Experimental investigation of a photovoltaic thermal collector with energy storage for power generation, building heating and natural ventilation

Guohui Gan and Yetao Xiang

Department of Architecture and Built Environment, University of Nottingham, University Park, Nottingham NG7 2RD, UK

Corresponding author: Guohui Gan

Email: guohui.gan@nottingham.ac.uk; Tel. +44 115 9514876

Abstract

A phase change material (PCM) can be used for thermal management of photovoltaics and thermal energy storage. This paper presents a photovoltaic thermal (PVT) system integrated with a PCM as a thermal storage medium for managing the photovoltaic temperature and together with a ventilation duct for preheating supply air or natural ventilation of a building. The novelty of the integrated PVT/PCM system lies in using the PCM as a passive technique not only for PV cooling but also for building heating and ventilation. Experiments have been carried out on a prototype PVT system for different sizes of PCM. The results show that a 30 mm thick PCM layer with a phase change temperature of 25°C can maintain the PV temperature below 45°C and improve the PV electrical efficiency by 10% for about 210 minutes under 600 W/m² insolation. Increasing the PCM thickness by 10 mm increases the time for thermal control by 60 to 70 minutes. The PVT/PCM system is able to generate a 15 L/s ventilation rate in a vertical duct of 1100 mm wide, 1200 mm high and 100 mm deep during the melting phase and at least 20 L/s during the solidification phase. Use of metal fins to enhance heat transfer in the PCM can increase the PV electrical efficiency further by 3% and the ventilation rate by 30%.

Keywords

Photovoltaics, solar absorber, phase change material, energy storage, thermal management, natural ventilation

1. Introduction

Solar energy has been widely utilised for electricity generation and passive heating, cooling and ventilation of buildings as well as for other applications. The most widely used technology that converts solar energy into electricity is photovoltaic (PV) and crystalline silicon is the most common PV material. The electrical conversion efficiency of a crystalline PV cell decreases with increasing temperature. To increase the electrical efficiency, excess heat absorbed by the PV cells needs to be removed. One way to remove and then make use of the excess heat is combining the PV with solar thermal to form a photovoltaic thermal (PVT) system. A PVT system is a solar collector that consists of a photovoltaic module as the thermal absorber coupled with a heat extraction mechanism through air or water to harvest both electrical and thermal energy. A building integrated PVT (BIPVT for short) is usually designed as a wall- or roof-mounted PV array with an air gap on the backside as a heat extraction duct through which heat from the PV is delivered to the building directly during the daytime or stored in a thermal

mass medium for use in the night time. A phase change material (PCM) is able to store a large amount of thermal energy as latent heat at a temperature of phase change. It can also be used for thermal management of PV.

Extensive research and development of the PVT and BIPVT as well as integration with the PCM have been carried out in recent years. For simple PVT systems that are designed as a form of conventional solar thermal collector, water is often used as a heat transfer medium. Zondag et al. [1] investigated seven different water-based PVT collectors and indicated that the total efficiency for all types of PVT exceeded 50%. A simulation of hybrid PVT systems for domestic hot water applications by Kalogirou and Tripanagnostopoulos [2] showed that the economic viability could be enhanced where there would be a need for both hot water and electricity.

A PVT system using air as a heat transfer medium can be designed as a conventional air-based solar collector [3, 4] or as part of a building envelope, i.e., BIPVT. The performance of a BIPVT system depends on the efficiency of heat transfer to air and varies widely from 14% to 60% [5]. The heated air can be used directly to meet part of the ambient heating demand, to heat water through a heat exchanger, or to assist natural convection for better building ventilation. There are different types and structures of BIPVT and one of them is represented by a double-skin PV façade. However, such a BIPVT structure could lead to a high temperature in the façade and possible overheating of the building during the hot period without adequate façade ventilation and internal solar shading [6]. Anderson et al. [7] analysed the design of a BIPVT collector with fins and their results showed that both the electrical and thermal efficiencies were greatly affected by the fin efficiency and thermal conductivity between PV cells and their supporting structures as well as lamination methods. Zogou and Stapountzis [8] investigated a PVT façade using a combination of flow visualisation and hot wire anemometry measurements to enhance the understanding of flow and turbulence inside the façade with natural and forced convection modes. It was demonstrated that the flow rate and heat transfer characteristics were critical to the performance of the PV façade.

Use of PCMs to control PV temperatures has been studied by many researchers in order to increase the electrical conversion efficiency in recent years. Hasan et al. [9] experimentally investigated the performance of five PCMs for four PV/PCM systems under the same controlled conditions. It was found that a maximum temperature decrease of 18°C could be

reached for about 30 minutes and a 10°C temperature decrease was maintained for five hours at 1000 W/m² insolation. Biwole et al. [10] showed that adding a PCM on the back of a solar panel could maintain the operating temperature under 40°C for 80 minutes at 1000 W/m² insolation. Experimental measurement and simulation of PCM cooling of a PV panel by Stropnik and Stritih [11] showed that the PCM could decrease the PV surface temperature by as much as 35.6°C for a duration of one day. Similarly, a PCM led to a maximum PV temperature drop of 26.3°C even in a cold environment of Tehran [12]. Hachem et al. [13] showed from measurement and simulation that the electrical efficiency of PV panels was increased by an average of 3% using white petroleum jelly as a PCM and by 5.8% using a combination of the PCM, copper and graphite. A simulation by Malvi et al. [14] for a hybrid PVT system with PCM thermal storage revealed that the electrical efficiency could be typically increased by 9% but the increase in electrical performance was accompanied by a decrease in thermal performance. An experimental investigation by Yang et al. [15] revealed that using a PCM increased the total thermal and electrical efficiency of a PVT system from 63.9% to 76.9%.

