Applied Energy 238 (2019) 1582–1595

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy saving performance assessment and lessons learned from the operation of an active phase change materials system in a multi-storey building in Melbourne

Morshed Alam, Patrick X.W. Zou*, Jay Sanjayan, Sayanthan Ramakrishnan

Department of Civil and Construction Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, Australia

HIGHLIGHTS

- Performance of an active PCM system installed in an 11 storey building was studied.
- Operational parameters of the active PCM system were monitored for 25 months.
- PCM reduced chiller cooling load by 12–37% in winter but remained inactive in summer.
- PCM only utilized 15% of its heat storage capacity to shift the peak cooling load.
- The factors that contributed to the underperformance of active PCM were reported.

ARTICLE INFO

Keywords:
Phase change materials
Building energy efficiency
Thermal energy storage
Active PCM
PCM heat exchanger
Microencapsulated phase change material

ABSTRACT

While the energy saving performance of an active phase change materials (PCMs) system in buildings has been widely investigated using prototype-scale experiments and numerical assessments, their performance during the operational phase of a real building has been less understood. This study assessed the energy-saving performance of an active PCM system installed in an eleven storey building in Melbourne. Macro-encapsulated PCM with the phase transition temperature of 15 °C was installed in a large PCM tank. Water was used as the heat transfer fluid (HTF) to extract and store cooling energy from the PCM tank. The performance of the active PCM system was monitored for 25 consecutive months, and the results were analyzed on a seasonal basis. Building design documents and the maintenance manuals were studied to understand the difference between design intent and actual operation. The analyzed results revealed that the active PCM system reduced cooling load on the chiller by 12–37% only during colder months, but, remained dormant during the summer. Even in the case of maximum effectiveness, the PCM tank only utilized 15% of its available heat storage capacity to reduce the cooling load. The factors that contributed to the underperformance of active PCM system include mismatch between designed and actual operation of the PCM system, inefficient operation logic of the system, poor material quality, and limited knowledge of maintenance staffs during the operation stage. The lessons learned from the operation of this active PCM system in this multi-storey building were reported and discussed.

1. Introduction

Energy is an indispensable source for a country's social and economic development. Buildings account for 32% of primary energy use and 19% of energy-related greenhouse gas (GHG) emissions globally [1], making this sector as one of the largest users of energy and sources of emissions. Moreover, the building energy consumption is projected to be doubled by 2050 due to the rapid population growth, growing trend of urbanization and lifestyle changes, which will also lead to a significant increase in GHG emissions globally [1]. In this context, energy conservation and associated emission reduction in the building sector have been recognized as the highest priority of many governments and policymakers, leading to the introduction of various energy conservation goals and regulations in buildings. Incorporation of latent heat thermal energy storage (LHTES) system with phase change materials (PCM) in buildings has recently received significant attention as a potential technology to enhance building energy efficiency. The application methods of PCM in buildings can generally be categorized as

---

* Corresponding author.
E-mail address: pwzou@swin.edu.au (P.X.W. Zou).

https://doi.org/10.1016/j.apenergy.2019.01.116
Received 7 September 2018; Received in revised form 13 November 2018; Accepted 17 January 2019

passive, active and free cooling applications [2–5].

1.1. Passive application

In passive application method, PCM are incorporated into building elements such as brick and concrete walls [6,7], wall plasterboards [8–10], floors [11–14], ceilings [15–17] and roofs [18]. The passive application of PCM offers many advantages including, the versatility of installation, large heat transfer surfaces and no additional equipment required for operating the PCM. Thermal performance assessment conducted on full-scale buildings showed that the passive application method significantly reduces the indoor temperature fluctuations and energy consumptions. For instance, Kuznik et al. [19] assessed the thermal enhancement of a renovated office building room containing PCM wallboard in the lateral walls and ceiling, compared to an identical room without PCM. The results showed that incorporation of PCM resulted up to 2.2 °C reduction in indoor air temperature and extended the comfort hours. Zhou et al. [20] studied the performance of a passive PCM application method coupled with night ventilation, the so-called hybrid space-cooling system, using a 3-storey office building. The results revealed that the thermal storage of PCM with night ventilation saves about 76% of the daytime cooling energy consumption, compared to control room without PCM and night ventilation. More recently, Jamil et al. [21] studied the thermal performance of Bio-PCM mats (i.e., macro-encapsulated PCM) installed on the ceiling of a duplex building. The results revealed a peak indoor temperature reduction of up to 1.1 °C in most of the thermal zones along with a reduction of 34% in thermal discomfort hours. Authors also reported that efficient placement of PCM along with the opening of windows at night would reduce the thermal discomfort hours by 52%. Lee et al. [22] showed that reduction of heat flux through PCM integrated walls depends on the location of PCM in the walls and orientation of the walls. In the USA, the peak heat flux reductions were 51.3% and 29.7% for the south wall and west wall, respectively. Mixing of PCM with cellulose insulation materials of the walls can also reduce the daily average heat flux through the walls by 25.4% [23]. Silva et al.[24] reported that PCM integrated window shutter decreased the maximum indoor temperature up to 8.7% and increased the minimum indoor temperature by 16.7%. However, the passive PCM application method often suffers from inadequate cold storage at night (i.e., solidification of PCM), leading to an inadequate cooling performance on the following day. This is due to the low thermal conductivity of PCM which significantly reduces the heat transfer rate to and from PCM. Heat transferability of PCM can be improved significantly through the addition of high thermal conductivity materials and optimization of the structure of phase change devices [25]. Heat transferability of PCM can also be improved through active and free cooling applications which are discussed in following sections.

1.2. Free cooling application

In this method, the coolth of night ambient air is stored in PCM using a mechanical device (i.e., fan) and then supplied to the building during the daytime to meet the cooling energy demand [26,27]. A packed bed PCM storage unit was developed and incorporated in the ventilation system by Yanbing et al. [28]. The experimental results showed that the temperature of the room with PCM system is much comfortable than the other three neighborhood rooms, and the cooling power of the system was equivalent to 300 W during the hot day times. Turnpenny et al. [29,30] developed a heat storage unit system by embedding heat pipes into the PCM unit. During the daytime, the PCM pipes absorb the heat loads of the room and reduce the room temperature. At night, cooling energy is stored in the PCM unit by drawing the cool ambient air over the heat pipes. Authors demonstrated through an experimental study that this unit can provide adequate cold storage to prevent overheating of the office building in UK summer conditions. Weinläder et al. [31] observed that the ventilated ceiling with PCM reduced the maximum operative room temperature by up to 2 °C. Through numerical analysis, Alam et al. [32] showed that the free cooling method reduces the average indoor air temperature by up to 1.8Â°C during typical summer days in Melbourne, Australia. Sun et al. [33] reported a 50% reduction of cooling demand in telecommunication base through the integration of PCM based free cooling unit. Yuan et al. [34] proposed a new coupled cooling method of PCM combined with pre-cooling of building envelope to keep the indoor temperature of a refuge room in underground mine comfortable for a longer period in the event of an emergency. A numerical model of the proposed coupled system has been developed and validated against the experimental data. The coupling of PCM with the pre-cooling of envelope solves the problems of large demand of PCM and small operating temperature difference at the same time. Moreover, this method meets the requirements of safety, no power, stability and reliability under special environment and widens the application range of PCM system for temperature control. However, the design of the heat exchanger unit is an important factor for a free cooling system to run efficiently [35–37]. Zalba et al. [38] showed that the most influential parameters during solidification process are the encapsulate thickness, inlet air temperature, and air flow rate. Similar findings were also reported by later studies [39–41].

1.3. Active application

The active methods utilize the latent heat of PCMs by integrating them into traditional HVAC systems such as absorption chillers [42,43], evaporative and radiative heating-cooling system [44,45], air-conditioning system [46,47], and domestic ground heat pumps [48,49]. Helm et al. [42] studied the performance of an absorption cooling system containing a salt hydrate PCM with the melting temperature of 27–29 °C. The results of pilot scale experiments showed that the PCM absorbed up to 50% of daily rejected heat load when the outdoor was above 30 °C and ensured a 32 °C constant cooling water supply to the chiller. Zhang and Niu [50] designed and numerically evaluated the performance of a hybrid cooling system consisting of 18 °C micro-encapsulated PCM (MPCM) slurry storage tank and nocturnal sky radiator. During night time, the radiator stores the coolth of ambient air into the storage tank. At daytime, the cold storage of MPCM slurry contributes to meet the building cooling load demand through chilled beams. The proposed system saved up to 77% and 62% energy in low rise buildings in Lanzhou and Urumqi of China, respectively. In another study [51], the integration of PCM in the radiant floor system has been found to reduce peak floor temperature by 3.5 °C and decrease the cooling water usage by 25% in the summer season. Several studies incorporated PCM heat-exchanger in the air-duct to pre-condition the air to improve HVAC efficiency [52,53].

