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A comparative study on the effectiveness of passive and free cooling application methods of phase change materials for energy efficient retrofitting in residential buildings

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Abstract

This study compared the effectiveness of passive and free cooling application methods of Phase change materials (PCMs) when used as energy efficient retrofitting in a residential building. A modern duplex residential building in Melbourne, Australia was considered for the case study. In passive application, PCM was installed in the ceilings of the house. In free cooling application, outdoor air was supplied to the indoor after passing it through a PCM storage unit. The study was carried out using building simulation software EnergyPlus V8.4 and computational fluid dynamics (CFD) software ANSYS V15.1. The developed simulation models of passive and free cooling applications were validated using relevant experimental data. The validated simulation models were then used to investigate the effectiveness of these PCM application methods in the selected building. The results showed that, for the studied house, free cooling application of PCM is more effective than the passive application in reducing the internal zone temperature. Under typical summer climatic conditions of Melbourne, free cooling application resulted in up to 1.8°C reduction in zone air temperature, compared to only 0.5°C when PCM was applied as passive heat storage system. The outcome of this study would be helpful in selecting the effective PCM application method for these types of residential buildings in similar climates.

Keywords: Phase change materials (PCMs); passive cooling; heat exchanger; free cooling; thermal simulations

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1. INTRODUCTION

Building sector accounts for approximately 40% of total energy consumption and one-third of greenhouse gas emission around the world [1]. The energy demand in this sector is growing each year because of the increasing population growth, high living standards and people spent more time in indoor [2]. A thermal energy storage (TES) system can well help to reduce building energy use, contribute to efficient energy management and to improve occupant thermal comfort in indoors. Moreover, an appropriate and economical way of TES in buildings can contribute to eliminating the mismatch between supply and demand, when they do not coincide in time. Therefore, development of TES systems in buildings has been attracting more and more attention around the world. TES systems can be achieved by sensible heat storage, latent heat storage and chemical energy storage. However, compared to other two methods, latent heat storage method with the application of phase change materials (PCMs) has received considerable attention in the last couple of decades due to its potential benefits of high volumetric heat capacity and narrow temperature variation during the phase transition process [3]. PCMs absorb or release the energy equivalent to their latent heat when the temperature of the material undergoes or overpasses the phase change temperature.

The application of PCMs in buildings can generally be categorized into three methods which are passive, active and free cooling methods [4-6]. Passive methods are referred to the technologies where the TES system is operated without the external supply of energy. Typical applications of passive methods are PCM integrated into building fabrics such as walls, floors, ceiling and roofing materials. A large number of studies reported that passive application of PCMs in buildings can significantly reduce the building energy consumption and improve indoor thermal comfort. For instance, Athienitis et al. [7] reported a reduction of 4^{o}C in maximum room temperature when PCM integrated wallboards are applied as internal wall elements of a passive solar test room in Montreal, CA. Castell et al. [8] showed that under free floating conditions, maximum air temperature of the concrete cubicles with PCM integrated bricks reduces by up to 1^{0}C. Energy consumption of the cubicles containing PCM was also reduced by 15% compared to the cubicles without PCM. Ahmed et al. [9] also observed a reduction of 20^{0}C in the indoor temperature amplitude of a test cell through the application of a composite wallboard with vacuum insulation panel and PCM during summer in France. In another study [10], incorporation of microencapsulated PCM in the concrete wall was found to reduce the maximum temperature by 1°C and increase minimum temperature by 2.8°C. However, the effective utilization of PCMs in passive applications largely depends on the thermo-physical properties of PCM and local climatic conditions[3]. The primary drawback of passive application method is that the PCM may not solidify completely at night. This is because PCM mainly interacts with indoor air temperature and during summer, the indoor air temperature is not low enough to solidify the PCM. Even if the indoor temperature is lower than the phase change temperature, the duration is not sufficient to solidify the PCM because of low heat transfer rate.

To overcome the issues with passive application methods, active and free cooling application methods have been studied by the previous researchers. An active TES system integrates the PCM into an HVAC system such as air-conditioning unit[11, 12], floor heating system[13, 14] and domestic ground heat pumps[15] to reduce the peak energy demands and annual energy consumptions. Yamaha et al. [16] proposed an air distribution system with PCM in the air ducts for peak load shifting purposes. It has been shown that, with an adequate amount of PCM, a constant room temperature could be maintained without any cold source operation. Furthermore, the melting temperature suitable for the system is around 19°C.