Integration of PCMs with BIPV or BIPVT for thermal control has also been investigated. Huang et al. [16] were among the first researchers to conduct experimental measurements of a PCM for temperature regulation of BIPV under controlled conditions. Tests were carried out with and without metallic fins in the PCM. The performance of the PCM was also studied in more detail using a numerical method [17]. More extensive research was carried out by the researchers in this field for different PCMs [9] and different climates [18]. Aelenei et al. [19] investigated a BIPV-PCM system installed in an office building façade. The PCM was however separate from the PV module with the two components as the opposite sides of a ventilation passage. A mathematical model was developed for simulation of the system and experiments were also conducted for model validation with good agreement between simulation and experimental results. Park et al. [20] numerically and experimentally investigated the performance of the BIPV-PCM system by varying the melting temperature and the thickness of the PCM layer and found that using a 100 mm thick PCM layer decreased the PV temperature by 10°C at an insolation over 700 W/m² and that the optimal melting temperature of the PCM was 25°C under the climatic conditions of South Korea. Sharma et al. [21] tested a PCM to maintain the solar cell operating temperature and improve the performance of building integrated concentrated PV systems under controlled conditions. It was shown that a relative electrical efficiency improvement of 7.7% was attained using PCM at 1000 W/m² irradiance

and that the improvement increased with irradiance. Elarga et al. [22] numerically studied the thermal and electrical performance of a PV-PCM system in a double skin façade under forced convection. The use of a PCM layer in the cavity of the PV façade decreased the PV temperature by up to 20°C and the monthly cooling demand by 20–30%. Wang et al. [23] determined the performance of a BIPVT system integrated with a PCM and a micro-channel flat-plate heat pipe together with a water pump and storage tank to store excess heat and enhance the overall efficiency of the system. It was shown that the main benefit of the system resulted from thermal storage and release by the PCM. Curpek et al. [24] experimentally investigated the influence of a PCM on a ventilated BIPV façade using an outdoor test cell and found that the PCM decreased the PV temperature by up to 14°C and air temperature in the façade by 5°C.

A major weakness of a PCM is its low thermal conductivity. A number of techniques have been employed to overcome the weakness such as a composite high conductive material, fins and capsules to extend the heat transfer surface and multiple PCMs. Wang et al. [25] studied the melting procedures of three PCMs in cylindrical heat storage capsules with the lowest melting temperature PCM at the centre and the remaining two arranged in the order of increasing melting temperature from the centre to outer surface. The results showed that the melting time was 37–42% less in the three-PCM capsules than for a single PCM capsule. Stritih [26] compared a finned surface with a plain surface for a PCM storage unit and indicated that the fins increased the thermal release process but reduced heat transfer during heat storage. Huang et al. [27] studied a PV/PCM system with a range of metal fin configurations incorporated into the PCM to limit passively the PV temperature increase. A comparison with a conventional air-cooling system through experiments and simulations demonstrated that applying metal fins had a significant effect on controlling the PV temperature increase. Further investigation indicated that optimisation of internal fins could greatly improve the PV temperature control [28]. Nada and El-Nagar [29] found that integrating a BIPV module with a PCM box enhanced its daily mean electrical efficiency by about 6% and the enhancement could be increased further to 13% by adding 2% Al_2O_3 nanoparticles to improve the thermal conductivity of the PCM. Salem et al. [30] used a similar approach to enhance the performance of PV cells and found that a 1% concentration of the nanoparticles in a mixture of Al_2O_3 , PCM and water would produce the highest PV electrical output.

Previous work has shown that a PCM is able to control the PV temperature increase and that

enhancing the rate of heat transfer in the PCM is vital for fast thermal response and long thermal control periods. However, the extra electrical output produced by incorporating a PCM is currently insufficient to cover the additional costs. Hasan et al. [31] measured the performance of a PV-PCM system for the cool climate of Ireland and the hot climate of Pakistan and then carried out energy and economic analysis of the PV-PCM system for the two climates. It was shown that the system was not cost effective in a cool climate but would be in a hot climate. However, the analysis was based on the assumption that the projected future PV cost would be 30% less than that in 2005. The actual PV prices in recent years have dropped much faster than projected such that the module prices are now only a small fraction of those in 2005 while PCMs remain relatively expensive. Thus, the financial benefit of using a PCM only for thermal regulation of PV systems even for a hot climate may not be realised. Japs et al. [32] also experimentally studied two types of PCM for cooling of two PV modules under outdoor summer conditions in Germany and their analysis for scaled-up PV power plants up to 10 MW_p showed that their economic benefit was negative for most days but only positive in certain period of a day because of assumed higher prices for electricity on the spot market when the energy yield was higher. In other words, there would be no economic benefit using the PCMs at any time under a fixed unsubsidised daytime electricity price or a flat rate tariff, which is likely for comparatively small BIPV systems. Therefore, it is important to maximise energy utilisation from a PV/PCM system in order to make it economically viable. This can be achieved by combining the system with interior building environment control to reduce heating load and/or enhance natural ventilation, which has not been thoroughly investigated previously.

The objective of this study is to determine experimentally the performance of a novel PVT system integrated with a PCM as a thermal storage medium for building applications by means of natural ventilation. The PVT/PCM system comprised of a PV panel, a PCM unit and a ventilation duct for energy harvesting, storage and utilisation. The heat stored in the PCM unit could be utilised to enhance natural ventilation or preheating supply air. The novelty of the work lies in using the PCM not only for PV temperature control but also for passive heating and ventilation of a building. The system was designed and the thermal and electrical performance measured under laboratory conditions. The laboratory was naturally ventilated and centrally heated through thermostatically controlled radiators.

In the following sections, key materials for the PVT/PCM system and experimental methods are first presented. Results from the experiments are then analysed and discussed followed by

an uncertainty analysis of experimental measurements. Finally, conclusions from the study are provided.

2. Materials and methods

The PVT/PCM system for this study consisted of a PV panel, a PCM unit made of an aluminium container accommodating the PCM and a ventilation duct. The PV panel served as the absorber plate of a thermal collector and was integrated with a PCM on the backside to control the temperature and store the absorbed heat. The stored heat was released to air in the duct behind the PCM container by means of natural ventilation. The system was positioned vertically as a type of wall-mounted PVT for better natural ventilation. A schematic diagram is shown in Figure 1.

Figure 1 Schematic diagram and photos of the experimental system

2.1 Materials

Key materials for the PVT/PCM system were PV modules and PCM.

2.1.1 PV modules

In a BIPVT system, PV modules produce not only electricity but also usable heat. Both electrical and thermal outputs depend on the type of PV as well as environmental conditions. Most PVT systems make use of crystalline silicon PV due to the high efficiency and monocrystalline silicon PVs are most beneficial in terms of longevity and efficiency. For the

present study, two monocrystalline PV modules (Biard 100W Solar Panel) were used and the key specifications are given in Table 1.