1.4. Research context

The literature review shows that the active PCM integration methods can significantly improve the energy efficiency of the HVAC system. It is worth noting here that these studies were either conducted on pilot scale experiments or numerical analysis of full-scale buildings assuming proper installation and smooth operation of the PCM system as intended with no disturbances from surrounding environments and activities. However, in a real-world, a number of factors from the construction and operational stages may lead to higher energy consumption in buildings than predicted during the design stage [54]. Operation stage is particularly important for an active PCM system because the inefficient operation of the system could lead to significant energy wastage in charging and discharging of PCM tank and the primary objective of PCM system, which is to save building operational energy, may not be realized [55]. To the authors' best knowledge, no studies are available in the existing literature that reports the factors that may influence the energy-saving performance of the active PCM system in a complex real building environment. This study aims to identify the factors that should be considered to ensure the efficient operation of an active PCM system through a comprehensive case study. The specific objectives are:

1. To understand the operation of active PCM system in the case study building through document analysis and observation of building management system.
2. To calculate the energy saving performance of the active PCM system through analyzing the operational data downloaded from the building management system.
3. To investigate the causes of discrepancies between designed and actual energy saving performance of the active PCM system.

Section 2 includes a comprehensive description of the case study buildings and the installed PCM system. Section 3 describes the methods of data collection and analysis. The results are reported and the causes of any discrepancies are discussed in Section 4. The Section 4 also includes the lessons learned from the case study. Finally, the conclusions from this study are reported in Section 5.

2. Case study

The selected case study is an 11 storey educational building and is located approximately 8 km from Melbourne CBD, Australia. The building design has achieved 5-star GreenStar sustainability rating from Green Building Council of Australia. The active PCM system is installed in the level 11 of the building and is designed to minimize the daytime cooling load on the chiller of this building and increase the building energy efficiency. The detail description of the installed active PCM system has been presented in the following sections.

2.1. Active PCM system in the case study building

In the selected case study building, required heating and cooling load is supplied via active and passive chilled beams. A secondary chilled water (SCHW) system serves those active and passive chilled beams throughout the building via a secondary chilled water loop as shown in Fig. 1. The required chilled water for the SCHW loop is generated from the primary chilled water (CHW) system water loop via a plate heat exchanger (HX-11-03). A water-cooled electric chiller is used to generate chilled water in the CHW system water loop. In addition to the chilled water being generated directly from the CHW system, the SCHW loop is also supplemented by the phase change material tank (also shown in Fig. 1) to reduce the daytime cooling demand on the chillers. Cooling energy stored in the PCM tank is transferred to the SCHW system via PCM heat exchangers (HX-11-02). At night, the 'coolth' of the ambient air temperature is stored in the PCM tank using the adiabatic cooler in the condenser water system (CCW).

The PCM tank is located in the plant room (11th level) of the building. The exterior view of the tank is shown in Fig. 2. The internal dimensions of the PCM tank are 5000 mm long × 4000 mm wide × 2000 mm high. All sides, roof, and base of the tank are insulated to prevent unwanted heat transfer with the surrounding environment. Inside the PCM tank, 5120 FlatICE PCM panels are stacked in 40 layers. Each layer has 8 blocks along the length and 16 blocks along the width of the tank as shown in Fig. 3. Each PCM panel has a dimension of 500 × 250 × 45 mm and contains an external guided circle (see Fig. 4) which ensures a small gap between the containers when stacked inside the tank.

In order to store or extract cooling energy from the PCM panel, water is used as a heat transfer fluid (HTF). The gaps between the containers allow water to flow over the container and maximizes the heat transfer between the PCM panel and water. Two stainless steel diffuser plates, spaced at 200 mm from the walls, are employed to confine the PCM panels on both sides. The plates contain a number of 8 mm holes along the gap between containers as shown in Fig. 3. This arrangement ensures even water flow through the gaps between containers and maximizes the extraction of cold storage from the PCM tank. PCM panels are made of high-density polyethylene (HDPE) container and contain 3 kg inorganic hydrated salt. The manufacturer specifications of the PCM are given in Table 1.

2.2. Operation of secondary chilled water (SCHW) system

The SCHW system operates in two stages to meet the cooling demand. Stage-1 involves the extraction of cooling energy from PCM tank via the phase change material heat exchanger (HX-11-02) and the operation of chilled water heat exchanger (HX-11-03) as a supplement. Stage 2 includes solely the operation of the chilled water heat exchanger to supply chilled water generated by the chiller to the chilled beams.

2.2.1. PCM discharging in stage 1

Whenever there is a call for cooling, the system starts with stage 1.

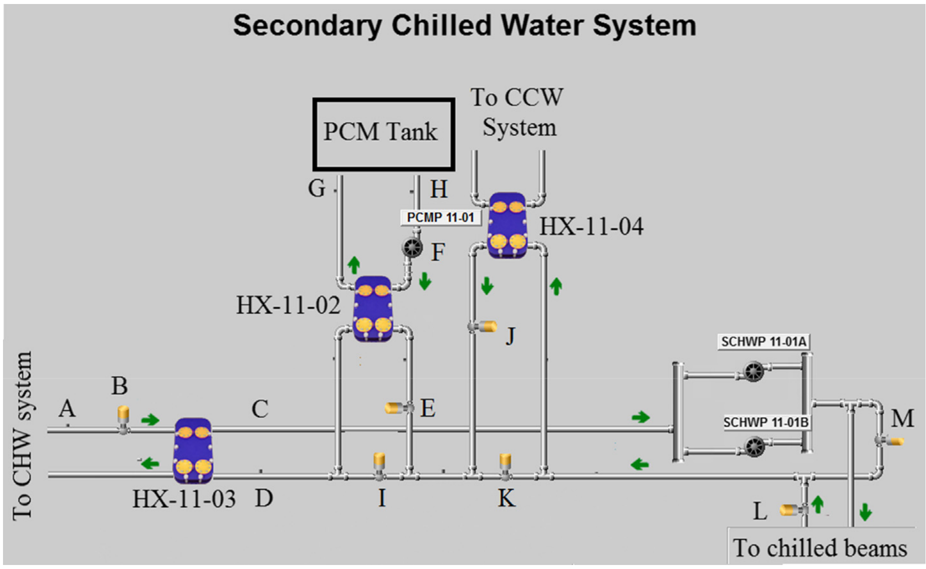

Fig. 1. Secondary chilled water system integrated with PCM tank.

Fig. 2. Phase change materials tank in the case study building.

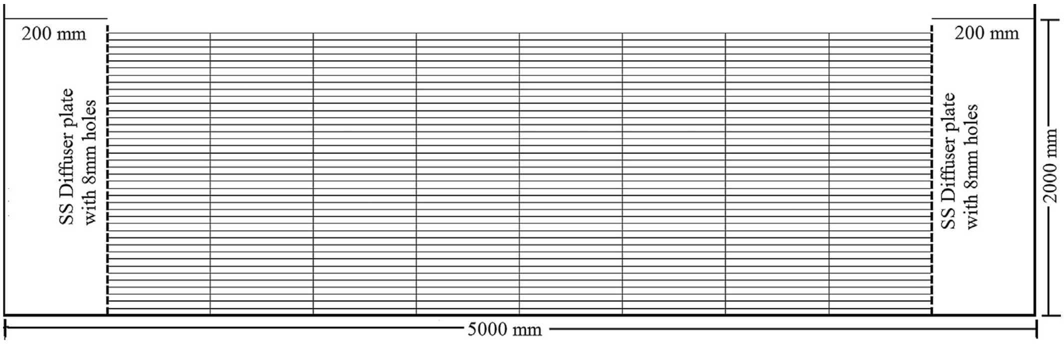

Fig. 3. Schematics of PCM block arrangement in PCM tank.

Fig. 4. FlatICE PCM blocks inside the PCM tank.

When stage 1 is active, and energy stored in PCM tank is sufficient to provide cooling then the bypass valve ‘I’ (see Fig. 1) is closed, control valve ‘E’ is open and phase change pump ‘F’ is run at a predetermined speed. Once the stored cooling energy of PCM is exhausted or is insufficient to generate the required chilled water for the SCHW loop, the system moves to stage 2. The cooling energy from the PCM tank is deemed insufficient when the PCM flow temperature (point ‘H’ in Fig. 1) is greater than 14 °C. This is because the SCHW circuit operates at 14 °C flow (point ‘C’) and 18 °C return (point ‘D’) temperature for the chilled beams. PCM flow temperature higher than 14 °C will not contribute to maintaining the desired flow temperature at point C.

When stage 1 or stage 2 is active, either of the SCHWP 11-01A or SCHWP 11-01B pump runs at predetermined speed, the bypass valve ‘M’ (see Fig. 1) is closed and return valve ‘L’ is open to supply chilled water to the chilled beams. The HX 11-03 control valve ‘B’ modulates open to maintain flow temperature (at point ‘C’) at 14 °C.

Table 1
Properties of PCM used in the FlatICE block.

Properties	Value
Phase change temperature	15 °C
Density	1510 kg/m^3
Latent heat capacity	160 kJ/kg
Specific heat capacity	1900 kJ/kg·K
Thermal conductivity	0.43 W/m·K

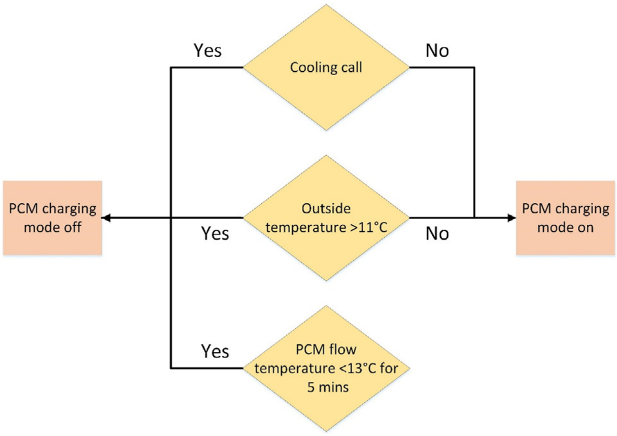

Fig. 5. Conditions for PCM tank charging mode on/off.

