Chapter

Solar Thermal Energy Storage Using Paraffins as Phase Change Materials for Air Conditioning in the Built Environment

Wenye Lin, Zhenjun Ma, Haoshan Ren, Jingjing Liu and Kehua Li

Abstract

Thermal energy storage (TES) using phase change materials (PCMs) has received increasing attention since the last decades, due to its great potential for energy savings and energy management in the building sector. As one of the main categories of organic PCMs, paraffins exhibit favourable phase change temperatures for solar thermal energy storage. Its application is therefore effective to overcome the intermittent problem of solar energy utilisation, thereby reducing the power consumption of heating, ventilation and air conditioning (HVAC) systems and domestic hot water (DHW) systems. This chapter reviews the development and performance evaluation of solar thermal energy storage using paraffin-based PCMs in the built environment. Two case studies of solar-assisted radiant heating and desiccant cooling systems with integrated paraffin-based PCM TES were also presented. The results showed that paraffin-based PCM TES systems can rationalise the utilisation of solar thermal energy for air conditioning while maintaining a comfortable indoor environment.

Keywords: thermal energy storage, phase change materials, HVAC systems, solar energy, built environment

1. Introduction

As one of the major energy consumers, buildings account for around 45% of the global energy consumption with a similar share of greenhouse gases emissions [1]. Due to population increase, urbanisation, economic growth and improvement in the quality of life, energy usage in the building sector continues to rise. A study from the International Energy Agency [2] showed that without action, the energy demand in buildings could increase by 30% by 2060. A significant proportion of the energy demand from buildings is for building services, including heating, ventilation and air conditioning (HVAC) and domestic hot water (DHW) [3], in which the energy demand for HVAC is projected to increase by more than 70% from 2010 to 2050 [4]. Since the recent decades, the integration of renewable energies has been widely recognised as one of the effective solutions to reduce the HVAC power consumption in buildings, especially the utilisation of solar thermal energy. As one of the most attractive renewable energies, solar thermal energy is not only an ideal heat source for direct indoor space heating but also can be used to provide renewable cooling (e.g. absorption/adsorption cooling). However, due to the fact that solar energy is intermittent, the integration of solar thermal systems with thermal energy storage (TES) is therefore essential to rationalising energy management [5]. Among various TES technologies, TES using phase change materials (PCMs) has been receiving increasing attention. PCMs are substances that can absorb, store and release a large amount of thermal energy within a narrow temperature range through phase transitions [6], in which solid–liquid PCMs with substantial alternatives and a small change in volume during the phase change process are well suited for TES applications in the built environment [7]. Compared to sensible heat storage, TES using PCMs not only shows a significant reduction in the storage volume [8] but also enables the use of thermal energy at relatively constant temperatures [9].

PCMs are mainly categorised as organic, inorganic and eutectic materials, in which organic PCMs can be further classified as paraffins and non-paraffins [10], as shown in **Figure 1**. As PCMs, paraffins have a wide range of phase change temperatures [11], covering the temperature range from subzero to over 100°C [12]. Besides the desired phase change temperature ranges, paraffins have the advantages of congruent phase transition, self-nucleation to avoid supercooling, non-corrosiveness, long-term chemical stability without segregation and commercial availability at reasonable costs [13, 14]. However, paraffins have flammability, low thermal conductivity and relatively low volumetric latent heat storage density [15, 16].

The favourable phase change temperatures of the paraffins with phase transition temperatures at around and above 60°C, together with the other aforementioned advantages, make it one of the desired candidates for solar TES in the built environment to facilitate the solar-assisted HVAC and DHW generation. This chapter mainly focuses on solar TES using paraffin-based PCMs (with phase change temperature of and higher than 60°C) to facilitate the indoor air conditioning in the built environment. This chapter is structured as follows: Section 2 provides an overview of the solar TES using paraffin-based PCMs which can be used to facilitate the