Table 1 Specifications of the photovoltaic module

Peak power	100 W
Cell type	Monocrystalline
Maximum power voltage	19.3 V
Maximum power current	5.18A
Open circuit voltage (Voc)	22.9 V
Short circuit current (Isc)	5.56 A
Maximum system voltage	750 V
Cell efficiency	18%
Temperature coefficient of Isc	0.06±0.01
Coefficient of Voc	-(78±10)
Coefficient of peak power	-(0.5±0.05) %/°C
Power tolerance	±3%
Normal operating cell temperature	45°C±2°C
Dimension	1200×540×30 mm
Weight	8 kg
Number of solar cells	36 (4×9)
Standard Test Conditions (STC)	Irradiance = 1000 W/m ² , AM = 1.5 spectrum, and cell temperature = 25°C
Manufacturer reference	CHN10036MB

The two modules were placed side by side to form a PV panel of 1080 mm wide and 1200 mm high.

2.1.2 PCM

For residential applications, heat stored in the PVT/PCM system would mainly be used for night heating or ventilation. Selection of a PCM would then depend on not only the requirement for thermal management of PV (preferring a material with a low phase change temperature for given ambient conditions) but also the need for the stored heat for later use (a high phase change temperature). Generally, the optimal melting temperature for a PCM integrated in a building

fabric is close to indoor thermal comfort temperatures and it is about 25°C as shown by Park et al. [20]. Although the material (container) for the present system is not directly exposed to the occupants in a building, the comfort temperature can still be used as one of the criteria for selection. Besides, the system could be adapted to form part of a (double skin) building façade with transparent glazing as the back side of the ventilation duct. Such a low phase change temperature may present a problem for solidifying the PCM at night due to its low thermal conductivity if the ambient temperature is too high. However, the nighttime air temperature in the UK is generally low (about 15°C in the warmest summer month July) and is much lower for the heating season with an average of about 5°C. The low nighttime temperature together with measures to enhance heat transfer within the material such as metal fins would enable solidification of the PCM to be completed and this is discussed for the effect of fins. After careful consideration, salt hydrates PCM (PLUSICE S25) was chosen due to its relatively high thermal conductivity and high phase change enthalpy. The PCM solidifies and melts at 25°C. Its main constituent is calcium chloride hexahydrate ($\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$). The phase change temperature of pure calcium chloride hexahydrate is about 30°C but the temperature can be adjusted to, e.g., 25°C when mixed with another type of salt such as magnesium chloride hexahydrate ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$). Table 2 shows the properties of the selected PCM, including the latent heat of fusion during phase change (phase change enthalpy or latent heat capacity), density, volumetric heat capacity (the product of latent heat and density), specific heat and thermal conductivity. The density and thermal conductivity of the PCM in the liquid state were lower than those in the solid state whereas the specific heat of liquid PCM was higher.

Table 2 Thermal and physical properties of PCM

Phase	Phase change temperature (°C)	Latent heat of fusion (kJ/kg)	Volumetric heat capacity (MJ/m ³)	Density (kg/m ³)	Specific heat (kJ/kgK)	Thermal conductivity (W/mK)
Liquid	25	180	275	1530	2.2	0.54
Solid				1710	1.4	1.09

The capacity (quantity) of PCM used in the experiments was estimated from the weather data of a peak sunny day in the UK using the method introduced by Jiang et al. [33] who developed a simple analytical method to estimate the optimal phase change characteristics. For a PCM

with a melting temperature of 25°C, the optimum capacity was found to be in the range of thicknesses between 20 mm and 50 mm when attached to the backside of PV.

An aluminium box with an adjustable depth (1100 mm wide and 1200 mm high with depths of 20 mm to 50 mm) was constructed as a container for the PCM. Figure 1 also shows a photograph of a PCM container with two holes cut out on the back near the top. These holes were used to fill the container with a liquid state PCM. Another container labelled 'container attached on PV back' in the figure was constructed with the PCM filled at the top. This was however used for preliminary investigation of the system.

2.2 Experimental system

The experimental setup is shown in Figure 1. To construct the test system and ensure high conductivity, the PV panel and aluminium box were bonded together with a special thermal grease to provide a good thermal contact and prevent short-circuiting the cells. A rectangular air duct of 1100 mm wide, 1200 mm high and 100 mm deep was made behind the PCM container using the backside of the PCM container as a duct wall. The duct was connected to horizontal inlet and outlet openings of 100 mm high and the vertical duct height between the centres of the openings was 1100 mm. Celotex Insulation board with a thermal conductivity of 0.022 W/mK and thickness of 100 mm was used for insulation of the duct as well as the top, bottom and two sides of the PV and PCM container.

Accurate measurements of the PV performance require the use of a solar simulator to produce a desired spectrum of thermal radiation. The emphasis of the present study was however on the phenomena associated with heat from heat transfer and storage to natural ventilation. Therefore, insolation was simulated simply with nine 500 W halogen lamps. The distance between the lamps and PV panel was adjusted to achieve radiation on the panel as uniform as possible. The resulting mean insolation (heat flux) was 600 W/m² for the tests. This level of heat flux was close to the maximum hourly mean direct solar radiation or the maximum mean global radiation averaged for the sunshine hours on a vertical surface in the UK [34].

The assembled system was tested for two processes – thermal charging and discharging. In the first phase, the artificial lights were switched on to simulate the heat charging and storage and the electrical performance of the PV panel was also recorded. In the second phase, the lights were turned off to simulate the energy release process.

Poor conductivity of PCMs is known to be a common problem in heat storage and release. Therefore, another aluminium box of 30 mm internal thickness was fabricated with vertical aluminium fins 2 mm thick and 30 mm spacing to improve the thermal performance.

2.3 Instrumentation

Temperatures of the materials and air, air velocity, insolation and electrical output were measured. A total of 24 T-type thermocouples were used to measure temperatures of the PVT/PCM system. Six thermocouples were positioned on the front and back surfaces of the PV panel to measure the surface temperature as a representation of PV cell temperature. Twelve thermocouples were located at three depths within the PCM to measure spatial temperature variations. Three thermocouples were fixed in the vertical duct and two thermocouples in the duct inlet and outlet to measure air temperatures. An additional thermocouple was used to measure the ambient temperature in the laboratory. Table 3 presents the positions of temperature measuring points for the system with a 30 mm deep PCM container. The bottom back corner of the PV panel was designated as the reference point ($X = 0$, $Y = 0$). The thermocouples were calibrated with a digital thermometer with an accuracy of $\pm 0.2^\circ\text{C}$ for a range of 10°C to 80°C . Figure 2 shows the calibration curve for the thermocouples.

