced convection on the inside surfaces, should be selected close to the average temperature of the inside surface of the wall.
4) The wider temperature range of phase change and the non-linearity of the enthalpy-temperature curve of the PCM located outside results in a slightly higher optimal phase change temperature. The wider phase change range improves the adaptive capacity and robustness of PCM to the temperature variations, but may compromise the performance of PCM to achieve the highest energy savings.

5) PCM placed on the outside surface of exterior wall is recommended when PCM is applied for passive cooling of buildings in tropics.
6) Solar reflective paint can effectively reduce the cooling loads by reflecting solar radiation but has negligible resistance to conductive heat. PCM with high latent heat capacity is an ideal complementation to the solar reflective paint to reduce the cooling loads by absorbing the conductive heat.
7) Thermal insulation paint provides limited insulation effect on buildings due to its thin thickness. The addition of PCM into to the paint greatly improves the heat capacity of the thin coating and reduces the cooling loads by absorbing the incoming heat.

It should be noted that this study is conducted with a focus on the efficacy of PCM in tropical climate. Some conclusions may not be applicable to the application of PCM in other regions with different weather patterns.

5.2 Future work

This study is conducted based on the simulation for one-day-period. Even though the daily weather condition is similar in Singapore, a more accurate study should be conducted to test the efficacy of PCM for longer period.

Secondly, experiments need be carried out to validate the simulated results. During the practical application, study on the selection of phase change temperature should be conducted considering the impacts of sub-cooling and low conductivity of PCM, which may influence the solidification of PCM. In addition, the durability of PCM is another issue need to be tested for the application.

Finally, the selection of phase change temperature when PCM applied to buildings with different operating time could be studied individually. For instance, the HVAC system of a hospital is whole-day operated and in office building the main activities are carried out in daytime. PCM should be selected to provide benefits focused on the operating time of the building.

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