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Indoor characterisation of a photovoltaic/ thermal phase change material system

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Abstract

Photovoltaic/ thermal (PV/T) systems integrate photovoltaic and solar thermal technologies and have the added advantage of producing both electrical and thermal energy simultaneously. This study has been carried out to investigate the performance of a PV/T phase change material (PCM) system under experimental climatic conditions. Electricity is generated by the PV during daylight hours and the heat produced is absorbed and stored in PCM. Water flows through a pipe network within the PCM and absorbs the stored heat in the PCM. In the PV/T-PCM system, water remained at a higher temperature for an extended period of time as well as shifting the time period of available heat when compared to the reference systems.

Peer-review by the scientific conference committee of SHC 2014 under responsibility of PSE AG

Keywords: Photovoltaic/ thermal systems; phase change material; thermal perfomance

1. Introduction

The annual global energy consumption is increasing by approximately 2% per annum [1]. According to the U.S. Energy Information Administration fossil fuels produce 80% of the energy consumed worldwide [2]. However, fossil fuels are a limited commodity and the advancement of renewable sources of energy is essential in order to maintain a sustainable environment. Renewable energy technologies have been shown to offer a viable solution to addressing the issue of climate change and global warming [3]. For centuries now, solar power has been harnessed using innovative methods to trap the suns energy.

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The most common of these are photovoltaic solar cells and solar systems which are used to generate electrical and thermal energy. This study presents a novel hybrid PV/T – PCM system which consists of a photovoltaic (PV) solar panel attached to a thermal absorbing material where the system utilizes the thermal energy generated by the PV to heat water. It is charged using waste heat energy generated by the PV. At a later time, the PCM discharges the absorbed heat energy to the water. A pipe network positioned inside the PCM container acts as a heat exchanger, transferring heat from the PCM to the water. The experiment is carried out under the simulated conditions of that in a hot climate as presented in Rehman et al [4].

1.1. Background

In a hybrid PV/T system both electricity and heat are produced; the heat generated by the PV cell is captured and absorbed by water or air. The incorporation of thermal collectors with PV technology has been seen to increase the overall efficiency of a PV/T system as thermal energy is produced as a by-product of the production of electrical energy [5]. For many PV/T systems, the electrical efficiency is lower than the electrical efficiency of a PV system alone however; the overall energy efficiency is still higher than a PV due to the production of hot air or water.

The assessment of a natural air circulation PV system comparing air and water as a heat transfer fluid with and without glazing showed water circulation proved more efficient than air [6]. Zodag at al. [7] investigated the performance of four groups of PV/T systems of nine different designs. Their thermal and electrical efficiencies were compared in addition to the yearly yield of hot water. It was shown that a sheet and tube was the most feasible design, though was not the most efficient when compared to other systems; it was the ease of manufacture that made it the best option. The fluid channel below the transparent PV was found to have the highest efficiency with an annual average efficiency of 43.5%. A model of a PV/T system using water as a transfer fluid found the thermal and electrical efficiencies could reach 63.65% and 8.45%, respectively [8].

Phase change materials (PCM) absorb thermal energy as latent heat at a constant phase change temperature. At initial heating, PCM heats sensibly and when it reaches the melting/solidification temperature, PCM absorbs latent heat, progressively melting. Melted PCM continues to warm further as it melts heating sensibly, as in Figure 1 [9].

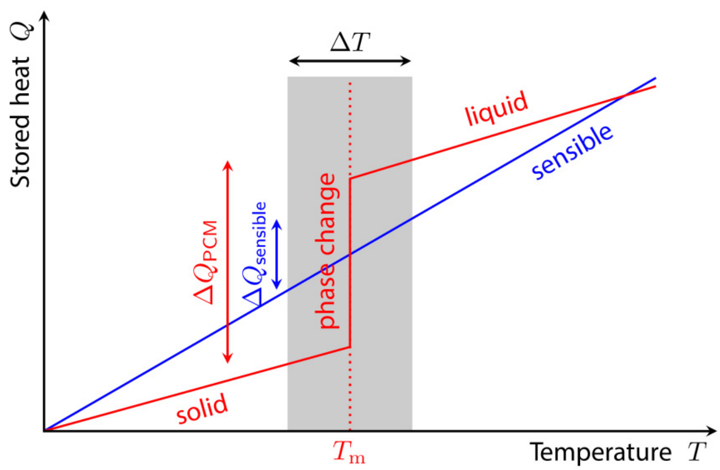

Fig. 1. Graphical representation of the variation of stored heat of a PCM with increasing temperature [9]

The duration and temperature range over which the phase change takes place depends on the mass of the PCM and the thermal conductivity of PCM and any enhanced heat transfer elements therein. There has been considerable research on types of PCM, their applications and physical properties [10-12].