Table 3 Position of temperature measuring points

Point	Position (m), in terms of number x (X, Y)
6 for PV panel (2 along each height)	2 x (0, 0.25); 2 x (0, 0.5); 2 x (0, 0.75)
4 for PCM at bottom	(0.008, 0.3); 2 x (0.016, 0.3); (0.024, 0.3)
4 for PCM at middle height	(0.008, 0.6); 2 x (0.016, 0.6); (0.024, 0.6)
4 for PCM at top	(0.008, 0.9); 2 x (0.016, 0.9); (0.024, 0.9)
1 for air duct at bottom	(0.08, 0.3)
1 for air duct at middle	(0.08, 0.6)
1 for air duct at top	(0.08, 0.9)
1 for air inlet	(0.13, 0.05)
1 for air outlet	(0.13, 1.15)

Figure 2 Calibration of thermocouples against a digital thermometer

The air velocity was measured at the duct outlet using a hot wire anemometer (TESTO 425) with an accuracy of ± 0.03 m/s. The mean air velocity at the outlet was obtained from the measurement of air velocities at 20 points. That is, the rectangular opening was divided equally into 20 smaller rectangular areas (five divisions along the width and four divisions along the height) and the air velocity at the centre of each area was measured. The average for the 20 measured points was taken as the mean air velocity at the outlet which was then used to calculate the ventilation rate through the duct.

The insolation on the PV panel from the artificial lights was measured using a solar power meter (ISM 400) with an accuracy of ± 10 W/m² or $\pm 5\%$, whichever is greater. A plate ammeter shunt (10 A and 75 mV) and two 100 W resistors were connected and used to measure the electrical output of the PV panel. All temperature and electrical data were recorded at an interval of 60 seconds using a DT800 data logger.

2.4 Experimental design and procedure

Figure 3 shows a schematic diagram of three steps for setting up the experimental system. First, the PCM in liquid form was poured into the aluminium box attached to the back of the PV panel (Fig. 3a). The ventilation duct was then configured behind the PV/PCM unit (Fig. 3b). After the PCM solidified and the temperature for the whole system stabilised, the lights were switched on to start an experiment with the temperatures for the PV, PCM and air together with

the air velocity, insulation and PV output monitored to establish the electrical and thermal performance (Fig. 3c). The artificial lights were on continuously until the PCM completely melted for the melting process and then the lights were switched off to observe thermal release during the solidification process.

Figure 3 Schematic diagram for setting up the experimental system

Four different configurations for the PVT/PCM system were tested as listed in Table 4. A number of tests were carried out for the first configuration to establish the performance of the system and efficient experimental procedure in terms of duration of each process. An additional test was carried out without the PCM in the container to assess the effect. All tests were carried out under the same conditions with the ambient temperature maintained at about 20°C during the period for electricity generation by the PV. The duration of the processes for testing varied with the configurations.

Table 4 Test configurations

Case	PCM thickness (mm)	Fins installed
1	30	No
2	No PCM	No
3	20	No
4	50	No
5	30	Yes

3. Results and discussion

The thermal charging and discharging processes are analysed for the first case followed by the analysis of the effects of the PCM thickness and metal fins.

3.1 Thermal energy charging process

The PV temperature management by the PCM depends on the thermal performance of the PCM. Figure 4 shows the temperature at three points inside the PCM - front, middle and back positions (8 mm, 16 mm and 24 mm, respectively, from the backside of PV) of the PCM unit. As the melting temperature of the PCM was 25°C, when the temperature at a point exceeded this value, the PCM would have started to melt there. After the artificial lights were turned on, it took about 50, 130 and 180 minutes, respectively, for the PCM at the front, middle and back points to melt. A rapid temperature increase after completion of melting was observed at the front point between 275 and 295 minutes and at the middle and back points between 300 and 320 minutes.

Figure 4 Temperature at three points in the PCM (Case 1)

The effectiveness of the PCM for thermal management is shown in Figure 5 from the comparison of the mean PV temperature for the PVT/PCM (Case 1) with that of PVT without the PCM (Case 2). The mean PV temperature was taken as the average temperature for six different points at the front and back sides of PV panel. The PVT system without the PCM reached a steady state at 61°C in about 70 minutes, while the system with the PCM reached its steady state at a much lower temperature of 45°C in 90 minutes. For both cases, initially, the

temperature increased rapidly but the rate of increase was slower with the PCM than without. For the PVT/PCM system, when the temperature of a layer of PCM close to the heat-absorbing PV exceeded its melting temperature, the PCM absorbed the heat transferred from the PV mainly as latent heat and thus kept the PV temperature stable until all the PCM in contact with the PV changed from solid to liquid completely at about 210 minutes. Afterwards, the PV temperature increased again as the sensible heat of the melted PCM increased but remained lower than that without the PCM at the end of thermal charging period (350 minutes). From the comparison, it is concluded that a 30 mm thick PCM with a phase change temperature of 25°C can maintain the PV temperature below 45°C for about 210 minutes under 600 W/m² insolation.

Figure 5 Comparison of mean PV temperature with and without PCM (Case 1 vs Case 2)

The improvement of electrical performance using the PCM can be assessed from the relationship between the electricity conversion efficiency with temperature, i.e.,

$$\eta = \eta_{\text{ref}} \left(1 - \beta(T_p - T_{\text{ref}}) \right) \quad (1)$$

The efficiency improvement is then defined as

$$(\eta_1 - \eta_2)/\eta_2 = \beta(T_{p2} - T_{p1}) / \left(1 - \beta(T_{p2} - T_{\text{ref}}) \right) \quad (2)$$

where β is the temperature coefficient of peak power, equal to 0.005 (1/°C) according to module specifications, T_p is the measured PV temperature (°C), T_{ref} and η_{ref} are the PV temperature (°C)

and efficiency (%) under the standard test conditions, respectively. Subscripts 1 and 2 represent the values for the systems with and without the PCM, respectively.

Figure 6 shows the electrical performance improvement owing to the PCM. The improvement resulted from the lower PV temperature offered by the PCM and consequent less decrease of electrical efficiency for the system with the PCM. In terms of variation with time, initially, the increase was rapid because of the slower PV temperature increase with the PCM than without. During the melting phase of the PCM, the improvement in the electrical efficiency remained nearly constant. Due to the limited amount of PCM, the PCM effectively fully melted at 210 minutes and from then on the level of improvement in the efficiency decreased.