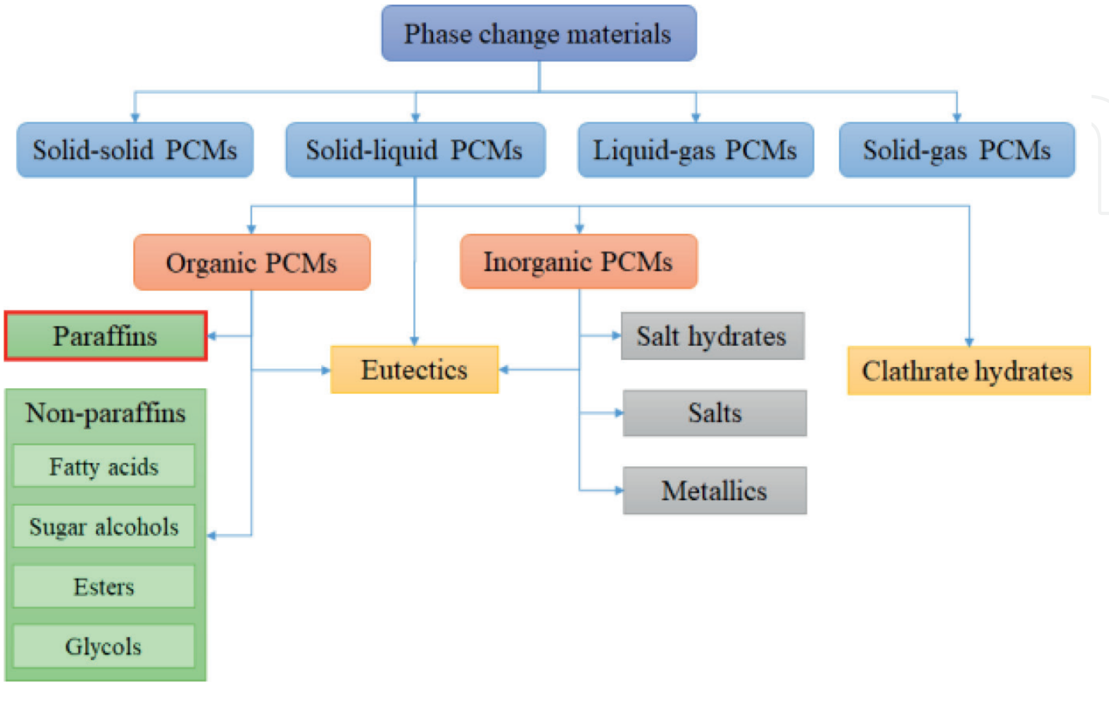

Figure 1.
PCM classifications.

indoor air conditioning. Sections 3 and 4 present two case studies of solar-assisted radiant space heating and desiccant cooling systems with paraffin-based PCMs, respectively. Section 5 provides a summary of this chapter.

2. Overview of thermal energy storage using paraffin-based PCMs in buildings

There are two main popular approaches to utilising paraffins as PCMs in the built environment. Paraffin-based PCMs can be integrated with solar thermal collectors to improve the system thermal efficiency, meanwhile serving as on-site TES. Alternatively, they can be used as independent TES units coupling with solar thermal collectors to provide continuous heat supply for the demand side. In both approaches, the charging of paraffins with the heat generated needs to be fulfilled first, followed by the retrieval of the heat using heat transfer fluids (HTFs) for specific applications (e.g. space heating or cooling). Accordingly, the following review is mainly segmented into two subsections based on the two stages. The utilisation of paraffin-based PCM TES in different solar hot water systems was also discussed and included in the first subsection, since there is a potential utilisation of the hot water generated to drive air conditioning systems. The paraffin-based PCMs used for TES in the built environment in this overview are summarised in **Table 1**.

2.1 Solar thermal energy storage using paraffin-based PCMs

2.1.1 Integration of paraffin-based PCMs with solar thermal collectors

Integrating PCM with solar collectors can not only reduce the highest temperature of the solar collectors, thereby extending the lifetime [17] and increasing the system thermal efficiency [18], but also fulfil on-site thermal storage [19]. For instance, a paraffin with a phase change temperature of around 60°C was enhanced using nano-Cu additives and laminated in a flat plate solar collector by Al-Kayiem and Lin [20] for water heating application. The experimental study showed that considerable thermal efficiency improvement was achieved with integrating the paraffin in the solar collector; however, the enhancement in thermal conductivity using nano-Cu particles showed limited benefits. A number of PCM/compressed expanded natural graphite (CENG) composites were prepared and integrated beneath a flat plate solar water heater by Haillot et al. [19, 21] for thermal performance enhancement. The characterisation of a number of PCM candidates demonstrated that the paraffin-based PCM composite, i.e. RT65/CENG, was the most suitable material to be used, due to its high thermal stability, conductivity and storage density. It was found that the solar fraction of the system using RT65/CENG composite can be effectively enhanced in summer; however, a low solar fraction was found in winter due to the high heat loss of the flat plate solar collectors.

With respect to the low heat loss, the integration of paraffin-based PCMs with evacuated tube collectors seems to be more promising. For instance, a paraffin wax with a melting temperature of 67°C was filled in the manifold of evacuated tube heat pipe solar collectors as a PCM TES unit by Naghavi et al. [22] to improve the performance of hot water supply. The numerical study demonstrated that the proposed system with PCM can maintain a high thermal efficiency of 55–60% which was less sensitive to the change of the draw-off water flowrate, compared to a conventional DHW system without PCM TES. Tritriacontane (i.e. $C_{33}H_{68}$) and erythritol were integrated into evacuated tubes simultaneously by Papadimitratos et al. [23] to gain the functionality of thermal storage while enhancing the system