The free cooling system also utilises the external energy supply to operate the TES systems. However, as opposed to active TES systems, an HVAC unit is not required in this application. More precisely, the free cooling system stores the coldness of night ambient temperature and extracts it during day-time by supplying the indoor/outdoor air through PCM storage unit. Turnpenny et al. [17] developed a heat storage unit system by embedding heat pipes into PCM unit and circulating the room air to extract cold storage during the daytime. At night, cold storage is supplied to the PCM unit by drawing the cool ambient air over the heat pipes. Authors claimed that this unit can provide adequate cold storage to prevent overheating of the office building during UK summer conditions. Yanbing et al. [18] also developed a packed bed PCM storage unit to be installed in the space between the hung ceiling and the floor above. The experimental results showed that the temperature of the room with PCM system is much comfortable than the other three neighbourhood rooms and cooling power of the system was equivalent to 300W during the hot day times. Weinläder et al. [19] monitored the performance of a ventilated cooling ceiling integrated with PCM in two offices and a conference room in Germany and monitored the room temperatures during summer 2009 and 2010. During the day, the ventilation was purely in circulating operation, while cool outside air was used during the night to regenerate the PCM .The results showed that the ventilated ceiling with PCM reduced the maximum operative room temperature in the office rooms by up to 2°K compared to a reference room without a cooling system. An extensive review of the free cooling applications with PCM can be found in [20]. It was reported [20] that the thermo-physical properties of PCMs and geometry of encapsulation as main challenges for the effective utilisation of PCM in this application. Furthermore, heat transfer performance enhancement of PCM and lack of real case investigations are presented as current barriers for free cooling application of PCMs in buildings.

The abovementioned studies show that all of the passive, active and free cooling application of PCM has the potential to reduce indoor air temperature and to increase building energy efficiency and thermal comfort. The actual magnitude of reduced temperature, enhanced thermal comfort and energy savings largely depends on local climatic conditions and the thermo-physical properties of PCM. However, there is no research reporting the comparison of the effectiveness of different PCM application methods for a certain type of building and climate scenario. Such comparative analysis would be a good approach for the purpose of optimising the TES system of a particular building type and climatic conditions. Therefore, the main aim of the present study is to investigate the effectiveness of passive and free cooling application method of PCM when used as energy efficient retrofitting in a residential building. A modern duplex residential building in Melbourne was used in this study. In passive application, PCM was installed in the in the external building fabrics such as ceilings and external walls. In free cooling application, a separate PCM storage unit was utilised to supply the cold storage by ambient air. The investigation was carried out using dynamic thermal simulation software EnergyPlus where both the passive application model and free cooling model have been validated using relevant experimental data.

2. METHODOLOGY

2.1. Overview

The present study was carried out in two stages, where stage 1 considers the passive application of PCM by numerically investigating the performance of passive PCM application using a validated building simulation model. Stage 2 investigates the performance of PCM in the free cooling application. In this method, a pilot scale experimental set-up was developed in a climate controlled environmental chamber as it was not possible to install the free cooling unit in the real house due to lack of proper guidelines available regarding the design of the free cooling system with PCMs. The performance of this free cooling system in real buildings can be approximated through proper modelling of the system. This pilot scale experiment was used to validate the developed simulation model in the free cooling system. The validated free cooling model was then used to investigate the effectiveness of free cooling application in the studied duplex house.

2.2. Building description

The selected duplex house from Melbourne is a privately owned four-bedroom house with floor area of 326 m^2 and was built on 2009. Figure 1 shows the floor plan of the studied duplex house. The construction details of the house are given in Table 1.