2.2.2. PCM charging

Fig. 5 shows the conditions of PCM tank charging. The PCM tank charging mode is activated when the following conditions are true for 1 h:

1. There is no cooling call from the building
2. Outdoor ambient air temperature is less than 11 °C

Once the PCM charging mode is activated, the valves in SCHW system (in Fig. 1) have been commanded to the positions shown in Table 2. The table also shows the valve positions during the PCM discharging mode. Once the required valve combination for PCM charging is true for 60 s, the duty secondary chilled water pump (either SCHWP 11-01A or SCHWP 11-01B), phase change material pump (F), and condenser water pump in CCW system are commanded on at a fixed speed. The charging mode is deactivated if there is a cooling call or the ambient temperature is over 11 °C. Charging mode is also deactivated when the PCM flow temperature (point ‘H’ in Fig. 1) is below 13 °C for 5 min. The CCW system consists of three adiabatic coolers which operate simultaneously when there is a cooling call. In PCM charging mode, the third (ACC- 11-03) adiabatic cooler (shown in Fig. 6) is isolated to provide cooling water for the PCM tank utilizing the cold ambient temperature and via the heat exchangers HX-11-04 and HX-11-02.

Table 2
Valve positions during PCM charging and discharging modes.

Valve	PCM charging	PCM discharging
SCHW bypass valve (M)	On	Off
SCHW return valve (L)	Off	On
HX-11-04 bypass valve (K)	Off	On
HX-11-04 control valve (J)	On	Off
HX-11-02 bypass valve (I)	Off	Off
HX-11-02 control valve (E)	On	On

3. Methodology

3.1. Data collection and analysis

The performance of the active PCM system was monitored for 25 months (May 2016 to June 2018) by analyzing recorded data in a set of predefined points of the system. Table 3 illustrates the monitored parameters along with their operation mode and measurement accuracy. The parameters were recorded at a frequency of 5 min. The notations given in the brackets must be referred to the location in SCHW system shown in Fig. 1. The specifications of the pumps were recorded from the HVAC Commissioning report of the building and are presented in Table 4.

The monitoring of the active PCM system resulted in a large amount of data that provided important insights into the PCM system performance in supplying the cooling energy. In order to systematically assess the collected data, the following indicators are used in this study:

3.1.1. Cooling energy supplied by the PCM tank to the SCHW system

When there was sufficient cold storage in PCM tank and there was a cooling call to the system (conditions mentioned in Section 2.2.1 were met), cooling energy supplied by PCM tank to the SCHW system was calculated as follows:

$$Q_{cpcm} = \dot{m}C_p(T_G - T_H) \times t \tag{1}$$

where Q_{cpcm} is the cooling energy supplied by PCM (KJ), $\dot{m}$is the mass flow rate of water through the PCM tank (kg/s), C_p is the specific heat capacity of water (KJ/kg·K), T_G and $T_H$are the water inlet (point G in Fig. 1) and outlet temperatures (point H in Fig. 1) from the PCM tank respectively and the t is the duration.

3.1.2. Cooling energy supplied by the CHW system to the SCHW

During stage 1 and stage 2 cooling, the cooling energy supplied by the CHW system to SCHW system was calculated using Eq. (2)

$$Q_{CHW} = \dot{m}C_p(T_D - T_C) \times t \tag{2}$$

where Q_{CHW} is the cooling energy supplied by CHW system (KJ), $\dot{m}$is the mass flow rate of water through the heat exchanger HX-11-03 (kg/s), C_p is the specific heat capacity of water (KJ/kg·K), T_C and T_D are the water flow (point C in Fig. 1) and return temperatures (point D in Fig. 1) from HX-11-03 and t is the duration.

The percentages of cooling energy supplied by PCM tank (E_{PCM}) and CHW system compared to total cooling energy consumed by the chilled beam system were calculated via:

$$E_{PCM} = \frac{Q_{cpcm}}{Q_{cpcm} + Q_{CHW}} \times 100 \tag{3}$$

$$E_{CHW} = \frac{Q_{CHW}}{Q_{cpcm} + Q_{CHW}} \times 100 \tag{4}$$

3.1.3. Cooling energy stored in the PCM tank

When the PCM charging conditions mentioned in Section 2.2.2 were met, cooling energy stored in PCM tank was calculated using Eq. (5)

$$Q_{spcm} = \dot{m}C_p(T_H - T_G) \times t \tag{5}$$

where Q_{spcm} is the cooling energy stored in PCM tank (KJ), $\dot{m}$is the mass flow rate of water through the PCM tank (kg/s), C_p is the specific heat capacity of water (KJ/kg·K), T_G and $T_H$are the water inlet (point G in Fig. 1) and outlet temperatures (point ‘H’ in Fig. 1) from PCM tank respectively and t is the duration.

3.1.4. PCM tank cooling capacity

As mentioned in Section 2.1, the PCM tank contains 5120 FlatICE PCM blocks. Each block contains 5.74 kg PCM. Using the manufacturers’ specifications of hydrated salt (Table 1), the total capacity of

Fig. 6. Adiabatic cooler of the CCW system.

Table 3
Monitored parameters of active PCM system.

Parameter	Unit/operation mode	Accuracy
CHW Flow Temperature (A)	°C	± 0.2 °C
HX 11-03 Control Valve (B)	On/off	–
HX-11-03 SCHW Flow Temperature (C, T_C)	°C	± 0.2 °C
HX-11-03 SCHW Return Temperature (D, T_D)	°C	± 0.2 °C
HX-11-02 Control Valve (E)	On/off	–
PCMP-11-01 Run Status (F)	On/off	–
PCM Flow Temperature (G, T_G)	°C	± 0.2 °C
PCM Return Temperature (H, T_H)	°C	± 0.2 °C
HX-11-02 Bypass Valve (I)	On/off	–
HX-11-04 Control Valve (J)	On/off	–
HX-11-04 Bypass Valve (K)	On/off	–
SCHW PCM Charging Call	On/off	–
CHW/SCHW Cooling Call	On/off	–
SCHW Stage 1 Cooling Status	On/off	–

the PCM tank can be calculated as follows:

$$\begin{aligned}\text{Total PCM tank cooling load capacity} &= \text{Number of PCM blocks} \\ &\quad \times \text{weight of each block} \\ &\quad \times \\ &\quad \text{latent heat capacity of each block} \\ &= 5120 \times 5.74\text{kg} \times 160\text{KJ/kg} \\ &= 4,702,208\ \text{KJ}\end{aligned}$$

Hence, if the PCM tank is fully charged, it can provide 4702.2 MJ or 1307 kW cooling load shifting capability to this building.

4. Results and discussions

4.1. *Energy saving performance of the active PCM system*

Fig. 7 presents cooling energy stored and delivered by the PCM tank to generate chilled water in the SCHW loop. The cooling energy delivered by PCM tank was calculated using Eq. (1). The graph shows that the PCM tank provided cooling energy during late autumn (May), winter (June–August) and early spring (September-October). The tank was inactive during the summer period (December–March). This was because, the phase transition temperature of the PCM used in this building is 15 °C. According to the building operational manual, this active PCM system relies on ambient temperature to charge the PCM tank at night which means that the outdoor temperature must be cooler than 15 °C to solidify the PCM. However, according to the building management system, charging of PCM tank only starts when the outdoor ambient temperature is cooler than 11 °C. While flowing through the condenser water pipe and transferring heat across two heat exchangers (HX 11-04 and HX 11-02), the temperature of the condenser water rises which reduces the charging potential of PCM tank. After careful considerations, the designer has set the onset of PCM charging at 11 °C to ensure that the condenser water is cold enough to charge the PCM tank. Eq. (5) was used to calculate the energy stored in the PCM tank while charging. During the summer months of 2016–2017 and 2017–2018, the monthly mean minimum temperatures were between 14.6 °C and 17.3 °C as shown in Fig. 7. During, 2016–2017 summer, only 9 nights out of 4 months experienced minimum temperature below 11 °C. The 2017–2018 summer nights were even hotter where only 4 nights experienced minimum temperature below 11 °C. Therefore, in Melbourne, the outdoor temperatures at night were not cold enough (not less than 11 °C) to charge the PCM tank during summer nights as shown in Fig. 7.

Fig. 7 also shows that mean minimum night temperatures during

Table 4
Specification of pumps used in PCM charging and cooling process.