PCM has been extensively investigated in the thermal management of PV. A series of small scale indoor experiments found calcium chloride regulated the front surface temperatures for a prolonged period of time compared to other PCMs tested [13]. Aluminium fins were integrated into a PV/PCM system to investigate the melting process of PCM and the effect of differently spaced fins on the melting fraction of the PCM both theoretically and experimentally using PCM RT27 [14]. A finite element numerical heat transfer model investigated the temperature evolutions, velocities and melt fraction of PCM in a PV/PCM system [15]. Capric-palmitic was found to have the highest temperature regulation with conduction dominating heat transfer.

More recent attention has focused on the provision of integrating PCM with PV/T systems to store and make use of waste heat generated by the PV. A one dimensional energy balance model of a PV/T-PCM system has been simulated and with the inclusion of an applicable PCM the PV output can increase by approximately 9% compared to PV only and an average water temperature rise of 20ºC[16]. A model of a BIPV-PCM system installed in an office façade has been validated using field testing. The maximum electrical efficiency has been shown to reach 10% with thermal efficiencies of 12% [17]. An investigation into the concept of a BIPV-PCM system found the design advantageous due to the reduction of materials required during construction, removal of heat in the summer by PCM and the harnessing of solar energy reduces the need for conventional grid power [18].

The aim of the presented work is to give an evaluation of a novel PV/T-PCM system under conditions of high solar radiation to enhance heat storage and improve the overall efficiency of a PV/T-PCM system. Such a system has been previously investigated under conditions of the maritime island climate of Ireland. It was a found PCM can be used in a PV/T system for the absorption of heat generated by the PV. The heat was stored for an extended period of time compared to a system without the PCM. It was found 12% percent of the energy stored in the PCM was transferred to the water [19; 20].

2. Experimental set-up

The experimental set-up is similar to that presented in [20], however this experiment assesses three systems, PV/T-PCM, PV/T and PV, under higher temperature conditions; as shown in Figure 2(a) and presented in Table 1.

Table 1. List of systems fabricated

System	PCM	Pipe network	Container	Panel
PV/T-PCM	Yes	Yes	Yes	Yes
PV/T	No	Yes	Yes	Yes
PV (reference)	No	No	No	Yes

Fig. 2. (a) Experimental set-up (b) Heat mat

A stainless steel container of dimensions 1m x 0.471m x 0.065m was attached to each PV and PV/T system as in Figure 3(a). The container encloses a copper pipe network which allows for the flow of water through both the PV/T- PCM and PV/T systems as in Figure 3(b). The container of the PV/T-PCM system holds the PCM. The PV acted as a reference.