2.3. Passive application method

The passive application of PCM in the duplex house was investigated numerically with the installation of a commercially available Bio-PCM^{TM} in the ceilings of the building. The simulation model was developed using building energy and thermal load simulation software EnergyPlus V8.3 from the U.S. Department of Energy (DOE). The whole duplex house was divided into 17 thermal zones as shown in Figure 1. All the zones are simulated using conduction finite difference algorithm (ConFD) which provides the opportunity to simulate materials with variable thermo-physical properties such as PCM. A 2 minutes time-step was used in the model as suggested by Tabares-

Table 1. Construction details of the experimental house

Name	**Construction (outside to inside layer)**
External Walls	Brick veneer construction, 40 mm air-gap, insulation and 10 mm wall plasterboard installed to the internal surface.
Internal Walls	Wall Plasterboard, 90 mm Air gap, Wall Plasterboard
Roof	Roof tiles
2nd Level Ceiling	Flat ceiling having 13 mm ceiling plasterboard and ceiling insulation; PCM installed between insulation and plasterboard in Bed 2
Ground Floor	Concrete, Ceramic tiles
2nd Level Floor	Ceiling Plasterboard, 90 mm Air gap, Floor Timber, Carpet
Door	Timber

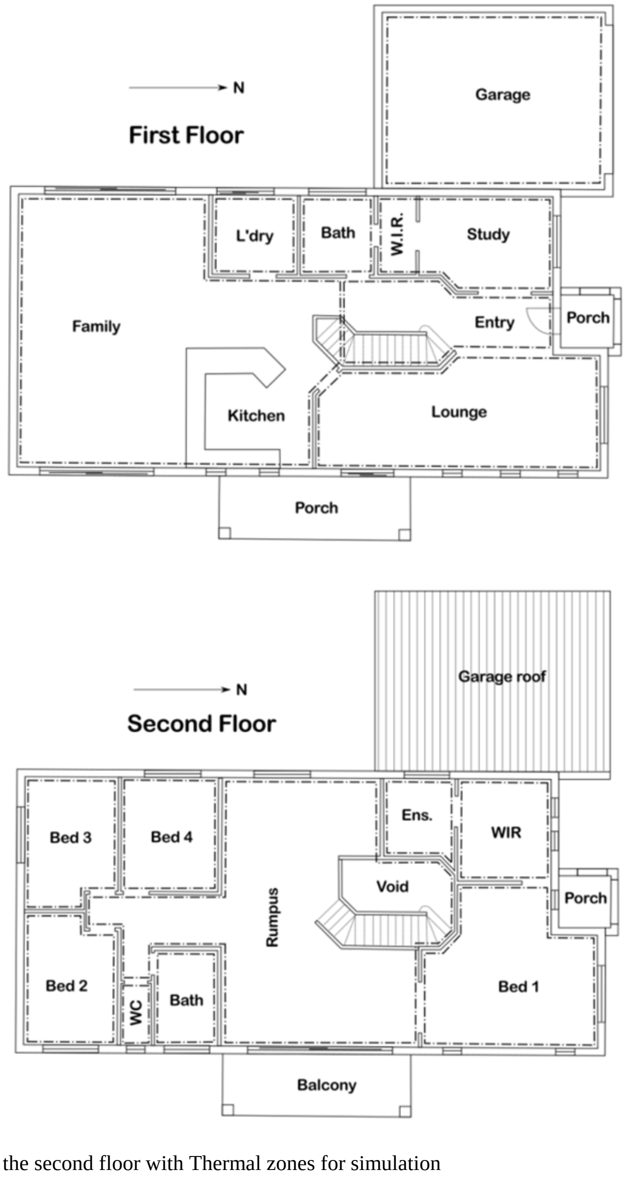

Figure 1 The house plan of first and the second floor with Thermal zones for simulation

Velasco et al [21] for accurate simulation of PCM in EnergyPlus. The internal gains were taken into account in the simulation by using “People” and “ElectricEquipment” object. In the simulation model, actual user behavior of the house was considered which was determined via interviewing the occupants and following the data input sheet that was given to the occupants to record window opening/closing time, window blind usage schedule every day during the experimental period. The ground heat transfer process, infiltrations, and natural ventilation were modelled using the “GroundHeatTransfer:Slabmodule”, “Design flow rate” and “Wind and Stack model” of the EnergyPlus software, respectively [22]. Further details of developed EnergyPlus model can be found in [23]. The developed passive application model of PCM has been validated using the experimental data and the details of the validation process have been presented in a previous study of the present authors [23] and therefore, have not been repeated here.