Index	PCM	Phase change temperature	Application location	Application	Ref.
1	RT65	55–66°C	Solar collector—flat plate	Water heating	[19]
2	Paraffin	58.7–60.5°C	Solar collector—flat plate	Water heating	[20]
3	Paraffin	64°C	Solar collector—evacuated tubes	Water heating	[22]
4	Tritriacontane	72°C	Solar collector—evacuated tubes	Water heating	[23]
5	Paraffin	58–62°C	Solar collector—evacuated tubes	Water heating	[24, 25]
6	Paraffin	60°C	TES unit—packed bed and HTF tank	Water heating	[28]
7	Paraffin	62°C	TES unit—packed bed and HTF tank	Water heating	[29]
8	Paraffin	60 ± 2°C	TES unit—HTF tank	Water heating	[30]
9	Paraffin	55–62°C	TES unit—HTF tank	Water heating	[31]
10	Paraffin	60–62°C	TES unit—packed bed and heat exchanger	Water heating	[32]
11	Paraffin	56.06–64.99°C	TES unit—heat exchanger	Water heating	[33]
12	Paraffin	60°C	TES unit—heat exchanger	Air heating	[34]
13	RT65	55–66°C	TES unit—packed bed	Water heating	[21]
14	RT60	55–61°C	TES unit—heat exchanger	Solid desiccant cooling	[35]
15	RT65	57–68°C	TES unit—heat exchanger	Solid desiccant cooling	[35]
16	RT70HC	69–71°C	TES unit—heat exchanger	Solid desiccant cooling	[35]
17	Paraffin	67.2°C (optimal value)	TES unit—heat exchanger	Solid desiccant cooling	[36]
18	RT82	77–85°C	TES unit—heat exchanger	Liquid desiccant cooling	[37, 39]
19	RT100	99°C	TES unit—heat exchanger	Liquid desiccant cooling	[40]
20	Paraffin	6–62°C	Building envelopes	Floor radiant heating	[41]

Table 1.
Summary of paraffins used as PCMs for TES in the built environment.

thermal efficiency. A series of experiments were carried out based on the PCM-enhanced solar water heaters. The results showed that the evacuated tubes with integrated paraffin (i.e. tritriacontane) outperformed the ones with erythritol under a normal operation mode with continuous water circulation, due to its proper phase change temperature at around 72°C. It was also found that the thermal efficiency was improved 26% under the normal operation by using both PCMs simultaneously, compared to a traditional solar water heating (SWH) without using

PCMs. A paraffin wax with the melting temperature of 58–62°C was used as PCM and filled into evacuated tubes for thermal energy storage by Abokersh et al. [24]. The heat transfer between the water and PCM was achieved by different U-tube heat exchangers with and without fins inside the evacuated tubes, respectively. The experimental tests showed that the total energy efficiency can be improved by 35.8 and 47.7% for the PCM-enhanced evacuated tubes with and without fins, respectively, compared to a traditional forced recirculation SWH system. The further study [25] found that even the use of fins hindered the convective heat transfer within the molten PCM during the charging process, and its substantial contribution to the heat transfer enhancement during the PCM discharging process benefited the overall energy efficiency of the system.

2.1.2 Using paraffin-based PCMs as TES units

When PCM was used independent from solar thermal collectors, one of the scenarios is to install the PCM TES component in the heat transfer fluid tanks to fulfil hybrid sensible and latent heat storage. In this scenario, besides increasing the TES capacity, the paraffin-based PCMs also play the role in enhancing the thermal stratification for the water in the tanks [26], which relieves the loss caused by direct mixing of cold water with hot water. The selection of PCMs with proper phase change temperature and confinement geometry was reported to be significant [27]. For instance, an encapsulated PCM was packed in a water tank as a combined sensible and latent heat TES unit by [28] for DHW application. The PCM used is a paraffin (with a melting temperature of 60°C) encapsulated in spherical capsules. Two types of discharging experiments with continuous and batch-wise hot water retrieval processes were carried out, from which it was found that the batch-wise discharging best suited for the applications with intermittent hot water demands. A similar PCM TES packed bed with a paraffin (with a melting temperature of around 62°C) encapsulated in spherical capsules was tested by Ledesma et al. [29] for a SWH system. The numerical thermal performance analysis indicated the importance of system matching when coupled with the PCM TES unit and the SWH system whose outlet water temperature needs to be high enough for PCM charging. A paraffin encapsulated in aluminium cylinders was used as the heat storage media by Padmaraju et al. [30] for a DHW system. The comparative test results showed that the thermal energy stored in the paraffin-based PCM TES system far exceeded that stored in a sensible heat storage system of the same size of the storage tank. A similar conclusion was resulted by Kanimozhi and Bapu [31] through an experimental test based on a TES system with a paraffin filled in a number of copper tubes.

Different from the first scenario, the second scenario utilised the PCM TES units as heat exchangers for latent heat storage only. In this scenario, the higher heat transfer effectiveness is one of the keys to focus. For instance, a water-based multi-PCM pack bed TES unit for solar heat storage was numerically investigated by Aldoss and Rahman [32], in which three types of paraffins with different phase change temperatures were encapsulated in spherical capsules and placed at different sections of the TES unit serving as different thermal energy storage stages. It was found that the multi-PCM design can improve the system dynamic performance by increasing the charging and discharging rates. However, only limited thermal benefit can be achieved by further increasing the stage number. A paraffin wax (with the melting temperature of around 56–65°C) was pulled into the cell side of a shell and tube heat exchanger by Mahfuz et al. [33] for thermal energy storage in a SWH system. The energy, exergy and life cycle cost of the system were analysed experimentally under various flow rates. It was found that a higher flow rate was beneficial to gaining a higher energy efficiency and a lower life cycle cost, while it resulted in a lower exergy efficiency. An air-based PCM packed bed was tested by Karthikeyan and Velraj [34] to validate a number of latent TES packed bed models. The experimental measurement was used to identify the suitable models for PCM TES packed bed units when using different working fluids as the HTFs.