	Phase change material pump (PCMP-11-01)	Condenser water pump (CCWP-11-04)	Secondary Chilled water pump (SCHWP-11-01A)	Secondary Chilled water pump (SCHWP-11-01B)
Power (kW)	15	11	18.5	18.5
Flow rate (L/s)	28	21.5	26.1	26.1
Efficiency (%)	93	92	94	94
Speed (RPS)	1450	1450	1460	1460
VSD (HZ)	35.4 (71%)	41 (82%)	43 (86%)	42.9 (86%)

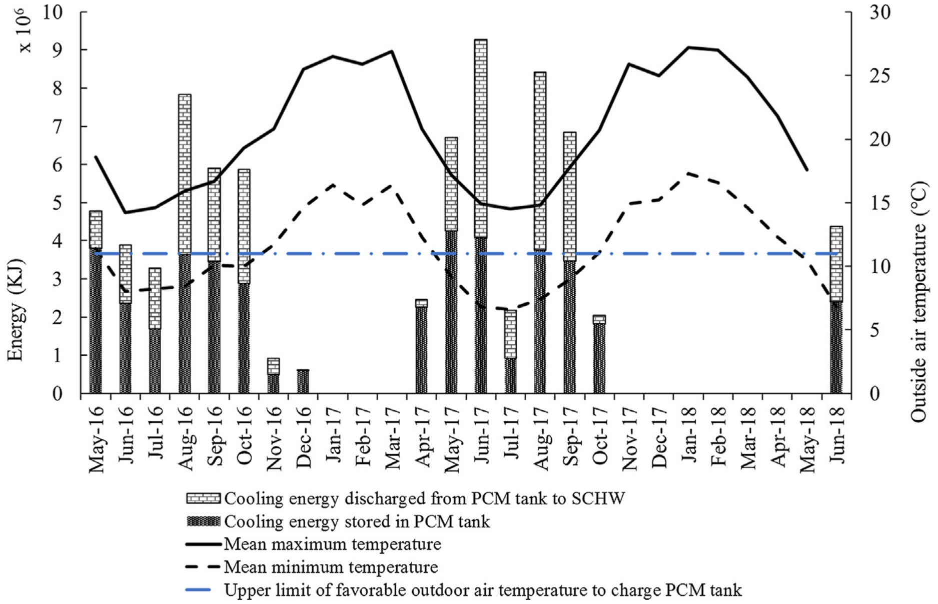

Fig. 7. Monthly cooling energy stored and discharged from PCM tank along with mean maximum and minimum outdoor temperature.

May to October were well below 11 °C (except May-16 and Oct-17) which provided favorable conditions for the PCM tank to be charged at night. During this period, the PCM tank supplemented the cooling energy requirement (Fig. 7) in the building by utilizing energy stored at night. Although in May 2016, the mean minimum temperature was 11.4 °C, this month experienced 11 nights with minimum temperature much lower than 11 °C. The mean minimum temperature of last 11 nights of May 2016 was only 8.5 °C which provided favorable conditions for the operation of PCM tank. The same explanation applies to the operation of the PCM tank in October 2017.

Fig. 8 shows the cooling energy delivered by primary chilled water (CHW) system to the secondary chilled water (SCHW) system (calculated using Eq. (2)) to meet the building cooling load and maintain thermal comfort. The figure shows that cooling energy delivered by the CHW system is much higher between November to May which is understandable due to higher mean maximum temperature as shown in Fig. 7. However, as discussed before, PCM tank provided cooling energy only during the winter months when the demand from CHW system was minimum and did not make any contributions during the summer months when there were higher cooling energy demand. Fig. 9 shows the cooling energy supplied by the PCM tank and CHW system as a percentage of total cooling energy delivered to SCHW system to meet the building cooling demand, calculated using Eqs. (3) and (4). As expected, the PCM tank contributed to meet cooling demand only during the winter months (June to August) compared to others. Between 12 and 37% of the total cooling load was delivered by PCM tank in those months. In addition, PCM tank also contributed around 2–5% of the total cooling load during May, September, and October. During the rest of the months, PCM tank remained inactive.

To explore further the contributions of the PCM system during winter, the average daily profile of the cooling energy supplied by PCM tank and CHW system during June 2016 and June 2017 have been presented in Figs. 10 and 11. The figures show that in those months, PCM system significantly reduced the cooling demand on the chiller since morning to 2 pm in the afternoon. However, the figures also

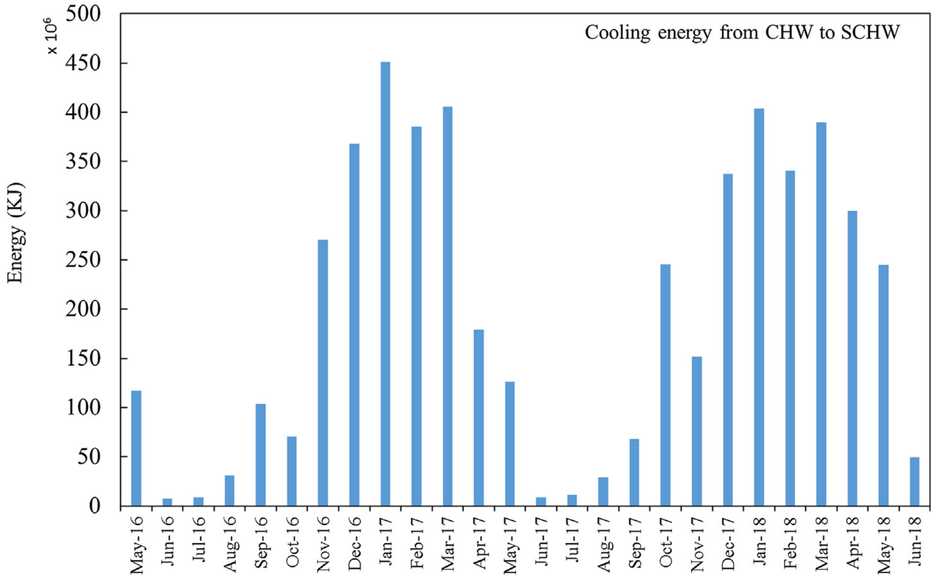

Fig. 8. Monthly cooling energy delivered by CHW system to SCHW system.

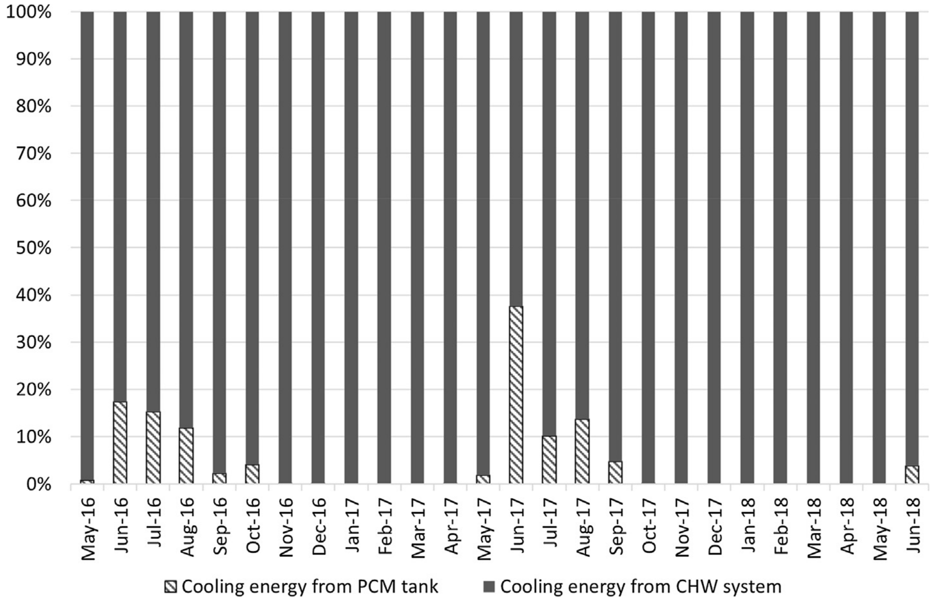

Fig. 9. Monthly cooling energy supplied by PCM tank and CHW system as a percentage of total cooling energy consumed.

revealed that the peak cooling load on Chiller occurs at around 3 pm in the afternoon. Sometimes, it is more beneficial to reduce the peak cooling load than the total cooling load. Therefore, if the objective is to reduce the peak cooling load, the operation of the PCM system should be set in a way that the system turns on during the time of peak demand.

Fig. 12 shows the monthly energy stored in PCM tank as a percentage of total PCM tank capacity. It can be seen that this ratio is higher during the winter than the other three seasons. This can be attributed to the availability of sufficient cold storage from ambient air at night during this period, as explained above. The box plot shows the median of the percentage of energy stored as well as the values within +/- 25% of the median. The whisker plot shows how large is the spread of the data (percentage of energy stored). For example, in June 2017, the median

energy storage was 2.4% of total PCM tank capacity which means that on 50% of the days in June 2017, the energy stored in the PCM tank was 2.4% of total capacity or lower. The box plot of June 2017 shows that on 50% of the day's energy stored in the PCM tank was between 1% and 4.2% of total PCM tank capacity. For 25% of the days in June 2017, the energy storage was between 4.2% and 7.2%. For the remaining 25% of the days, energy storage was less than 1%. Interestingly, during May 2016 and May 2017, the median energy storage were zero because more than 50% of the days in those months the energy stored in the PCM tank was zero because of unfavorable weather conditions. Fig. 12 also shows some outliers which points out that on some rare occasions the percentage of energy storage was much higher than the usual ranges (defined by box and whisker) due to favorable weather conditions on that particular day. However, these are not regular events and should not be used as an indicator of PCM tank performance. More importantly, the magnitude did not exceed 15% during the entire monitoring period even including the outliers. This indicates that even at maximum utilization of PCM tank, it was only using 15% of its available capacity to supply cooling energy to SCHW