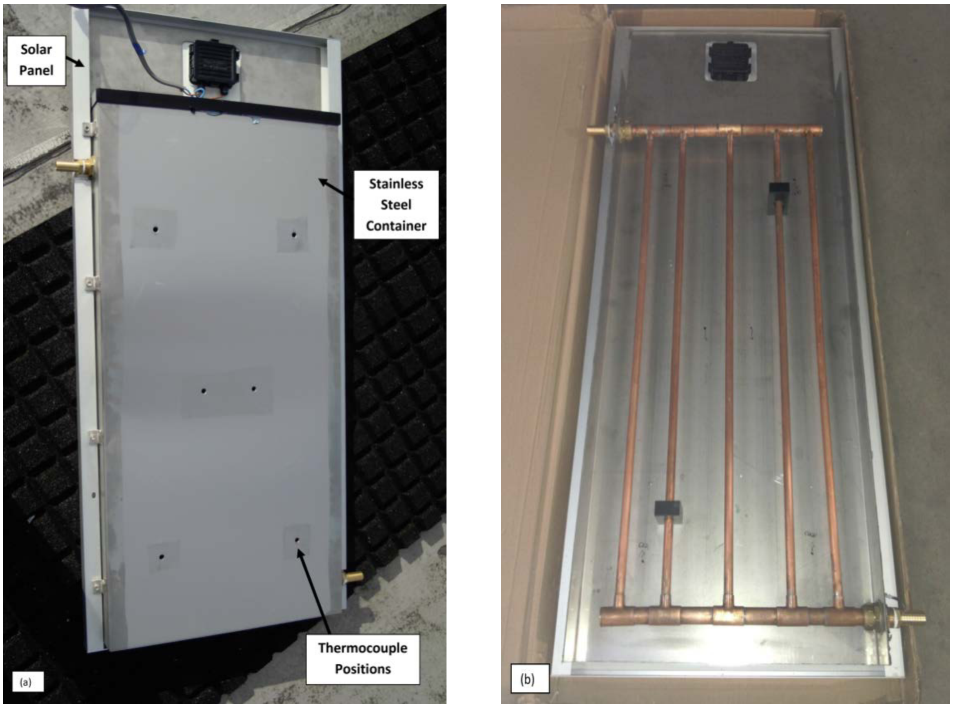

Fig. 3. (a) Sealed container (b) pipe network in position in container

Wire wound silicon rubber heat mats were used to simulate the temperature on the back of a solar panel from approximately 9am to 6pm simulating similar temperatures to that of a desert climate based on data recorded during the month of July[4]. The PV panels were removed for the duration of the experiment so the heat mats were in direct contact with the stainless steel container as in Figure 2(b).

The initial temperature of the heat mat was approximately 20ºC at 9am, this was increased incrementally to approximately 66ºC at 1pm and again the temperature was reduced in small steps to approximately 25ºC at 5.30pm. The heat mat was installed on the 9^{th}, 10^{th} and 11^{th} of September. The remaining days were tested under ambient conditions to investigate the energy storage potential and energy dissipation within the test systems.

Temperature variation throughout each system was recorded using calibrated T-type and K-type thermocouples with a maximum deviation of ±0.5ºC. These thermocouples were placed at the back of the PV, back of the container and inside the container. The temperature of the water in the pipe network and cylinders were also recorded. The data was recorded on Delta-T and Agilent 34972A data acquisition systems.

PCM used was a fatty acid eutectic, capric- palmitic (CP). It has been found to have a melting point of 22.4ºC; other thermophysical properties are reported in Table 2. The container required 22 kg of PCM. This was carried out by melting the capric and palmitic acid in required weight mixtures and melting the PCM using a series of hot plates. It was necessary to keep all PCM in liquid form at the time of pouring into the container; this ensured there was no segregation of PCM within the container.

Table 2. Properties of capric: palmitic acid

Property	Capric: palmitic acid
Melting point (ºC)	22.4
Heat of fusion ($kJkg^{-1}$)	195
Thermal conductivity ($Wm^{-1}K^{-1}$)	0.143
Specific heat capacity ($kJkg^{-1}K^{-1}$)	2.4

The ambient temperatures simulated for a hot climatic region [4] on the 9th, 10th and 11th of September are presented in Figure 4. The latter three days, 12th, 13th and 14th of September are the environmental conditions of a maritime climate in Dublin. Ambient temperature reaches highs of 19ºC and solar radiation exceeding 800W/m^2 on the days tested.