2.2 Paraffin-based PCM-assisted HVAC systems

After charged with thermal energy, the paraffin-based PCMs can be utilised to facilitate the indoor space heating directly or for indoor space cooling with the assistance of desiccant cooling devices. Either air or water can be used as the HTF in the systems, depending on the regeneration requirements. For instance, an air-based PCM TES unit was coupled with a solar-powered rotary desiccant cooling system by Ren et al. [35] to overcome the mismatch between energy demand for desiccant wheel regeneration and thermal energy generation from a hybrid photovoltaic thermal collector-solar air heater (PVT-SAH). The feasibility of using four paraffin-based PCMs (i.e. RT55, RT60, RT65 and RT70HC) as the TES media was investigated numerically in the proposed system. The results identified a near optimal system design for individual scenarios, in which RT65 was found to be the optimal paraffin-based PCM. When increasing the regeneration temperature from 60 to 70°C, the unsatisfied factor for supply air humidity ratio can be reduced from 24.2 to 6.0%, despite that it reduced the solar thermal contribution from 100.0 to 82.6%. The PVT-SAH and PCM-assisted rotary desiccant cooling systems were then further optimised to maximise its energy performance by the same authors [36] using a multilayer perceptron neural network and a genetic algorithm. It was found that the PCM phase change temperature was one of the most important factors, whose optimal value was 67.2°C. The design optimisation identified an optimal design; by using which, the specific net power generation and the solar thermal contribution of the proposed system can reach 10.32 kWh/m^2 and 99.4%, respectively, compared to that of 3.77 kWh/m^2 and 91.5% for a baseline case without optimisation. These studies indicated the importance of using the paraffin with proper thermal properties and optimal coupling of PCM TES in a solar-assisted desiccant cooling system for performance improvement.

Besides solid desiccant cooling, paraffin-based PCM TES designed for the regeneration of liquid desiccant materials was also reported. For instance, a triplex tube heat exchanger with integrated PCM as a TES unit was developed by Al-Abidi et al. [37, 38] and Mat et al. [39] for liquid desiccant air conditioning systems. A series of numerical modelling and experimental studies were carried out to investigate the thermal performance of the PCM TES unit. The results showed that the phase change time required can be reduced by more than 50%, if the triplex tube was intensively finned both internally and externally, and the melting process of the PCM can be accelerated by heating on both sides of the triplex tube. PCM TES units with various heat transfer enhancement techniques, including circular fins, longitudinal fins and multi-tube systems, were developed and experimentally investigated by Agyenim [40] to facilitate solar power absorption cooling systems and space heating/hot water systems. It was found that the multi-tube and longitudinal finned PCM TES units presented the most favourable charging and discharging performance, whose overall thermal energy utilisation efficiency reached 83.2% and 82.0%, respectively. It was therefore recommended to combine two heat transfer enhancement techniques to optimise the thermal performance of the PCM TES unit.

It is worthwhile to mention that another potential application of paraffins is to integrate paraffin-based PCMs into building envelopes for demand side management. For instance, a number of shape-stabilised PCMs were prepared by Zhang et al. [41], in which the ones with the melting temperature of 60–62°C were developed for the electric underfloor space heating system, thereby facilitating the peak-load shifting and making use of the electricity tariff. The authors highlighted that building energy efficiency can be significantly improved by combining radiant floor heating and thermal storage. Even though the PCM layer reported in this study used electrical heat as the heat source, it can be easily modified by integrating with hot water/air hydraulic piping/ducting to store and distribute the solar heat.

3. Case study I: solar-assisted heating system with integrated paraffin-based PCMs

The rationalisation of solar thermal energy utilisation is an alternative solution to facilitate indoor space heating. **Figure 2** illustrates the schematic of a solar-assisted radiant heating system with integrated paraffin-based PCM TES. It mainly consists of evacuated tube solar collectors, a paraffin-based PCM TES unit, two pumps, an auxiliary electric heater, the terminal heat-distributing devices which are radiant floor panels in this study and the corresponding piping system. In this system, the evacuated tube solar collectors were used to generate hot water, which can then be supplied for indoor space heating directly through the radiant floor heating panels, or used to charge the PCM TES unit, or both, during the daytime. During the night-time, the indoor space heating was achieved by circulating the water between the PCM TES unit and the radiant floor heating panels to retrieve the stored heat for indoor space heating. It is worthwhile to mention that the discharging water flow directed through the PCM TES is reversed compared to the charging water flow, so as to maximise the thermal performance of the PCM TES unit. The supply water temperature for the radiant floor panels was controlled to be constant by mixing a fraction of the return water with the hot water supplied from the evacuated tube or the PCM TES unit. The auxiliary electric heater can be used to maintain the desired supply water temperature when the thermal energy generated or stored is not sufficient. The indoor heating demand was satisfied by varying the hot water flow rate through the radiant floor panels through changing the operating speed of the supply water pump.