2.4. Free cooling application

2.4.1. Pilot-scale study

The pilot scale experimental setup of free cooling application method was developed inside the environmental chamber at smart structure laboratory of the Swinburne University of Technology, Melbourne, Australia. The objective of this experimental study was to collect data and validate the free cooling simulation model so that it can be further utilized in investigating the free cooling application of PCM in real buildings. The developed experimental test room is shown in Figure 2(a). The internal dimensions of the model house are 1m long, 0.66m wide and the height varies from 0.71m to 0.66m. The size of the single glazing window is 0.3 m X 0.32 m. The construction details of the house are presented in Table 2.

Table 2 Constructions of pilot scale house for free cooling application

Name	**Construction (outside to inside layer)**
External walls	12mm timber, R1.8 insulation with reflective foil on one side, 13mm plasterboard.
Roof	2mm corrugated iron sheet, R 1.8 insulation, 13mm plasterboard
Floor	10mm timber, R 1.8 insulation, 13mm plasterboard
Window	Single glazing

A schematic diagram of the experimental set-up is presented in Figure 2(b). The figure shows that ambient air (air inside the climate chamber) is circulated through the PCM storage tank before being supplied to the experimental house. The PCM used in this study consists of inorganic hydrated salt with a melting temperature of 22°C. Inside the PCM storage tank, a 22mm diameter and 6m long helical copper tube was immersed in PCM. A ventilation fan was used to force the air through 22mm diameter and 6m long copper pipe immersed in PCM inside the PCM storage tank. The PCM storage tank and the pipe connecting the experimental house and PCM storage tank were highly insulated to prevent the heat loss to ambient air. The K-type temperature sensors (Accuracy ± 0.1°C) were installed at the inlet of PCM storage tank, the exit of PCM storage tank (inlet of the experimental house), inside the PCM storage tank and inside the experimental house. A digital anemometer was also attached to the air inlet of the experimental house to monitor the supplied air flow rate. The monitored air inlet velocity to the experimental model house was around 1.9±0.1m/s. The experiment was run for five consecutive days, where the chamber temperature was varied following a sinusoidal curve from 20°C to 30°C for a period of 12 hours and was kept constant at 20°C for next 12 hours.

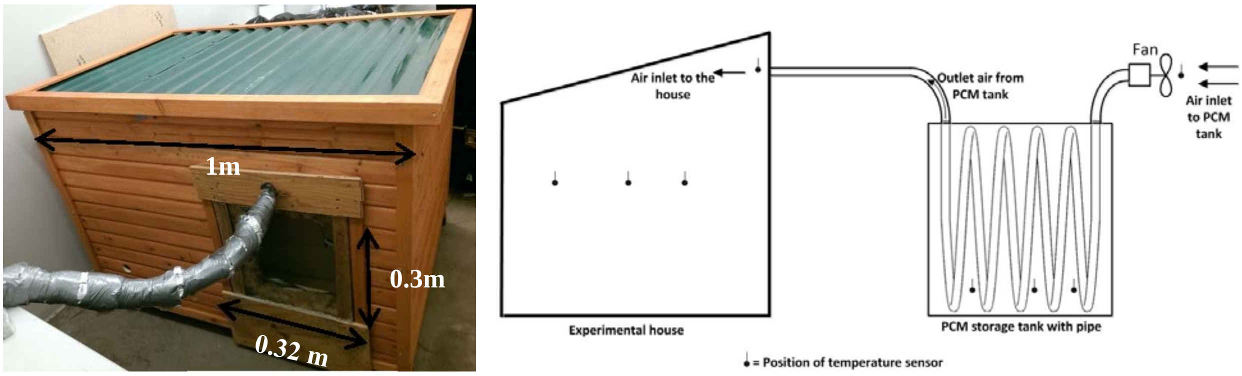

Figure 2 (a) Model house of free cooling experiment and (b) schematic of experimental setup

2.4.2. Simulation process

In the present study, the numerical model of free cooling was carried out in two parts: 1) PCM heat exchanger modelling using computational fluid dynamics (CFD) and 2) Building simulation using EnergyPlus. A CFD model of heat transfer between air and PCM heat storage unit was developed using ANSYS CFX V15.0. The mesh contains two regions: Fluid (air) and Solid (PCM) as shown in Figure 3(a). The fluid domain consists of pipe network through which air was supplied. The mesh was refined at the solid-fluid interface using advanced size function proximity and curvature. The PCM was assumed to be solid although, in reality, it changes to liquid when it exceeds the phase transition temperature (22.5°C in this case). However, the convective heat transfer in the liquid stage is negligible in this temperature range and this assumption will result in a very negligible error in the results. In this study, inorganic PCM with phase transition range 22-23°C was used. Phase transition characteristic of the PCM was taken into account through temperature-dependent specific heat data as shown in Figure 3(b).