Figure 6 PV efficiency increase due to PCM (Case 1 vs Case 2)

The ventilation rate resulting from the buoyancy effect in the duct is another important parameter for this study. Figure 7 shows the ventilation rate through the duct. The ventilation rate increased rapidly to 13 L/s during the first 50 minutes as the temperatures of PV and PCM increased, after which the increase became considerably less with an average ventilation rate of 15 L/s for about 200 minutes during the PCM melting process. The ventilation rate rose rapidly again after the PCM fully melted, reaching a maximum value of 28 L/s over the test period. Note that the second phase of rapid increase in the ventilation rate occurred at about 255 minutes rather than 210 minutes. This was because completion of melting of the PCM layer near the backside in contact with the ventilation duct was later than that near the front side as seen from the variation of PCM temperatures in Figure 4. Natural ventilation was

allowed to take place in the duct during the tests. However, if such a system was designed to make use of the stored heat for nighttime operation, the duct would be closed to reduce the ventilation heat loss. Hence, to maximise the benefits of the system, the volume of PCM should be sufficient to store all the thermal energy that is absorbed by and transferred from the PV in a hot day for given environmental conditions in order to keep the PCM unit function as desired all the time.

Figure 7 Ventilation rate in the duct (Case 1)

3.2 Energy release process

One of the important benefits of a thermal storage system is that it absorbs excess heat during the day and releases it at night to enhance ventilation and/or preheating supply air. Figure 8 presents the temperature at the centre of the PCM unit together with room air temperature during the heat release phase. As can be seen, it took about 13 hours for the PCM to approach its solidifying temperature, and even at the 17th hour, the temperature remained at about 26°C. This poor performance in terms of solidification was due to the high air temperature in the test room after the first phase of testing (melting process) - 25.4°C at the beginning, decreasing to 24.5°C, 23.9°C and 23.8°C after one, four and eight hours, respectively - resulting in a very small potential for solidifying the PCM. It would take more than a full day to achieve full solidification in the test room. Of course, for real applications in a temperate climate like the UK as was used to determine the type of PCM for testing, the outdoor environmental temperature would be much lower during the night time (about 15°C in Southern England in summer) and so the cooling potential would be larger and the solidification process faster.

However, because heat transfer within the PCM was also slow, solidification would not be complete in such a summer night without additional measures [35]. It was thus necessary to enhance heat transfer in the PCM such as inserting metal fins so as to achieve full solidification at night time and be ready for the next cycle of thermal management.

Figure 8 PCM and air temperatures in the thermal release phase (Case 1)

Figure 9 shows the ventilation rate in the duct during the thermal release process for a period of 24 hours. The heated PCM container maintained the ventilation rate at about 20 L/s for 700 minutes, after which it decreased gradually to 16.5 L/s at the end of the period.

Figure 9 Ventilation rate during the thermal release phase (Case 1)

At night times, the PVT/PCM system designed as part of a building envelope would behave as a thermal mass in the building, delaying and decreasing indoor temperature fluctuations. As the ambient would be cooler, a higher ventilation rate than that from the test could be expected. In summer, heat absorbed by the PCM during the day would be released at night and the ventilation duct in such a system would function as a chimney to draw cool air through the building and keep the indoor environment thermally comfortable. In winter, the stored heat would be released at night to the incoming air for the building, helping to increase the temperature. The ability of generating natural ventilation was one of the important benefits of the PCM unit for this study, as it helped absorb excess heat gains from the PV in the daytime and release it for use in the night time.

Ventilation air absorbed heat from the PCM container when flowing through the duct. Figure 10 illustrates the heat gain by air flowing through the ventilation duct during the thermal release phase. The amount of heat gain was obtained from the measured ventilation rate and inlet and outlet temperatures as well as the calculated air density and specific heat. The cumulative heat gain by ventilation air increased with time to 326 Wh in eight hours. The rate of heat gain decreased with increasing time and the gain was only 100 Wh for the next eight hours.

Figure 10 Heat gain by ventilation air during the thermal release phase (Case 1)

3.3 Effects of PCM configuration

In this section, the test results for four different PCM configurations of the experimental system presented in Table 4 are discussed.

3.3.1 Effect of PCM thickness

The thickness of PCM was reduced from 30 mm for Case 1 to 20 mm for Case 3 and then increased to 50 mm for Case 4. Figure 11 presents the mean PV temperature for the three cases. The PV temperature increased rapidly at the beginning, remained nearly constant during PCM melting and increased again once the PCM melted completely. The duration for the PCM to maintain a certain PV temperature increased with the thickness. A 20 mm thick PCM unit maintained the mean PV temperature below 45°C for 140 minutes while a 50 mm thick unit maintained the temperature for 330 minutes compared with 210 minutes for a 30 mm thick unit. Thus, an increase of 10 mm PCM thickness could increase the time to maintain the PV temperature at the low level by 60 - 70 minutes. However, a thicker PCM would add extra weight to the system and increase the capital cost. Besides, it would be difficult for a thick PCM to reach full solidification by natural means in a warm night.

Figure 11 Effect of PCM thickness on the mean PV temperature (Cases 1, 3 and 4)

Figure 12 shows the electrical conversion efficiency improvement for the three configurations using different PCM thicknesses compared with the PVT system without PCM. The PCM increased the electrical efficiency by about 10% and the duration of the increase increased with the PCM thickness. For the 20 mm thick PCM, this level of increase was maintained for 90

minutes, after which electrical efficiency started to decrease due to the increasing PV temperature whereas the temperature of the PV without PCM was stable by the time (see Figure 5). The same trend was observed for thicker PCM units - the time for about 10% efficiency improvement being 160 minutes and 290 minutes, respectively, for the 30 mm and 50 mm thick PCM units.

Figure 12 Effect of PCM thickness on the electrical efficiency increase (Cases 1, 3 and 4)

3.3.2 Effect of fins

Due to the low thermal conductivity of PCM, the thermal charging and discharging processes were slow. Therefore, heat transfer within the PCM was enhanced by means of internal aluminium fins in another aluminium container 30 mm deep (Case 5). Vertical fins were placed inside the 30 mm thick PCM container. The fins had a length of 1100mm, a thickness of 2 mm and both height and spacing of 30 mm.