The system performance was evaluated numerically using TRNSYS simulation studio [42]. In the system modelling, the building heating load of a typical Australian house with an air-conditioned floor area of 150 m^2 [43, 44] under Sydney winter

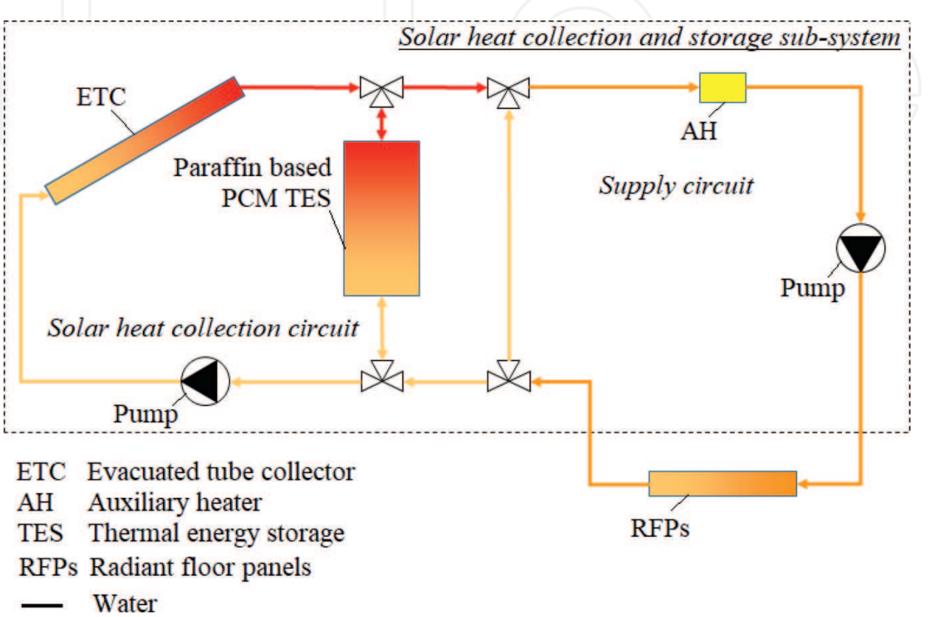

Figure 2.
Schematic of the solar-assisted radiant heating system with integrated paraffin-based PCM TES.

weather condition was modelled and used as the heating demand to be covered by the proposed system. This building heating load was simulated using Type 56 in TRNSYS based on the indoor air temperature setting of 20°C and the internal loads, occupancy schedule and internal adjustable shading settings required by the Australian Nationwide House Energy Rating Scheme (NatHERS) [45]. The evacuated tube solar collector, the auxiliary electric heater and the pumps employed were modelled using Type 71, Type 6 and Type 3 in TRNSYS, respectively. The radiant floor heating panels were modelled using an upgraded Type 1231 which was slightly revised by replacing the mean temperature difference with the log mean temperature difference to improve its accuracy. The PCM TES unit was a water-based tube-in-tank heat exchanger, in which the paraffin was encapsulated in the tube-side with water flowing through the cylinder-side. The PCM TES model was developed using an enhanced enthalpy method for accurate modelling of the phase change process and the finite difference method for discretisation of the energy balance equations. A similar PCM TES model can be found in Bourne and Novoselac [46]. The paraffin-based PCM used is a commercial PCM product RT69HC from Rubitherm [47], with a nominal phase change temperature of around 69°C. The key parameters used in the numerical system performance evaluation are summarised in **Table 2**.

Figure 3 presents the performance of the solar-assisted radiant heating system with the paraffin-based PCM over 3 winter days (note that the simulation results over an additional day before the 3 test days were not reported to avoid the influence from initial values). It can be seen from **Figure 3a** that the solar thermal energy collected and stored can fully cover the heating demand. The pumps were the only power consumers, in which the pump in the solar heat collection circuit was turned on during the daytime when the solar energy was sufficient to heat the water, while the power consumption of the pump in the supply circuit seemed to present a proportion trend to the heating load. Total power consumption was only 0.52 kWh which was much lower than the heating demand of 115.33 kWh over the 3 test days. **Figure 3b** illustrates the temperature variation of the inlet and outlet water of the paraffin-based PCM TES unit. When the hot water from the evacuated tube solar collector was drawn for PCM charging (highlighted with the red background), a clear thermal charging process can be observed, which presented a relatively constant outlet water temperature from the PCM TES unit. During the PCM discharging period, due to the reversed water flow through the PCM TES unit, a high outlet