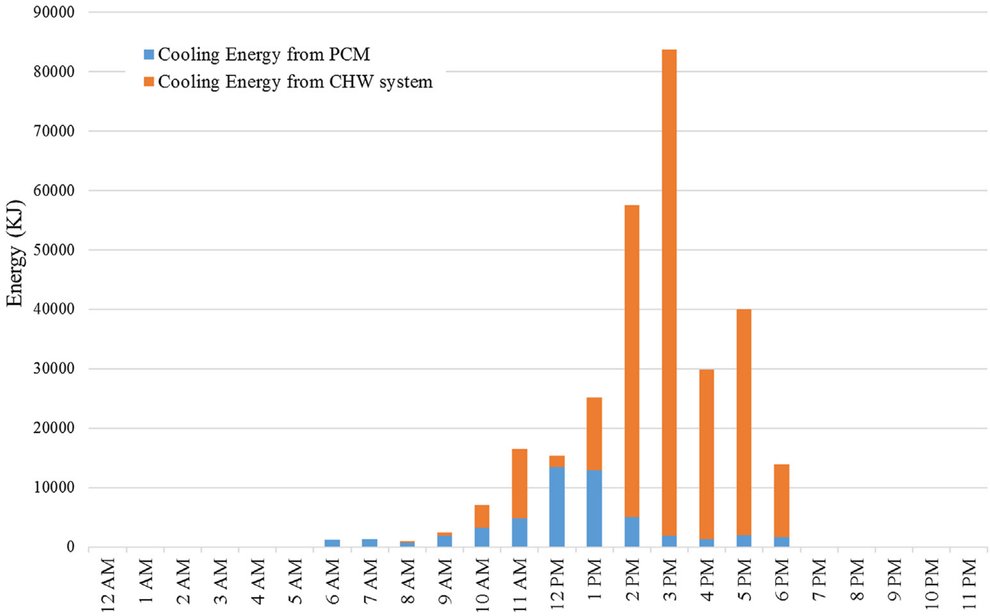

Fig. 10. Average daily profile of the cooling energy supplied by PCM and CHW system during June 2016.

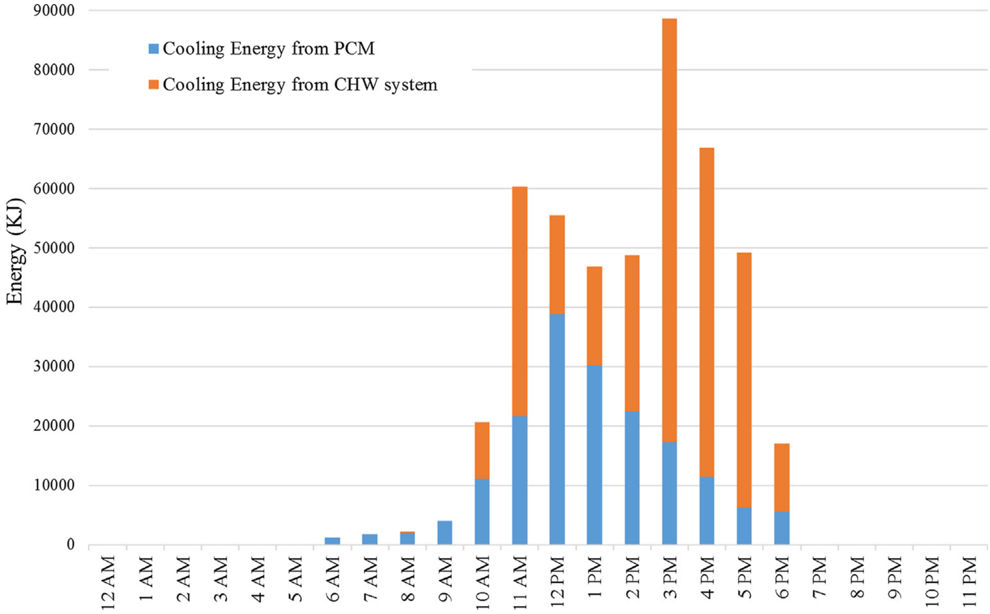

Fig. 11. Average daily profile of the cooling energy supplied by PCM and CHW system during June 2017.

loop.

It is already known that the PCM tank starts charging once the conditions in Section 2.2.2 are met. Three different pumps operate simultaneously to store cooling energy in the PCM tank. Fig. 13 shows the comparison of cooling energy stored in PCM tank and the total energy consumed by the three pumps to charge the tank. The power consumed by the pumps were determined with the aid of pump specification (Table 4) and hours of operation. The figure indicates that cooling energy stored in the PCM tank was consistently lower than the pumping energy used to store the cooling energy. Therefore, instead of saving energy, the PCM system was consuming more energy while charging and discharging which was negatively influencing the energy efficiency of this building.

Further analysis of the monitored data revealed that, on a number of occasions, all three pumps were running even when the difference between the flow (point 'H') and return (point 'G') temperatures of the PCM tank was lower than 0.1 °C. Fig. 14 shows the temperature difference between flow and return points in the PCM tank along with the energy stored in the PCM tank on 3rd June 2018. The figure also shows the energy consumed by the pumps to store that energy. As can be seen from the figure, the average difference between PCM flow and return temperature was only 0.023 °C with a maximum difference of 0.075 °C. The energy stored in the PCM tank was consistently lower than the energy consumed by the pump to store that energy. The total energy stored in the PCM tank on this occasion was calculated as 13.51 kWh. In order to attain this energy storage, three pumps were running for 11 h and consumed 419.65 kWh. Hence, there is a need to revise the PCM charging operation including minimum temperature differential as an

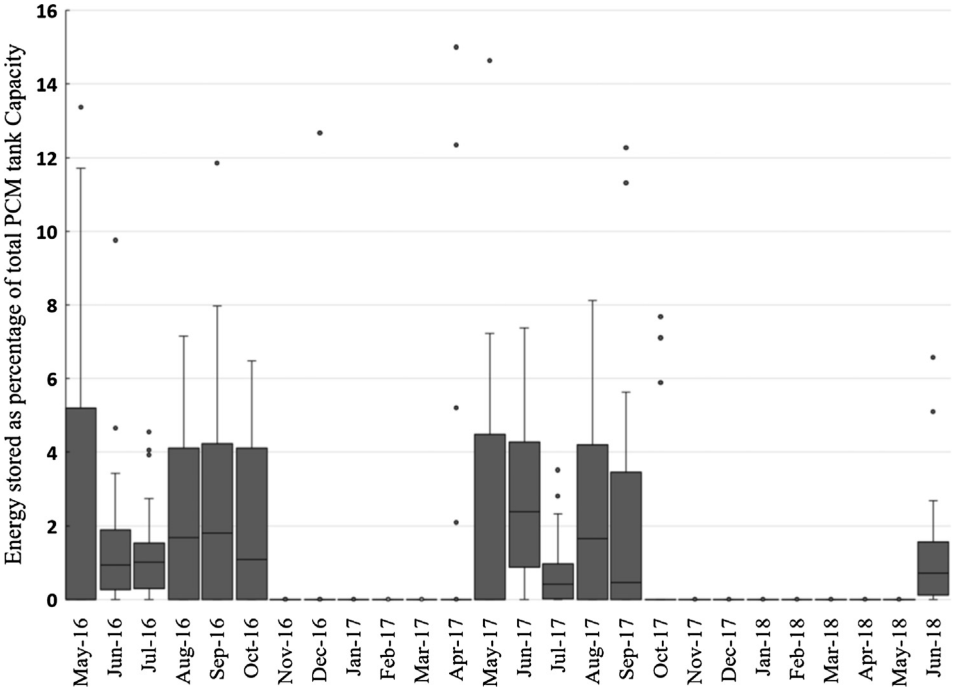

Fig. 12. Cooling energy stored in PCM tank as a percentage of total PCM tank capacity.

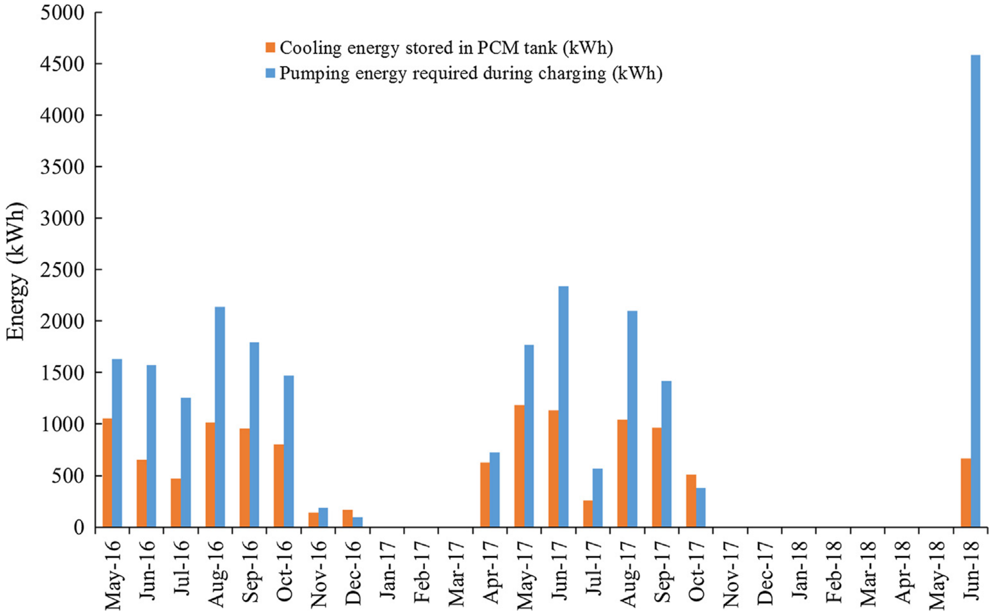

Fig. 13. Comparison of cooling energy stored in PCM tank and the pumping energy required to charge the tank.