In the experimental study, the PCM heat storage unit was insulated on all sides except at the top to minimize heat transfer between PCM and external air. Therefore, an adiabatic boundary condition was used on the bottom and side wall of the PCM domain and temperature boundary condition (ambient air temperature) was used at the top. For the fluid domain, velocity boundary condition was used at the inlet and static pressure boundary condition was used at the outlet. The time-dependent air temperature at the inlet was applied using the user functions approach. Using this CFD model of the heat exchanger, the temperature and velocity of ambient air after passing through the PCM heat exchanger was derived. This information was then fed to the building simulation model of the free cooling application. Building simulation model for free cooling application of PCM was similar to the passive application case except that there is no PCM element in the building fabrics and one extra algorithm is added (Figure 4) to the model to include the results of heat exchanger model. According to the algorithm, the calculated outlet air flow rate and air velocity from CFD model are supplied into EnergyPlus simulation model assuming as an HVAC system object. In summary, each simulation of free cooling application consists of CFD simulation of PCM heat exchangers and EnergyPlus simulation of the building thermal condition incorporating output of CFD model.

2.4.3. Validation of free cooling system model

The validation of free cooling system was carried out in both simulation models such as simulation of the CFD model and EnergyPlus model. In order to validate the CFD model of PCM heat exchanger, the experimental outlet temperature of the PCM storage unit was compared with simulated outlet temperature. The temperature data of the experimental heat storage unit at the inlet and outlet of the PCM storage unit and ambient temperature was obtained from relevant thermistors. Figure 5 shows the experimental and simulated outlet temperature of PCM storage unit and corresponding inlet temperature. A good agreement between the experimental and numerical results with RMS error of only 0.27°C. Therefore, the developed model can be used to predict outlet temperature of any types of PCM heat exchanger unit.

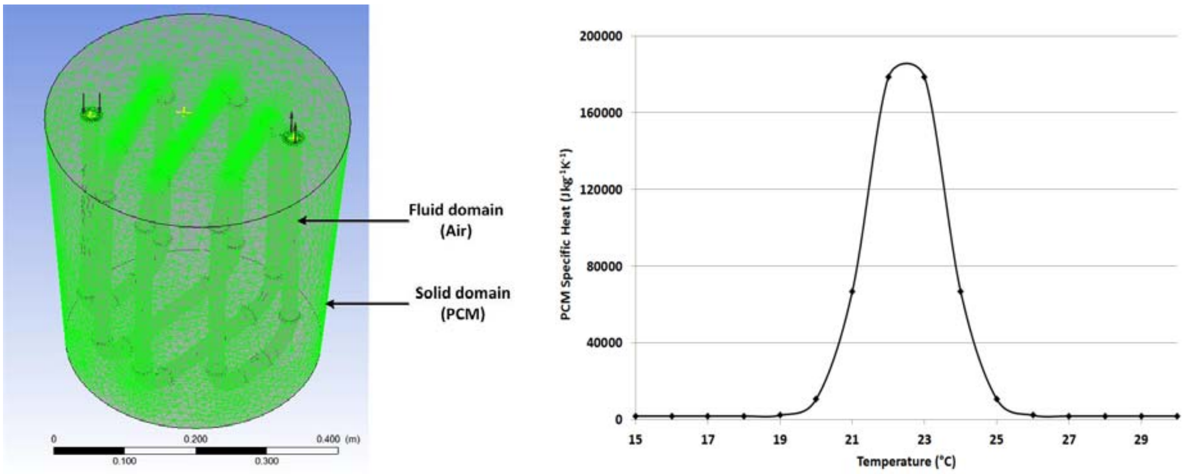

Figure 3(a) CFD model of PCM heat exchanger (b) temperature-dependent specific heat capacity of PCM