Figure 13 shows the mean PV temperature with fins installed inside the PCM container in comparison with that without fins. It can be seen that the fins were effective in moderating the PV temperature increase. This was achieved because the heat absorbed by the PV transferred to the interior of the PCM container faster such that more PCM could effectively play the cooling role. Without the fins, only a thin layer of PCM in contact with PV and container was effective in cooling at the beginning of the melting process. It took only 22 minutes with fins instead of 50 minutes without fins for the PV temperature to reach a steady state. The temperature decrease resulting from the use of fins varied between 4°C and 7°C with an average

of 5.5°C during the PCM melting period when the PV temperature was nearly stable (from 50 min to 210 min). This was on average equivalent of a 3% improvement in the electrical efficiency according to Equation 2 where subscripts 1 and 2 become the values for the systems with and without fins, respectively. The enhanced heat transfer from the use of fins in the PCM implies that the solidification process could be completed at night time the temperature of which was one of the parameters for deciding the phase change temperature and quantity of PCM. This was confirmed by a numerical simulation for the system with the air temperature fixed at 15°C [35]. The nighttime air temperature in the UK for the heating season is much lower. For example, at the beginning of October the mean air temperature at night in southern England is less than 10°C and the average for the heating season is around 5°C. Therefore, the 30 mm thick PCM with a phase change temperature of 25°C and integrated with metal fins would be able to solidify completely during the night in the heating season.

Figure 13 Effect of fins on the mean PV temperature (Case 1 vs Case 5)

The fins also enabled faster transfer of heat from the absorber to the duct, leading to a higher buoyancy-induced natural ventilation in the duct as shown in Figure 14. The system with fins increased the ventilation rate by about 30%. However, the difference decreased when the PCM with fins fully melted such that the backside temperature of the PCM container and the air flow rate in the duct approached those without fins as indicated for the ventilation rate after 270 minutes.

Figure 14 Effect of fins on the ventilation rate (Case 1 vs Case 5)

4 Uncertainty analysis

Gaussian error propagation law was used to determine the experimental uncertainties, by which the overall uncertainty is a function of those of independent uncorrelated variables. The uncertainties of the measured parameters were temperature ($\pm 0.2^\circ\text{C}$), air velocity ($\pm 0.03 \text{ m/s}$) and irradiance (heat flux) (the larger of $\pm 10 \text{ W/m}^2$ and 5%).

According to the Gaussian propagation law, the uncertainty of a result, R , as a function of n uncorrelated variables, $x_1, x_2, \dots, x_n$, i.e. $R = f(x_1, x_2, \dots, x_n)$, is given by

$$\delta R = \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \right)^2 (\delta x_i)^2}$$

The relative uncertainty is

$$\frac{\delta R}{R} = \frac{1}{R} \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \right)^2 (\delta x_i)^2}$$

The calculation of uncertainty is illustrated for electrical and thermal energy outputs. The PV electrical output during the day time varies with the irradiance and the electrical conversion efficiency which is dependent on the cell temperature. The thermal output during the night time is dependent on the air flow rate (or velocity) and air temperature rise through the ventilation

duct as a result of transfer of stored heat in the PCM. Thus, the uncertainty for the PV-PCM outputs can be estimated as follows.

4.1 Electrical output

The PV electrical output (P_e in W) is given by

$$P_e = I A \eta \quad (3)$$

where I is the irradiance on the PV panel (W/m^2) and A is the PV area (m^2).

Substituting Equation (1) into Equation (3) yields

$$P_e = I A \eta_{\text{ref}} \left(1 - \beta(T_p - T_{\text{ref}}) \right) \quad (4)$$

Since

$$\frac{\partial P_e}{\partial I} = A \eta_{\text{ref}} \left(1 - \beta(T_p - T_{\text{ref}}) \right)$$

and

$$\frac{\partial P_e}{\partial T_p} = -I A \eta_{\text{ref}} \beta$$

The uncertainty in electrical output is then

$$\delta P_e = \sqrt{\left(\frac{\partial P_e}{\partial I} \right)^2 (\delta I)^2 + \left(\frac{\partial P_e}{\partial T_p} \right)^2 (\delta T_p)^2} \quad (5)$$

i.e.

$$\delta P_e = A \eta_{\text{ref}} \sqrt{\left(1 - \beta(T_p - T_{\text{ref}}) \right)^2 (\delta I)^2 + (I \beta)^2 (\delta T_p)^2} \quad (6)$$

where δI is the uncertainty in measured irradiance I (W/m^2) and δT_p is the uncertainty in measured PV temperature T_p ($^{\circ}\text{C}$).

The relative uncertainty is

$$\frac{\delta P_e}{P_e} = \sqrt{\frac{(\delta I)^2}{I^2} + \frac{\beta^2 (\delta T_p)^2}{(1 - \beta(T_p - T_{\text{ref}}))^2}} \quad (7)$$

For $\beta = 0.5 \text{ } ^\circ\text{C}^{-1}$ and $T_{\text{ref}} = 25^\circ\text{C}$,

$$\frac{\delta P_e}{P_e} = \sqrt{\frac{(\delta I)^2}{I^2} + \frac{(\delta T_p)^2}{(225 - T_p)^2}} \approx \frac{\delta I}{I}$$

i.e., it is 5%, greater of 10/600 and 5% for insolation measurement.

Similarly the relative uncertainty in estimated PV efficiency according to Equation (1) based on the measured temperature would be about 1% at the start of experiments when the PV temperature was close to air temperature, decreasing to about 0.5% when the PV temperature was stabilised under constant irradiation.

4.2 Thermal output

The heat gain by air flowing through the ventilation duct of constant cross section (P_t in W) is related to three measured parameters - velocity, inlet temperature and outlet temperature, i.e.

$$P_t = V A_d \rho C_p (T_o - T_i) \quad (8)$$

where V is the duct mean air velocity (m/s), A_d is the cross sectional area of the duct (m^2), ρ and C_p are the air density (kg/m^3) and specific heat (J/kgK), respectively, T_i and T_o are the inlet and outlet temperatures ($^\circ\text{C}$), respectively.