Parameter	Radiant heating	Desiccant cooling
Area of the evacuated tube solar collector (m^2)	26.24	59.04
Type of paraffin-based PCM	Rt69HC [47]	RT69HC [47]
Total amount of the paraffin-based PCM (kg)	632.7	1476.3
Power of the pump in the solar heat collection circuit (W)	15	38
Maximal power of the pump in the supply circuit (W)	35	80
Supply water temperature setting (°C)	60	64
Maximal power of the supply fan (W)	—	533.3
Maximal power of the regeneration fan (W)	—	533.3
Desiccant wheel outlet air humidity setting (g/kg)	—	8.1

Table 2.
Key parameters used in the performance evaluation of the solar-assisted radiant heating and desiccant cooling systems with integrated paraffin-based PCM TES.

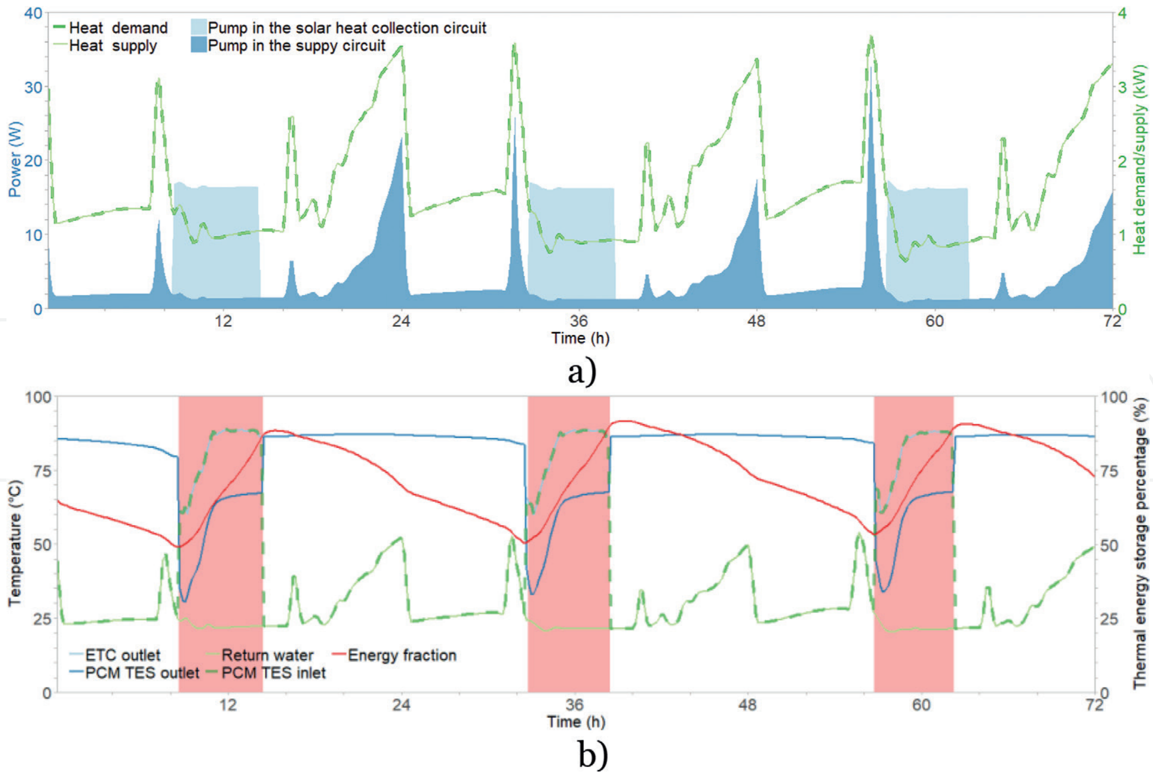

Figure 3.
Modelling results for the solar-assisted radiant heating system with integrated paraffin-based PCM TES. (a) Power consumption and heating energy demand. (b) Inlet and outlet water temperatures of the paraffin-based PCM TES unit.

water temperature from the PCM TES unit was achieved. It enabled the supply of a high-temperature water for space heating, even though the return water from the radiant floor heating panels was low. Correspondingly, the thermal energy storage percentage in the paraffin-based PCM increased during the PCM charging periods rapidly and then reduced during the PCM discharging periods gradually, which varied from 48.96 to 91.54% over the 3 test winter days.

4. Case study II: solar-assisted cooling system with integrated paraffin-based PCMs

Rotary desiccant cooling systems, which combine rotary desiccant dehumidification and evaporative cooling technologies, have been recognised as an alternative to conventional vapour compression air conditioning systems [48, 49]. It offers the advantages including being free from CFCs, using low-grade thermal energy, and independent humidity and temperature control, which therefore is more energy efficient and environmentally friendly than conventional vapour compression air conditioning systems [49]. In a rotary desiccant cooling system, the coolness is generated by removing the moisture from the process air using desiccant materials, while the desiccant materials then need to be regenerated using low-grade heat, for which solar thermal energy is one of the most promising sources.