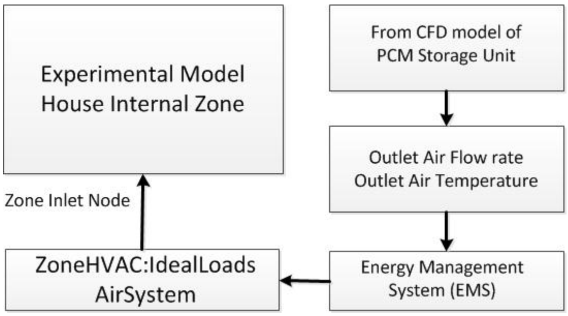

Figure 4 Algorithm of free cooling model in EnergyPlus

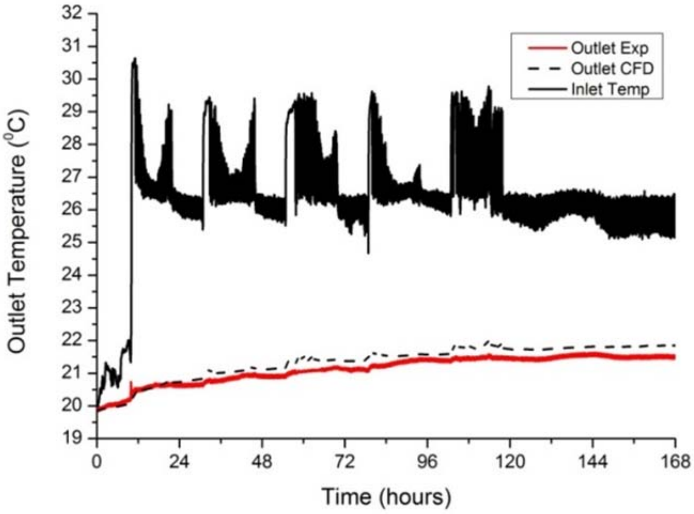

Figure 5 Simulated and experimental outlet temperature of PCM heat storage unit

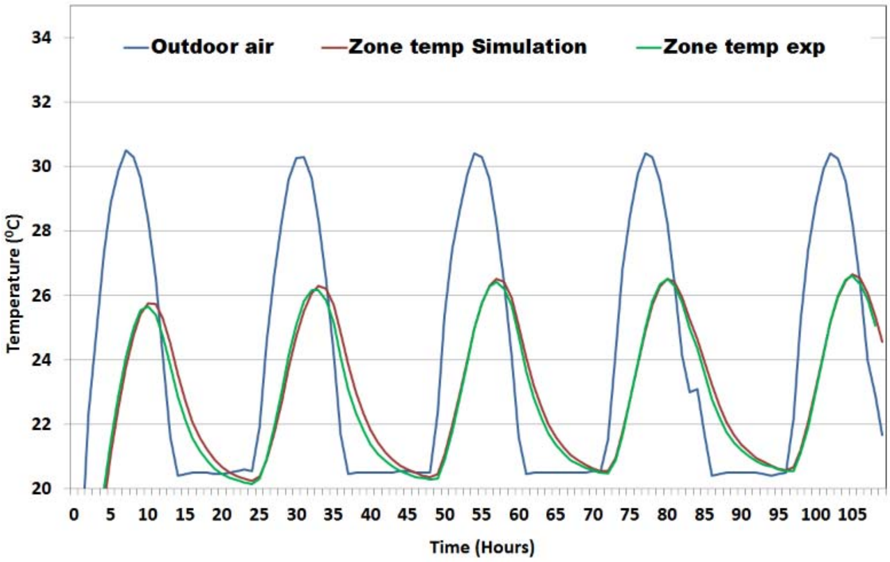

Figure 6. Comparison of simulated and experimental temperature of the model house.

For validating the free cooling energy plus model, an energy plus model of the pilot scale house was developed. The simulated zone temperature was compared with experimental zone temperature data recorded (section 2.4.1) and presented in Figure 6. The figure shows good agreement between simulated and experimentally recorded zone temperature with RMS error of only 0.320C. The validated free cooling EnergyPlus model was then applied to investigate the performance of free cooling application of PCM in the selected duplex house.