Since

$$\frac{\partial P_t}{\partial V} = A_d \rho C_p (T_o - T_i)$$

$$\frac{\partial P_t}{\partial T_i} = -V A_d \rho C_p$$

and

$$\frac{\partial P_t}{\partial T_o} = V A_d \rho C_p$$

Therefore, the uncertainty in thermal output is

$$\delta P_t = \sqrt{\left(\frac{\partial P_t}{\partial V}\right)^2 (\delta V)^2 + \left(\frac{\partial P_t}{\partial T_o}\right)^2 (\delta T_o)^2 + \left(\frac{\partial P_t}{\partial T_i}\right)^2 (\delta T_i)^2} \quad (9)$$

i.e.

$$\delta P_t = A_d \rho C_p \sqrt{(T_o - T_i)^2 (\delta V)^2 + V^2 ((\delta T_o)^2 + (\delta T_i)^2)} \quad (10)$$

The relative uncertainty is then

$$\frac{\delta P_t}{P_t} = \sqrt{\frac{(\delta V)^2}{V^2} + \frac{(\delta T_o)^2 + (\delta T_i)^2}{(T_o - T_i)^2}} = \sqrt{\frac{(\delta V)^2}{V^2} + \frac{2(\delta T)^2}{(T_o - T_i)^2}} \quad (11)$$

where δT ($= \delta T_i = \delta T_o$) is the uncertainty in temperature measurement ($^{\circ}\text{C}$).

The estimated relative uncertainty would be below 10% at the beginning of night cooling when the air temperature rise through the ventilation duct was over 4°C . However, as heat was released from the liquid PCM accompanied with decreasing temperature, the air temperature rise would decrease gradually to e.g. 2°C and 1°C after two and six hours, respectively. The corresponding uncertainty would increase to about 15% and 30%. Thus, the estimated uncertainty in heat gain measurement was considerable despite careful calibration of the temperature sensors to an accuracy of 0.2°C . Without calibration, the uncertainty for standard T-type thermocouples with an accuracy of 1°C would be four times larger.

The uncertainty estimated above appears quite large. This is because the derived uncertainty equation involves the air temperature increase/decrease as the denominator for estimating the uncertainty in temperature measurement rather than the temperature magnitude as often implicitly assumed or explicitly used for analysis in literature in the following incorrect form.

$$\frac{\delta P_t}{P_t} = \sqrt{\frac{(\delta V)^2}{V^2} + \frac{(\delta T_i)^2}{T_i^2} + \frac{(\delta T_o)^2}{T_o^2}} \quad (12a)$$

or more likely

$$\frac{\delta P_t}{P_t} = \sqrt{\frac{(\delta V)^2}{V^2} + \frac{(\delta T)^2}{T^2}} \quad (12b)$$

The temperature increase or decrease for fluid flow through a smooth passage such as a ventilation duct or a liquid pipe is normally quite small in comparison with the temperature magnitude. Typically, e.g., it is only a few degrees for liquid heating solar collectors [36] or even less for much longer borehole heat exchangers for ground source heat pumps (say 2 to 3°C for a 100 m deep and 200 m long U-tube heat exchanger). If equations similar to Equation (11) were used, the estimated relative uncertainty in the thermal output or efficiency of such

systems based on the measured fluid temperature rise/drop would likely be much larger than expected or reported in literature. For PVT or solar thermal collectors, the difference in estimated uncertainty using Equation (12) and Equation (11) would be around 10 fold. For comparison, using the temperature magnitude as the denominator, the relative uncertainty would be less than 1.5% for air temperature measurement in the ventilation duct employed in this study.

5 Conclusions

A PVT/PCM system for thermal control of PV and natural ventilation of a building has been designed and tested under laboratory conditions. The experimental results revealed that a PCM layer of 30 mm thickness with a phase change temperature of 25°C can maintain the PV temperature below 45°C for about 210 minutes under 600 W/m² insolation. A thicker PCM can maintain the low PV temperature for a longer time and every 10 mm increase in the PCM thickness can increase the time for thermal control by 60 - 70 minutes.

A limited number of tests from this study show that the thermal control by this type of PCM can increase the electrical conversion efficiency of crystalline PV by 10% under the testing conditions. The PVT/PCM system can also generate a 15 L/s ventilation rate in a vertical duct of 1100 mm wide, 1200 mm high and 100 mm deep during the melting phase and 20 L/s during the solidification phase even at an air temperature close to the phase change temperature. Higher ventilation rates can be achieved during the solidification phase when the ambient temperature is lower at night. Natural ventilation as well as PV temperature control can be enhanced by increasing heat transfer in the PCM. Integration of thermally conducting fins in the PCM increases the PV efficiency further by 3% and the ventilation rate by 30%. More importantly for the system studied, it would facilitate complete solidification of the PCM at night.

Even though experiments were conducted only at one set of conditions due to the fixed testing environment, the capability of the PVT/PCM system for both PV temperature control and building ventilation has been demonstrated. Besides, the results are useful for validation of a simulation model for this type of PVT/PCM for preheating and natural ventilation of a building which in turn can be used for investigation into the influence of different environmental conditions on the performance of the system and different designs of components for system optimisation.

Experiments were conducted in a laboratory with relatively stable conditions in order to make use of one apparatus for assessing the effects of PCM thickness and integration of thermally conducting fins within. However, the outdoor environmental conditions such as solar radiation and air temperature vary with time in a day and consequently it might not be possible to achieve complete melting and solidifying processes in the PCM for minimising the PV temperature rise while maximising the thermal energy storage every day in both cooling and heating seasons. Therefore, it is recommended to test the building-integrated PVT/PCM system with metal fins in the PCM container under real climatic conditions.

Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

1. H.A. Zondag, D.W. de Vries, W.G. J. van Helden, R.J.C. van Zolingen and A.A. van Steenhoven, The yield of different combined PV-thermal collector designs, *Solar Energy* 74(2003) 253-269.
2. S.A. Kalogirou and Y. Tripanagnostopoulos, Hybrid PVT solar systems for domestic hot water and electricity production, *Energy Conversion and Management* 47(2006) 3368-3382.
3. N. Aste, G. Chiesa and F. Verri, Design, development and performance monitoring of a photovoltaic-thermal (PVT) air collector, *Renewable Energy* 33(2008) 914-927.
4. Y. Tripanagnostopoulos, Photovoltaic/Thermal Solar Collectors, In A. Sayigh (Ed), *Comprehensive Renewable Energy*, Elsevier, Oxford, 3(2012) 255-300.
5. H.A. Zondag, Flat-plate PV-Thermal collectors and systems: A review, *Renewable and Sustainable Energy Reviews* 12(2008) 891-959.
6. L. Mei, D. Infield, U. Eicker, and V. Fux, Thermal modelling of a building with an integrated ventilated PV façade, *Energy and Buildings* 35(2003) 605-617.
7. T.N. Anderson, M. Duke, G.L. Morrison and J.K. Carson, Performance of a building integrated photovoltaic/thermal solar collector, *Solar Energy* 83(2009) 445-455.
8. O. Zogou and H. Stapountzis, Flow and heat transfer inside a PVT collector for building application, *Applied Energy* 91(2012) 103-115.
9. A. Hasan, S.J. McCormack, M.J. Huang and B. Norton, Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics, *Solar*