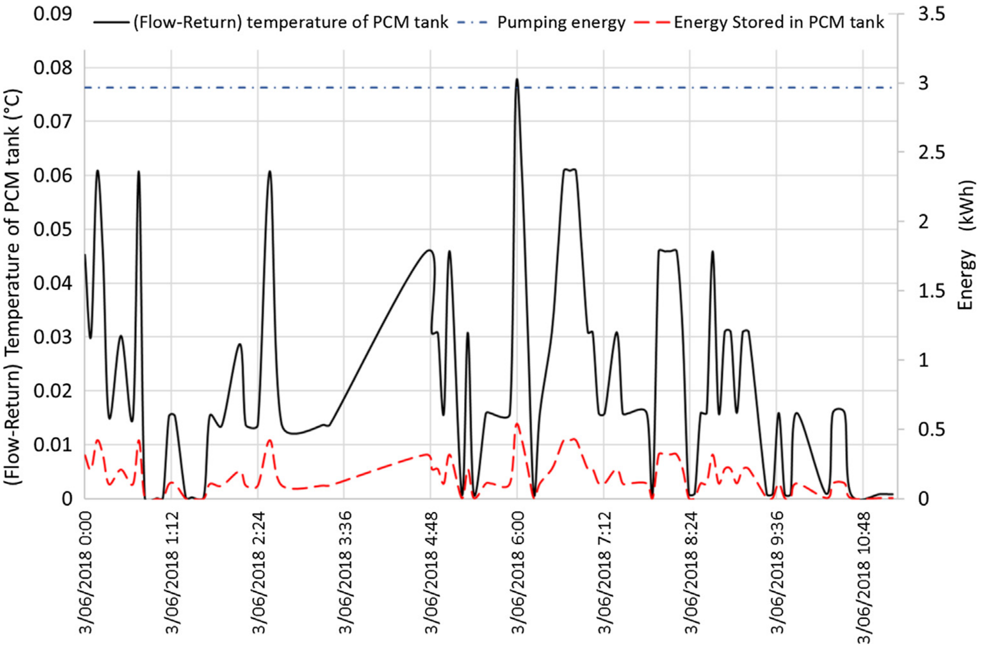

Fig. 14. Energy stored in PCM tank and associated pumping energy on 3rd June 2018.

additional condition in order to turn on the charging mode as shown in Fig. 5.

The minimum difference between the flow and return temperature of the PCM tank to turn on the charging mode can be calculated as follows:

$$\text{The rate of energy stored in the PCM tank} > \text{Total pumping power}$$

$$\dot{m}C_p\Delta T > 35.58\ \text{kW}$$

$$19.88\frac{\text{kg}}{\text{s}} * \frac{4.18\text{KJ}}{\text{kg}}\cdot\text{K} * \Delta\text{T} > 35.58\ \ \text{kW}$$

$$\Delta T > 0.43°\text{C}$$

Here,

$\dot{m}$ = mass flow rate of water thorugh the PCM tank

C_p = Specific heat capacity of water

ΔT = difference between flow and return temperature of the PCM tank

The power of the phase change pump, secondary chilled water pump and condenser water pump were multiplied by their respective efficiency (Table 4) and then added together to calculate the total pumping power. Hence, in this particular active PCM system, the difference between flow and return temperature must be over 0.43 °C before turning on the PCM charging mode.

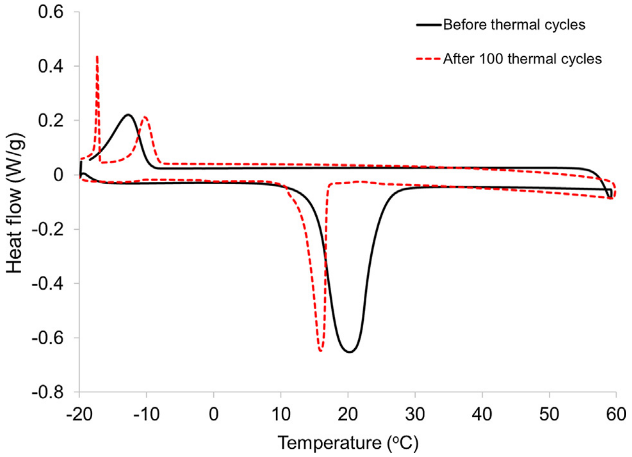

Fig. 15. Differential Scanning calorimetry measurement of the PCM used in the active PCM system.

4.2. Causes of discrepancies between predicted and actual energy saving performance of an active PCM system

According to the design document of this building, the PCM thermal storage tank was designed to reduce the daytime cooling load on chiller by 33%. However, as shown in previous section, the actual energy savings by the PCM tank system is much lower than then predicted savings except during several months in winter. In this section, the causes for such discrepancies have been explored.

A thorough review of Building User's Guide revealed that the PCM tank was designed to be charged at night using both ambient air and electric chiller. The electric chiller should be used when the outdoor ambient air is insufficient to solidify the PCM. In this way, the chillers can operate more efficiently due to cooler ambient temperatures at night compared to warmer daytime temperature. Cooling energy produced by the chiller depends on its capacity to reject heat to the environment via the condenser and adiabatic cooler. The refrigerant inside the chiller rejects heat to the condenser water inside a condenser. The condenser water then flows into the adiabatic cooler, rejects heat and recirculates into the condenser. At night, more heat can be rejected to the atmosphere due to the lower ambient temperature which can help to improve the efficiency of the chiller. Moreover, the operation of the chiller at night can take advantage of off-peak electricity tariff which is 25% lower than the peak in the case of the studied building. The cooling energy stored in the PCM tank should be used during the day to reduce the peak demand on the cooling plant (CHW system). However, in reality, this active PCM system was only operated in a free cooling mode (using the ambient air only to solidify the PCM) which caused the PCM tank to be inactive during the summer period. This happened because the requirements were not mentioned in the Building Management System (BMS) operating and maintenance manual and the current operation mode was programmed to charge the PCM using cold night ambient air only. Communication with operation manager revealed that they were not aware of this requirement of running the chillers to charge the PCM tank at night. They were running the building according to the instructions provided to them by the consultants, and they have not gone through the Building Users' guide. Moreover, from the communication with building operation manager and service engineer, it was also understood that there is a lack of understanding amongst the operation and maintenance staff regarding the operation and purpose of this active PCM technology. As a result, the PCM tank was not running efficiently to shift the peak loads to off-peak.

The actual specification of PCM can also be a critical parameter for the poor performance of the PCM tank system. This is because the performance assessment of PCM tank during the design stage (i.e. diurnal energy retrieval to storage ratio) was conducted using the latent heat capacity of PCM provided by the manufacturer. The actual thermal behavior of salt hydrate PCM was examined by studying its thermo-physical properties such as phase transition temperature and latent heat capacity. A representative salt hydrate sample (approximately 6 mg) was acquired from one of the flatICE panels and tested using the Differential Scanning Calorimetry (DSC) apparatus. The DSC measurements were conducted with heat flux DSC (Q1000 from TA Instruments) over the temperature range of −20 to 60 °C at a temperature ramping rate of 1 °C/min in Nitrogen (N_2) atmosphere. The temperature and enthalpy accuracy of Q1000 are 0.1 °C and 1%, respectively.

Apart from the thermo-physical properties of PCM, the thermal reliability should also be assessed to ensure there are no degradation on thermal capacity in the long-term operation. In this study, the thermal reliability of salt hydrate was assessed by subjecting the representative sample to 100 accelerated thermal cycles and measuring the performance after cycles. The temperature programme used for a single thermal cycle with a duration of 2 h was:

Step 1: Temperature ramp from 10 to 40 °C at the rate of 1 °C/min.
Step 2: Temperature kept at 40 °C for 30 mins.
Step 3: Temperature ramp from 40 to 10 °C at a rate of 1 °C/min.
Step 4: Temperature kept at 10 °C for 30 mins.

The DSC thermographs of the salt hydrate before and after 100 thermal cycles are presented in Fig. 15. Table 5 also reports the thermo-physical properties in terms of its onset and peak temperatures as well as the latent heat capacity. As can be seen from the figure and table, the salt hydrate used in this building has a very high degree of supercooling during the solidification process. Therefore, the solidification process of PCM required longer periods of cold storage supply and hence, making them unable to supply sufficient cold storage to operate the SCHW system. Furthermore, the measured latent heat capacity of PCM (53 J/g) was much lower than the manufacturer specified latent heat capacity (160 J/g). These differences may lead to a significant variation in the actual performance of the PCM tank to the expected design performance.

Nevertheless, the comparison of DSC thermographs before and after thermal cycles reveals that there is little degradation in latent heat capacity when the specimen is subjected to 100 thermal cycles. The small changes in the phase change enthalpies are in negligible levels and can be attributed to weight loss during thermal cycles. However, a substantial variation in phase transition temperature can be observed during the melting process. This may be due to a small amount of sample was used for thermal reliability test and hence, phase separation occurs at low temperature. Similar behavior has been reported by previous authors for various salt hydrate PCMs [56,57]. Thus, the PCM used in this study can be considered as thermally reliable without significantly losing its latent heat capacity.

Moreover, from November 2017 to May 2018, the PCM system was found to be inactive, since there were no cooling or charging of PCM tank as evident from Fig. 7. The PCM tank was completely inactive during April and May 2018 which were not expected when comparing the operation of the PCM system with previous years. Further analysis of the collected data revealed that in those months there was always a

Table 5
Thermo-physical properties of PCM before and after 100 thermal cycles.