3. RESULTS AND DISCUSSIONS

3.1. Passive and free cooling application during typical summer period

The passive and free cooling application of PCM have been analysed and compared during the period of 26th of February to 3rd of March (RMY weather data) to represent the typical summer climatic conditions in Melbourne. In both applications, 220kg of PCM was used in the Bed2 thermal zone of the duplex house. Figure 7 shows the zone air temperatures for No-PCM, passive application of PCM and free cooling application of PCM during the specified period in Melbourne. The figure shows that throughout the period of 6 consecutive days, free cooling application resulted in large temperature reduction compared to the passive cooling application. This is particularly demonstrated by an average of 1.53°C reduction in peak zone air temperature with a maximum reduction of 1.8°C when PCM is utilized as a free cooling system. On the other hand, passive application of PCM heat storage resulted in the average reduction in peak zone air temperature around 0.38°C with a maximum reduction of 0.5°C. However, before reaching a stable conclusion, the storage efficiency of both passive and free TES systems should be investigated to identify the factors that affect the heat storage/release rate when the same amount of PCM is utilised in different applications. To do that, the working cycle of PCM storage in both application methods was analysed.

Figure 8 shows the temperature of the PCM and inner surface temperature of the ceiling for the cases of with and without the passive PCM application. It should be noted that in the case of with PCM application, PCM was incorporated in the ceiling between insulation and plasterboard. The difference between the inner surface temperature of the ceiling for both cases is also presented in the secondary axis. The figure shows that peak ceiling surface temperature was reduced by an average of 1.7°C due to the passive application of PCM with a maximum reduction of 2.1°C. However, as reported earlier, the average reduction in peak zone temperature was only around 0.38°C (maximum 0.5°C), which is very low compared to the reduction of ceiling surface temperature. This may have occurred due to continuous internal heat gains that increased the indoor air temperatures. The figure also shows that PCM temperature varied between 25°C to 34°C during the studied period although the outdoor air temperature reached below 22^{o}C (i.e. solidification temperature of PCM) every day during studied period. This means that PCM was not solidified at night and thus it would not be able to work at full capacity during the day.

On the other hand, the operation of the free cooling system with PCM is illustrated in Figure 9, where the temperature of the air at the exit of the PCM heat exchanger was 5°C cooler than the inlet ambient air during the studied period. The average daily maximum temperature of the supplied air from the PCM heat exchanger (outlet temp) into the Bed 2 zone was 24°C which resulted in on average 1.53°C reduction of the daily average maximum temperature (from 32.5°C to 30.97°C on average) as shown in Figure 7. Figure 9 also shows that PCM temperature inside the heat storage tank is almost constant which means PCM did not completely melt or solidify. it could be due to the available capacity of PCM exceeded than required amount which may not be cost effective. Future studies are required to design a PCM heat storage unit to operate at the optimum utilization of PCM.