- Energy 84(2010) 1601-1612.
10. P.H. Biwole, P. Eclache and F. Kuznik, Phase-change materials to improve solar panel's performance, *Energy and Buildings* 62(2013) 59-67.
 11. R. Stropnik and U. Stritih, Increasing the efficiency of PV panel with the use of PCM, *Renewable Energy* 97(2016) 671-679.
 12. M. Rezvanpour, D. Borooghani, F. Torabi and M. Pazoki, Using $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ as a phase change material for thermo-regulation and enhancing photovoltaic panels' conversion efficiency: Experimental study and TRNSYS validation, *Renewable Energy* 146(2020) 1907-1921.
 13. F. Hachem, B. Abdulhay, M. Ramadan, H. El Hage, M.G. El Rab and M. Khaled, Improving the performance of photovoltaic cells using pure and combined phase change materials – Experiments and transient energy balance, *Renewable Energy* 107(2017) 567-575.
 14. C.S. Malvi, D.W. Dixon-Hardy and R. Crook, Energy balance model of combined photovoltaic solar-thermal system incorporating phase change material, *Solar Energy* 85(2011) 1440-1446.
 15. X. Yang, L. Sun, Y. Yuan, X. Zhao and X. Cao, Experimental investigation on performance comparison of PV/T-PCM system and PV/T system, *Renewable Energy* 119(2018) 152-159.
 16. M.J. Huang, P.C. Eames, B. Norton, Thermal regulation of building-integrated photovoltaics using phase change materials, *International Journal of Heat and Mass Transfer* 47(2004) 2715–2733.
 17. M.J. Huang, P.C. Eames, B. Norton, Comparison of a small scale 3D PCM thermal control model with a validated 2D PCM thermal control model, *Solar Energy Materials and Solar Cells* 90(2006) 1961–1972.
 18. H. Hasan, S.J. McCormack, M.J. Huang, J. Sarwar and B. Norton, Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates, *Solar Energy* 115 (2015) 264–276.
 19. L. Aeleneia, R. Pereira, H. Gonçalves and A. Athienitis, Thermal performance of a hybrid BIPV-PCM: Modeling, design and experimental investigation, *Energy Procedia* 48 (2014) 474 – 483.
 20. J. Park, T. Kim, S.B. Leigh, Application of a phase-change material to improve the electrical performance of vertical-building-added photovoltaics considering the annual weather conditions, *Solar Energy* 105(2014) 561–674.
 21. S. Sharma, A. Tahir, K.S. Reddy and T.K. Mallick, Performance enhancement of a building-

- integrated concentrating photovoltaic system using phase change material, *Solar Energy Materials and Solar Cells* 149(2016) 29-39.
22. H. Elarga, F. Goia, A. Zarrella, A. Dal Monte and E. Benini, Thermal and electrical performance of an integrated PV-PCM system in double skin façades: A numerical study, *Solar Energy* 136(2016) 112-124.
 23. Z. Wang, Z. Huang, F. Chen, X. Zhao and P. Guo, The integration of solid-solid phase change material with micro-channel flat plate heat pipe-based BIPV/T, *Building Services Engineering Research and Technology* 39(2018) 712–732
 24. J. Curpek M. Cekon and J. Hraska, PCM integrated in BiPV ventilated façade concepts: experimental test cell platform and initial full-scale measurements, in *IOP Conference Series.: Earth and Environmental Science* 290(2019) 012072.
 25. J. Wang, Y. Ouyang and G. Chen, Experimental study on charging processes of a cylindrical heat storage capsule employing multiple phase change materials, *Energy Research* 25(2001) 439-447.
 26. U. Stritih, An experimental study of enhanced heat transfer in rectangular PCM thermal storage, *International Journal of Heat and Mass Transfer* 47(2004) 2841-2847.
 27. M.J. Huang, P.C. Eames and B. Norton, Phase change materials for limiting temperature rise in building integrated photovoltaics, *Solar Energy* 80(2006) 1121-1130.
 28. M.J. Huang, P.C. Eames, B. Norton and N.J. Hewitt, Natural convection in an internally finned phase change material heat sink for the thermal management of photovoltaics, *Solar Energy Materials and Solar Cells* 95(2011) 1598-1603.
 29. S.A. Nada and D.H. El-Nagar, Possibility of using PCMs in temperature control and performance enhancements of free stand and building integrated PV modules, *Renewable Energy* 127(2018), 630-641.
 30. M.R. Salem, M.M. Elsayed, A.A. Abd-Elaziz and K.M. Elshazly, Performance enhancement of the photovoltaic cells using Al_2O_3 /PCM mixture and/or water cooling-techniques, *Renewable Energy* 138(2019) 876-890.
 31. H. Hasan, S.J. McCormack, M.J. Huang and B. Norton, Energy and cost saving of a photovoltaic-phase change materials (PV-PCM) system through temperature regulation and performance enhancement of photovoltaics, *Energies* 7(2014) 1318-1331.
 32. E. Japs, G. Sonnenrein, S. Krauter and J. Vrabec, Experimental study of phase change materials for photovoltaic modules: Energy performance and economic yield for the EPEX spot market, *Solar Energy* 140(2016) 51-59.
 33. F. Jiang, X. Wang and Y.P. Zhang, A new method to estimate optimal phase change material

- characteristics in a passive solar room, *Energy Conversion and Management* 52(2011) 2437-2441.
34. CIBSE Guide A – Environmental Design, Chartered Institution of Building Services Engineers, London, 2015.
35. Y. Xiang and G. Gan, Optimization of building integrated photovoltaic thermal air system combined with thermal storage, *Low Carbon Technologies* 10(2015) 146-156.
36. J.A. Duffie and W.A. Beckman, *Solar Engineering of Thermal Processes* (4th Edition), John Wiley & Sons, New Jersey, 2013.