	Melting process			Freezing process		
	T_{onset} (°C)	T_{Peak} (°C)	H_M (J/g)	T_{onset} (°C)	T_{Peak} (°C)	H_M (J/g)
Uncycled	15.1	20.1	52.97	−9.82	−12.58	15.03
100 cycles	13.46	15.92	51.34	−8.44	−10.32	14.74

cooling call from the building. As a result, PCM tank was never charged (condition in Fig. 5) in that period and did not deliver any cooling energy to the SCHW loop. Review of building maintenance log and communications with the building operation manager and service engineer revealed that the occupancy detection sensors were not working in several zones of the building on November 2017. This issue was impacting the operation of the heating and cooling system in those zones as the system only turns on when there is an occupant in the room. To overcome this issue temporarily, the occupancy control of the HVAC system was overridden in the BMS which resulted in 24/7 cooling call from the building irrespective of occupancy status. As a result, the PCM tank charging mode was off for 7 months until the problems with occupancy sensors were fixed on June 2018. During this time, the operational staffs were unaware of the fact that the PCM operation was affected by this overriding decision due to their lack of knowledge and understanding of the active PCM system.

Furthermore, although PCM tank started charging when the outdoor air temperature dropped below 11 °C, the temperature of the water that goes into PCM tank while charging (point ‘G’) never dropped below 13 °C. This minimum difference of 2 °C was occurred due to the losses while flowing through the pipe and across two heat exchanger which had significantly reduced the charging potential of PCM tank. Further study is recommended to investigate this temperature difference through examining the water loops and heat-exchanger performance. Based on the results and discussions, the causes for discrepancies between predicted and actual energy savings of an active PCM system in a real building have been summarized in Fig. 16 below:

4.3. Lessons learned

Following are the critical lessons learned from this study which can be applied to any building with active PCM system:

1. The control logic for charging and discharging the PCM tank should be checked at regular interval to explore the possibilities of improving its efficiency. The PCM tank should not be charged when the pumping energy required to charge the PCM tank is higher than the cooling energy stored in PCM tank.
2. If the active PCM system is installed to reduce the peak cooling load on the chiller, it’s operation should be controlled in a way that the PCM system turns on during the time of peak demand.
3. The specifications of the PCM should be carefully assessed before installation to ensure predicted performance of the PCM system is realized during the operation.
4. The difference between the design phase and the actual operation of the PCM system will cause the PCM tank to perform poorly. To maximize the efficiency of PCM tank and to minimize building energy consumption, the designed operation of the PCM system should be communicated clearly with building operational staffs.
5. The building design documents should be ensured as consistent with the operation documents. If there are any changes in the maintenance documents, this should be consulted with the designer to see the potential impact of the changes on the performance of the PCM system.
6. The building operations and maintenance staff should be provided with the necessary knowledge and training to understand whether the PCM system is performing as intended.

5. Conclusions

Thermal performance of an active phase change materials (PCM) system in a multistorey educational building in Melbourne was evaluated experimentally. The temperatures and operational information at various locations of the PCM system were monitored for 25 months. The analysis revealed that the installed active PCM system in this building reduced cooling energy demand on the chiller (CHW system) by

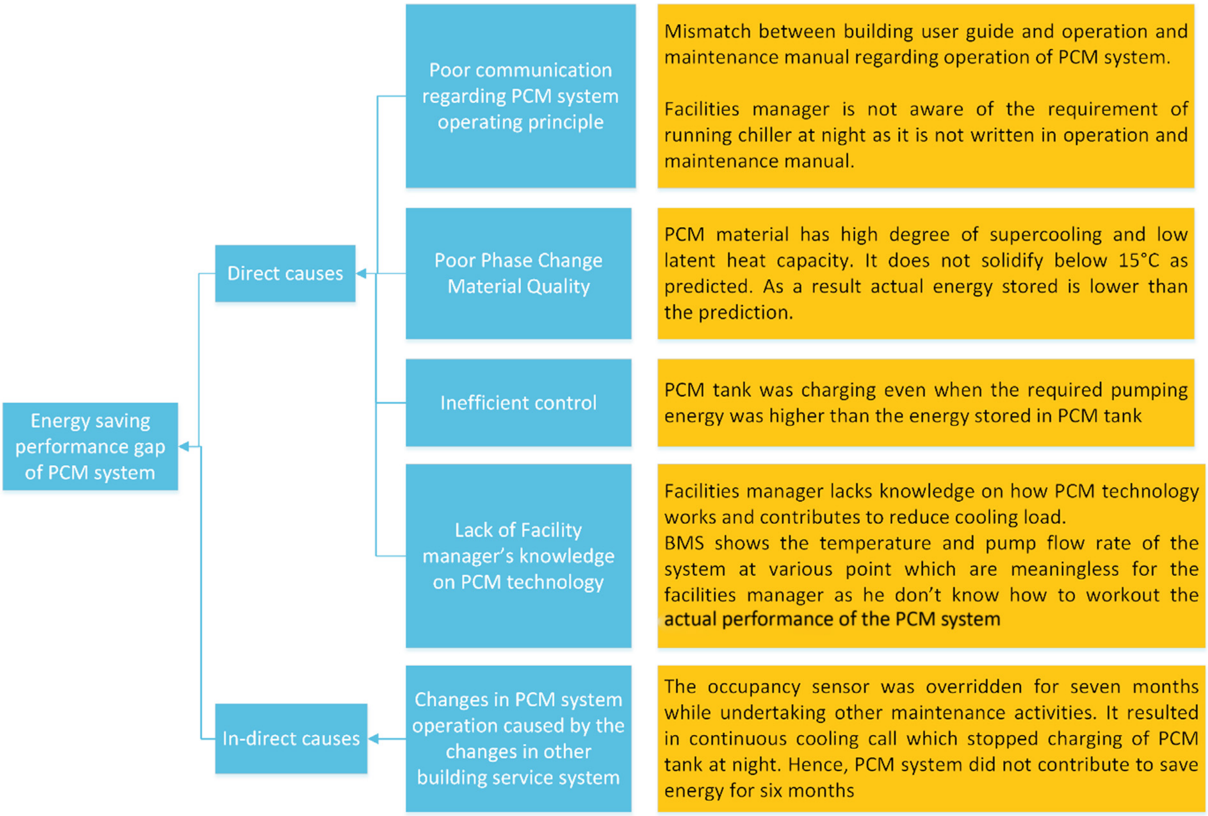

Fig. 16. Causes of energy saving performance gap of an active PCM system in a real building.

12–37% only during winter months (June to August). During summer, the system remained inactive and did not contribute to meet the building cooling demand because the ambient temperature was not cold enough to charge the PCM tank during summer nights. The PCM tank was utilizing only a fraction of its total theoretical latent heat capacity (specified by the manufacturer) in reducing the cooling load. Even in the case of maximum effectiveness, the PCM tank was only using 15% of its total capacity. Moreover, instead of saving energy, the active system was resulting in more energy consumption because the energy stored in the PCM tank was much lower the energy consumed by the pumps in storing the energy.

The lessons learned from the operation of PCM storage in this multistorey building were reported. The primary issues associated with the underperformance of the PCM tank in this building were identified as the mismatch between designed and actual operation of the PCM system, inefficient operation logic, poor material quality, and limited knowledge of maintenance staffs during the operation stage. To enhance the effectiveness of the active PCM system in a building, one should strictly follow the control logic of charging and discharging the PCM tank as intended by the designer. The control logic should also include a real-time comparison of energy stored in the PCM tank with energy consumed by the pumps to store that energy. This will ensure that the PCM system will not negatively influence the building energy performance. Moreover, there is a need to ensure that the properties of the supplied PCM materials match with the specifications from the manufacturer. Finally, the operation staff should be provided with sufficient training to help them to operate the PCM system efficiently.

Acknowledgment

This research was jointly funded by the Australian Research Council Industrial Transformation Research Hub for nanoscience-based construction material manufacturing (IH150100006), Sustainable Built Environment Naiotnal Research Center, Aurecon, Queensland Government Department of Housing and Public Works and Western Australia Government Department of Finance.

References

[1] Lucon O, Ürge-Vorsatz D, Zain Ahmed A, Akbari H, Bertoldi P, Cabeza LF, et al. Buildings. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, editors. Climate change 2014: mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA; ; 2014.

[2] de Gracia A, Cabeza LF. Phase change materials and thermal energy storage for buildings. Energy Build 2015;103:414–9.

[3] Du K, Calautit J, Wang Z, Wu Y, Liu H. A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges. Appl Energy 2018;220:242–73.

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

[5] Waqas A, Ud Din Z. Phase change material (PCM) storage for free cooling of buildings—a review. Renew Sustain Energy Rev 2013;18:607–25.

[6] Castell A, Martorell I, Medrano M, Pérez G, Cabeza LF. Experimental study of using PCM in brick constructive solutions for passive cooling. Energy Build 2010;42(4):534–40.

[7] Cabeza LF, Castellón C, Nogués M, Medrano M, Leppers R, Zubillaga O. Use of microencapsulated PCM in concrete walls for energy savings. Energy Build 2007;39(2):113–9.

[8] Ascione F, Bianco N, De Masi RF, de' Rossi F, Vanoli GP. Energy refurbishment of existing buildings through the use of phase change materials: energy savings and indoor comfort in the cooling season. Appl Energy 2014;113:990–1007.