Figure 4 illustrates the schematic of a solar-assisted desiccant cooling system with integrated paraffin-based PCM TES. It consists of the same solar heat collection and storage subsystem as the heating system introduced in Section 3 and a desiccant cooling subsystem including a solid desiccant wheel, a heat recovery ventilator, a water to air heat exchanger, an indirect evaporative cooler, an auxiliary electric heater, two fans and the corresponding ducting system. In this system, the solar heat collected by the evacuated tube solar collectors and/or stored in the paraffin-based PCM TES unit was used to heat the ambient air for the regeneration of the desiccant wheel, through the water to air heat exchanger. The PCM TES can also decouple the solar heat collection circuit and supply circuit, so that the retrieval of the stored thermal energy can occur by counterflow through PCM TES units during the daytime as well, if the hot water demand was higher than the hot water generated from the solar collectors. If the heat carried by the water was not sufficient for air heating, the auxiliary electric heater would be used. The desiccant wheel, together with the indirect evaporative cooler, and the heat recovery unit were used to cool the process air. In the indirect evaporative cooler, a fraction of process air was used as the secondary airflow and finally exhausted to the ambient. An ambient airflow was introduced and mixed with the return air after recovering the coolness from exhausted process air to compensate the airflow mismatch. The indoor cooling demand was satisfied by varying the airflow rate through changing the operating speed of the fans in the desiccant cooling subsystem. It is worthwhile to mention that a minimal supply airflow rate was assigned to the system operation to avoid the saturation of regeneration air after passing the desiccant wheel, and the relative humidity of the air can be further adjusted by a direct evaporative cooler before supplied to the indoor environment for space cooling.

A modelling system for this system was established using TRNSYS, in which the components for the solar heat collection and storage subsystem used were the same models as that in the heating system in Section 3. The heat exchanger, heat recovery ventilator, desiccant wheel, indirect evaporative cooler, auxiliary electric heater and fans were modelled using Type 5, Type 760, Type 716, Type 757, Type 6 and Type 111, respectively. The same typical Australian house was used to generate the building cooling load under Sydney summer weather conditions. **Table 2** also summarised the key parameters used in the numerical system performance evaluation of this system.

Figure 5 presents the performance of this solar-assisted desiccant cooling system with integrated paraffin-based PCM TES over 3 summer days. It can be seen from **Figure 5a** that the power consumption of the proposed system was from the

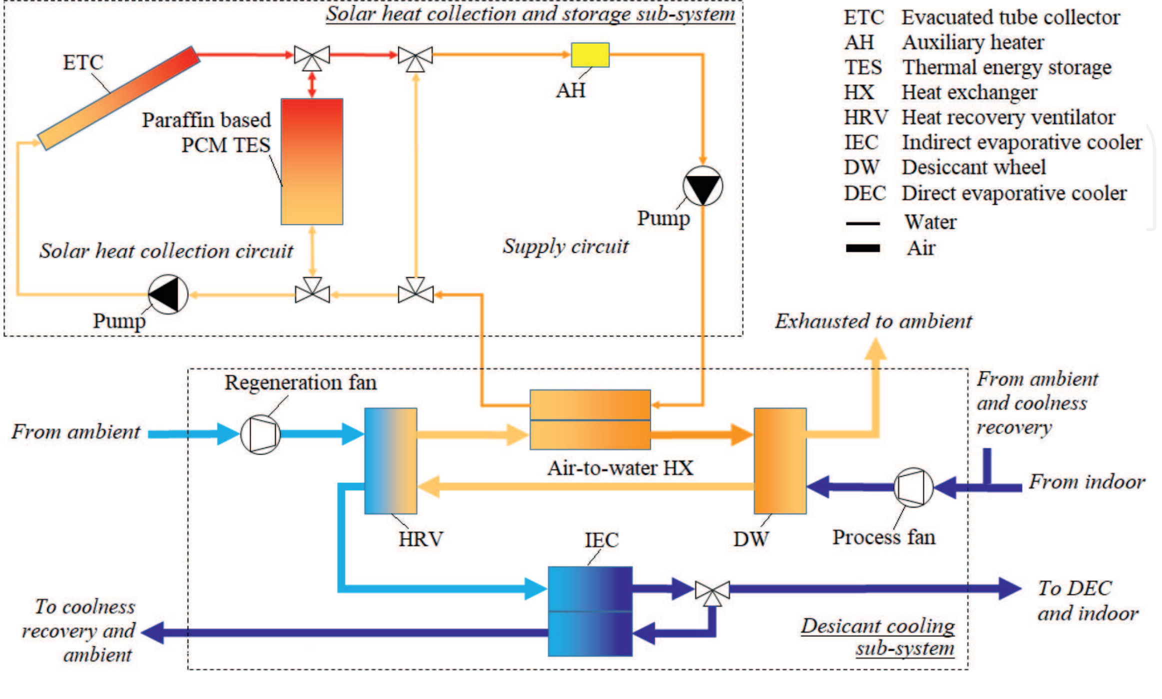

Figure 4.
Schematic of the solar-assisted radiant heating system with integrated paraffin-based PCM TES.