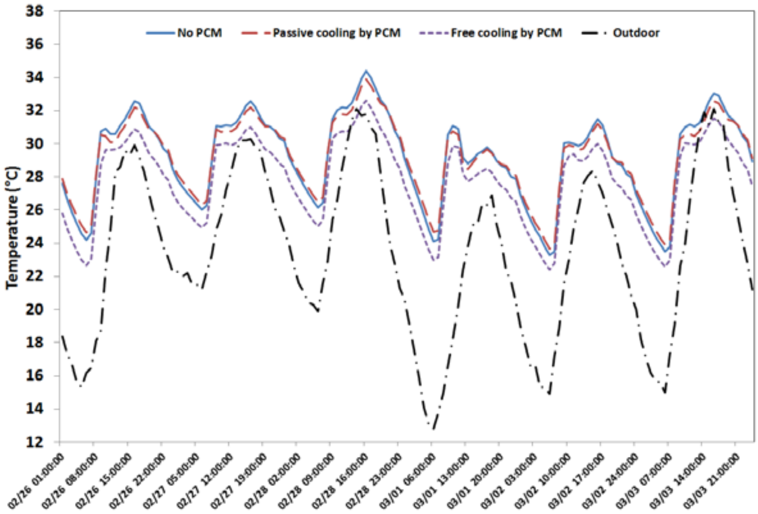

Figure 7 Bed 2 zone temperature during typical summer weather in Melbourne

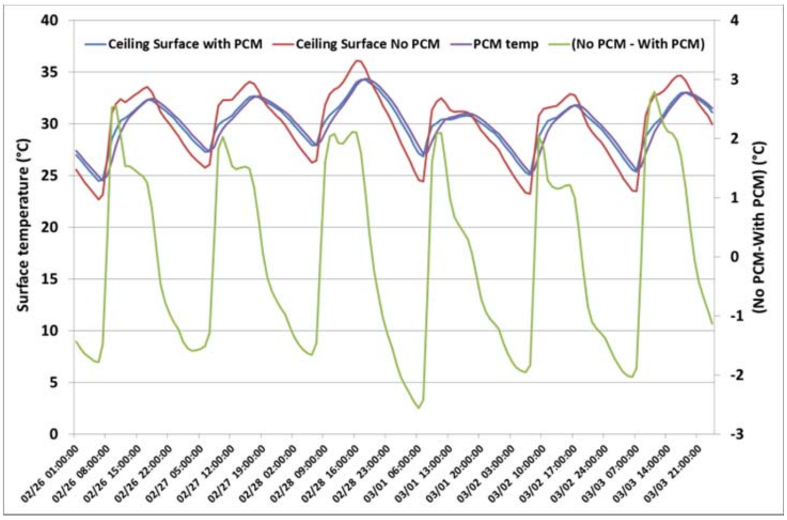

Figure 8 Ceiling Surface temperature in passive cooling application during typical summer

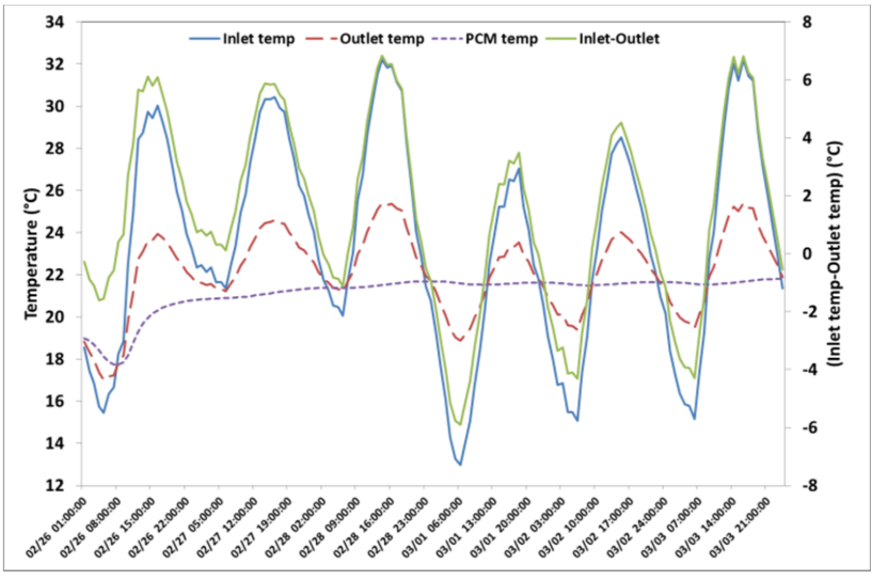

Figure 9 Temperature at different points of the PCM heat exchanger unit during typical summer test

4. Conclusions

In this study, the potential of passive and free cooling application methods of a PCM incorporated TES system in reducing internal zone temperature of a residential building have been investigated. The dynamic thermal simulations were performed by using experimentally validated EnergyPlus models to analyse and compare the performance of both of these applications. A pilot scale experimental study was also conducted to validate the free cooling application of PCM heat storage unit. Approximately, 220kg of PCM was utilized in the Bed2 zone of the duplex house for both passive and free cooling applications. The passive application was implemented by installing the PCM mats in the ceilings of the Bed 2 zone of the house. In free cooling application, a separate PCM storage unit was utilised to supply the cold storage by means of ambient air. The results showed that, for the studied house, the free cooling application of PCM is more effective in reducing zone air temperature compared to the passive application of PCM. During the studied typical summer period, free cooling application results in up to 1.8°C reduction in indoor zone temperature, compared to only up to 0.5°C in passive application case. Two drawbacks of passive application of PCM were observed. First, it suffered from poor solidification rate at night which prevented the PCM from running at full capacity during the day. Second, the significant reduction in ceiling surface temperature with PCM was not realized in the reduced zone temperature. Further research is required to overcome these barriers of passive application method. In free cooling application, PCM temperature in the PCM heat exchanger unit barely fluctuated which means more than the required amount of PCM was used which may not be cost effective. Further studies are required to economically design the PCM storage unit for free cooling application in buildings. The present study provided an understanding of the effectiveness of two PCM application methods would be helpful in selecting the best application methods in these types of residential buildings.

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