[9] Wang S-M, Matiašovský P, Mihálka P, Lai C-M. Experimental investigation of the daily thermal performance of a mPCM honeycomb wallboard. Energy Build 2018;159:419–25.

[10] Yao C, Kong X, Li Y, Du Y, Qi C. Numerical and experimental research of cold storage for a novel expanded perlite-based shape-stabilized phase change material wallboard used in building. Energy Convers Manage 2018;155:20–31.

[11] Ramakrishnan S, Wang X, Sanjayan J, Wilson J. Thermal performance assessment of phase change material integrated cementitious composites in buildings: experimental and numerical approach. Appl Energy 2017;207(Supplement C):654–64.

[12] Ramakrishnan S, Sanjayan J, Wang X, Alam M, Wilson J. A novel paraffin/expanded perlite composite phase change material for prevention of PCM leakage in cementitious composites. Appl Energy 2015;157:85–94.

[13] Barzin R, Chen JJJ, Young BR, Farid MM. Application of PCM underfloor heating in combination with PCM wallboards for space heating using price based control system. Appl Energy 2015;148:39–48.

[14] Devaux P, Farid MM. Benefits of PCM underfloor heating with PCM wallboards for space heating in winter. Appl Energy 2017;191:593–602.

[15] Sage-Lauck JS, Sailor DJ. Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building. Energy Build 2014;79:32–40.

[16] Ramakrishnan S, Wang X, Sanjayan J, Wilson J. Thermal performance of buildings integrated with phase change materials to reduce heat stress risks during extreme heatwave events. Appl Energy 2017;194(Supplement C):410–21.

[17] Alam M, Jamil H, Sanjayan J, Wilson J. Energy saving potential of phase change materials in major Australian cities. Energy Build 2014;78:192–201.

[18] KoŜny J, Biswas K, Miller W, Kriner S. Field thermal performance of naturally ventilated solar roof with PCM heat sink. Sol Energy 2012;86(9):2504–14.

[19] Kuznik F, Virgone J, Johannes K. In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. Renew Energy 2011;36(5):1458–62.

[20] Zhou G, Yang Y, Xu H. Energy performance of a hybrid space-cooling system in an office building using SSPCM thermal storage and night ventilation. Sol Energy 2011;85(3):477–85.

[21] Jamil H, Alam M, Sanjayan J, Wilson J. Investigation of PCM as retrofitting option to enhance occupant thermal comfort in a modern residential building. Energy Build 2016;133:217–29.

[22] Lee KO, Medina MA, Raith E, Sun X. Assessing the integration of a thin phase change material (PCM) layer in a residential building wall for heat transfer reduction and management. Appl Energy 2015;137:699–706.

[23] Lee KO, Medina MA, Sun X, Jin X. Thermal performance of phase change materials (PCM)-enhanced cellulose insulation in passive solar residential building walls. Sol Energy 2018;163:113–21.

[24] Silva T, Vicente R, Amaral C, Figueiredo A. Thermal performance of a window shutter containing PCM: numerical validation and experimental analysis. Appl Energy 2016;179:64–84.

[25] Zhang N, Yuan Y, Cao X, Du Y, Zhang Z, Gui Y. Latent heat thermal energy storage systems with solid-liquid phase change materials: a review. Adv Eng Mater 2018;20(6):1700753.

[26] Iten M, Liu S, Shukla A. A review on the air-PCM-TES application for free cooling and heating in the buildings. Renew Sustain Energy Rev 2016;61:175–86.

[27] Tyagi VV, Pandey AK, Buddhi D, Kothari R. Thermal performance assessment of encapsulated PCM based thermal management system to reduce peak energy demand in buildings. Energy Build 2016;117:44–52.

[28] Yanbing K, Yi J, Yinping Z. Modeling and experimental study on an innovative passive cooling system—NVP system. Energy Build 2003;35(4):417–25.

[29] Turnpenny JR, Etheridge DW, Reay DA. Novel ventilation system for reducing air conditioning in buildings. Part II: Testing of prototype. Appl Therm Eng 2001;21(12):1203–17.

[30] Turnpenny JR, Etheridge DW, Reay DA. Novel ventilation cooling system for reducing air conditioning in buildings.: Part I: Testing and theoretical modelling. Appl Therm Eng 2000;20(11):1019–37.

[31] Weinläder H, Körner W, Strieder B. A ventilated cooling ceiling with integrated latent heat storage—monitoring results. Energy Build 2014;82:65–72.

[32] Alam M, Sanjayan J, Zou PXW, Ramakrishnan S, Wilson J. Evaluating the passive and free cooling application methods of phase change materials in residential buildings: a comparative study. Energy Build 2017;148(Supplement C):238–56.

[33] Sun X, Zhang Q, Medina MA, Liao S. Performance of a free-air cooling system for telecommunications base stations using phase change materials (PCMs): In-situ tests. Appl Energy 2015;147:325–34.

[34] Yuan Y, Gao X, Wu H, Zhang Z, Cao X, Sun L, et al. Coupled cooling method and application of latent heat thermal energy storage combined with pre-cooling of envelope: Method and model development. Energy 2017;119:817–33.

[35] Medved S, Arkar C. Correlation between the local climate and the free-cooling potential of latent heat storage. Energy Build 2008;40(4):429–37.

[36] Lazaro A, Dolado P, Marín JM, Zalba B. PCM–air heat exchangers for free-cooling applications in buildings: experimental results of two real-scale prototypes. Energy Convers Manage 2009;50(3):439–43.

[37] Rouault F, Bruneau D, Sebastian P, Lopez J. Numerical modelling of tube bundle thermal energy storage for free-cooling of buildings. Appl Energy 2013;111:1099–106.

[38] Zalba B, Marín JM, Cabeza LF, Mehling H. Free-cooling of buildings with phase change materials. Int J Refrig 2004;27(8):839–49.

[39] Waqas A, Kumar S. Thermal performance of latent heat storage for free cooling of buildings in a dry and hot climate: an experimental study. Energy Build 2011;43(10):2621–30.

[40] Mosaffa AH, Infante Ferreira CA, Talati F, Rosen MA. Thermal performance of a multiple PCM thermal storage unit for free cooling. Energy Convers Manage 2013;67:1–7.

[41] Butala V, Stritih U. Experimental investigation of PCM cold storage. Energy Build 2009;41(3):354–9.

[42] Helm M, Keil C, Hiebler S, Mehling H, Schweigler C. Solar heating and cooling system with absorption chiller and low temperature latent heat storage: energetic performance and operational experience. Int J Refrig 2009;32(4):596–606.

[43] Belmonte JF, Izquierdo-Barrientos MA, Eguía P, Molina AE, Almendros-Ibáñez JA. PCM in the heat rejection loops of absorption chillers. A feasibility study for the residential sector in Spain. Energy Build 2014;80:331–51.

[44] Wang X, Niu J, van Paassen AHC. Raising evaporative cooling potentials using

combined cooled ceiling and MPCM slurry storage. Energy Build 2008;40(9):1691–8.

[45] Mazo J, Delgado M, Marin JM, Zalba B. Modeling a radiant floor system with Phase Change Material (PCM) integrated into a building simulation tool: analysis of a case study of a floor heating system coupled to a heat pump. Energy Build 2012;47:458–66.

[46] Fang G, Wu S, Liu X. Experimental study on cool storage air-conditioning system with spherical capsules packed bed. Energy Build 2010;42(7):1056–62.

[47] Cheng X, Zhai X, Wang R. Thermal performance analysis of a packed bed cold storage unit using composite PCM capsules for high temperature solar cooling application. Appl Therm Eng 2016;100:247–55.

[48] Moreno P, Solé C, Castell A, Cabeza LF. The use of phase change materials in domestic heat pump and air-conditioning systems for short term storage: a review. Renew Sustain Energy Rev 2014;39:1–13.

[49] Real A, García V, Domenech L, Renau J, Montés N, Sánchez F. Improvement of a heat pump based HVAC system with PCM thermal storage for cold accumulation and heat dissipation. Energy Build 2014;83:108–16.

[50] Zhang S, Niu J. Cooling performance of nocturnal radiative cooling combined with microencapsulated phase change material (MPCM) slurry storage. Energy Build 2012;54:122–30.

[51] Ansuini R, Larghetti R, Giretti A, Lemma M. Radiant floors integrated with PCM for indoor temperature control. Energy Build 2011;43(11):3019–26.

[52] Labat M, Virgone J, David D, Kuznik F. Experimental assessment of a PCM to air heat exchanger storage system for building ventilation application. Appl Therm Eng 2014;66(1):375–82.

[53] Chaiyat N. Energy and economic analysis of a building air-conditioner with a phase change material (PCM). Energy Convers Manage 2015;94:150–8.

[54] de Wilde P. The gap between predicted and measured energy performance of buildings: a framework for investigation. Autom Constr 2014;41:40–9.

[55] Hoogland M, Bannister P. Council House 2 (CH2) in review. ECOLIBRIUM 2014:44–50.

[56] Shukla A, Buddhi D, Sawhney RL. Thermal cycling test of few selected inorganic and organic phase change materials. Renew Energy 2008;33(12):2606–14.

[57] Tyagi VV, Buddhi D. Thermal cycle testing of calcium chloride hexahydrate as a possible PCM for latent heat storage. Sol Energy Mater Sol Cells 2008;92(8):891–9.