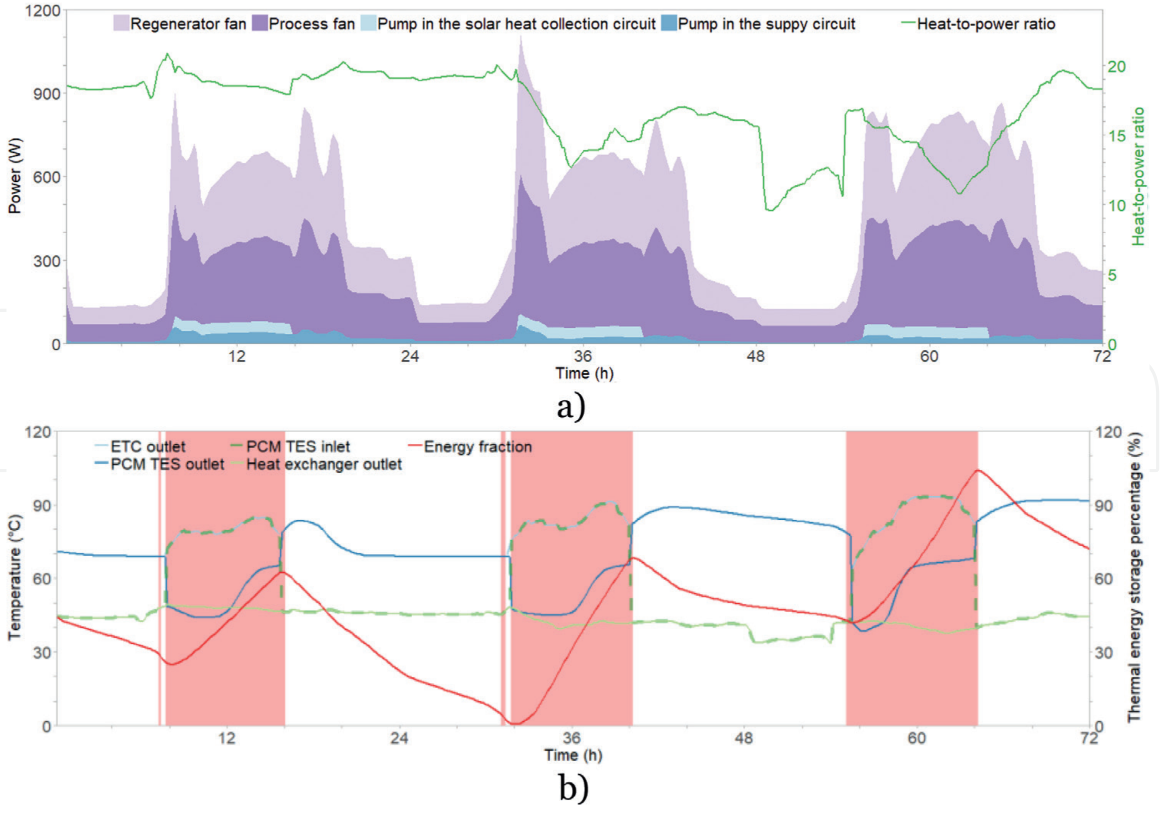

Figure 5.
Modelling results for the solar-assisted desiccant cooling system with integrated paraffin-based PCM TES. (a) Power consumption and heat-to-power ratio. (b) Inlet and outlet water temperatures of the PCM TES.

operation of the pumps and fans, and no additional heat from the auxiliary heater was needed. The supply fan and process fan in the desiccant cooling subsystem consumed much more power (30.55 kWh) than that of the pumps (2.43 kWh) in the solar heat collection and storage subsystem. Even the fans were the major power consumers, the power consumption was much lower than the heat demand for the desiccant wheel regeneration, resulting in a high heat-to-power ratio reaching an average value of 16.55; and the corresponding average system COP reached 14.37. From **Figure 5b**, an effective charging process can be found during the PCM charging period (highlighted with the red background), while during the PCM discharging period, an outlet water temperature above 68.88°C can be achieved due to the effective thermal energy retrieval. The corresponding thermal energy storage fraction in the paraffin-based PCM fluctuated from 0.52 to 103.85% over the 3 summer test days, indicating the full utilisation of the PCM thermal energy storage capacitance.

5. Conclusions

Paraffins, as one of the main categories of phase change materials, offer the favourable phase change temperatures for solar thermal energy storage. The application of paraffin-based PCM TES in buildings can effectively rationalise the utilisation of solar energy to overcome its intermittency. Two case studies, a solar-assisted radiant heating system and a solar-assisted desiccant cooling system with integrated paraffin-based PCM TES, were presented in this chapter. The results showed that both indoor space heating and cooling can benefit from the solar TES using paraffin-based PCMs. With the assistance of the solar thermal energy storage using the paraffin-based PCMs, the energy efficiency and the heating, ventilation and air conditioning systems can be significantly improved.

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