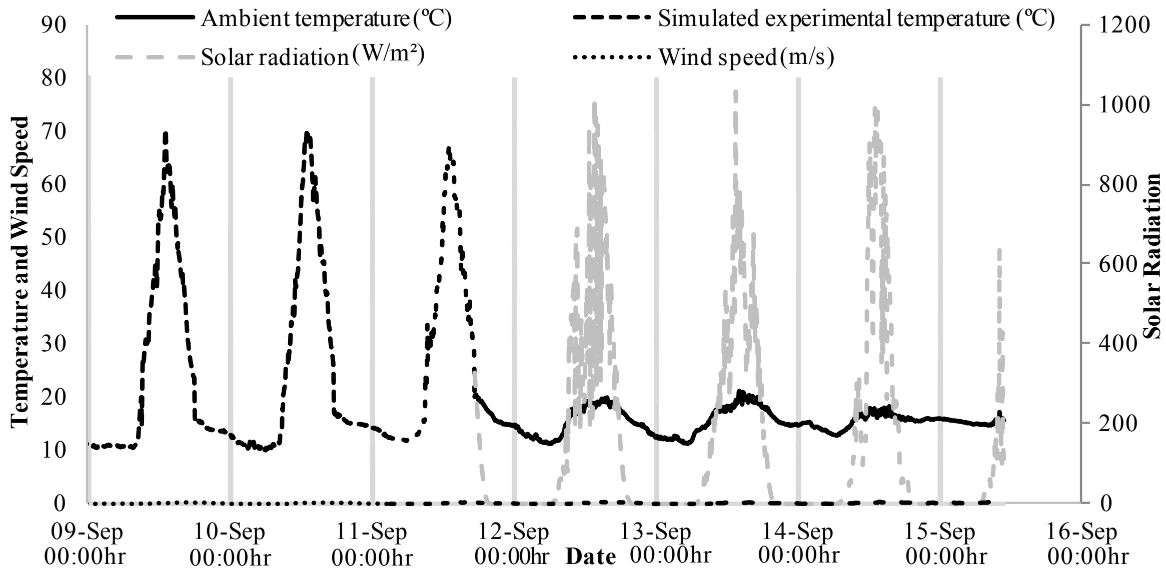

Fig. 4. Environmental conditions for the period of the experiment

3. Results and discussion

3.1. Charging and discharging

The temperature inside the container of the PV/T-PCM system is lower than that of the PV/T system due to the storage of heat by the PCM. There is a lag in the temperature increase of the inside of the container in the PV/T-PCM system compared to that of the PV/T system as the PCM is initially storing the heat, this is seen in Figure 5 when the temperature of the inside of the container of PV/T-PCM system is slower to increase than the temperature of the PV/T system and water. The lag is evident for the entire experiment suggesting the PCM is initially storing heat prior to increasing in temperature despite the climatic conditions.

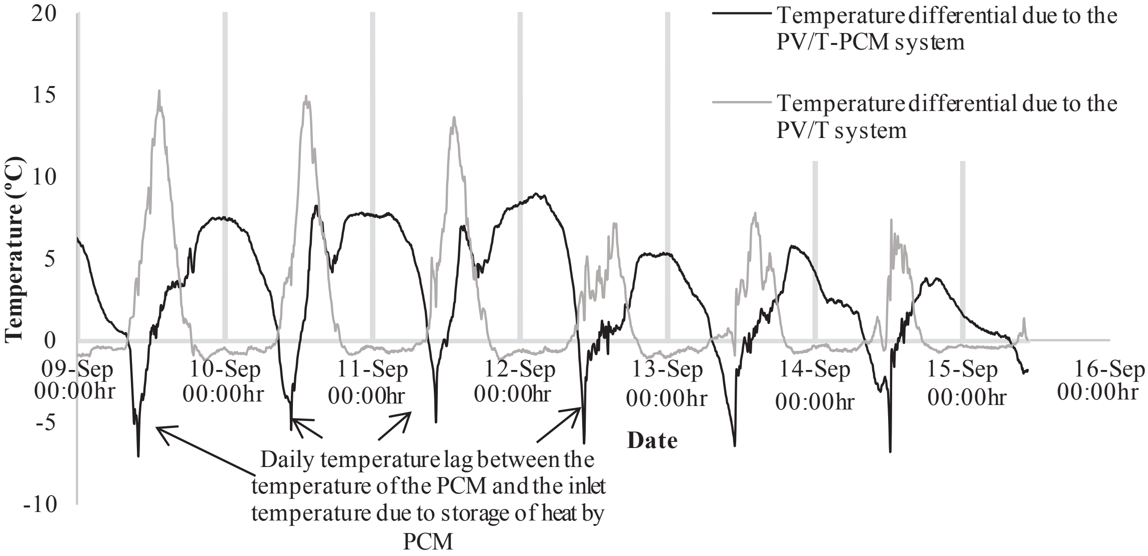

Fig. 5. Temperature differential due to the PV/T-PCM and PV/T systems against time

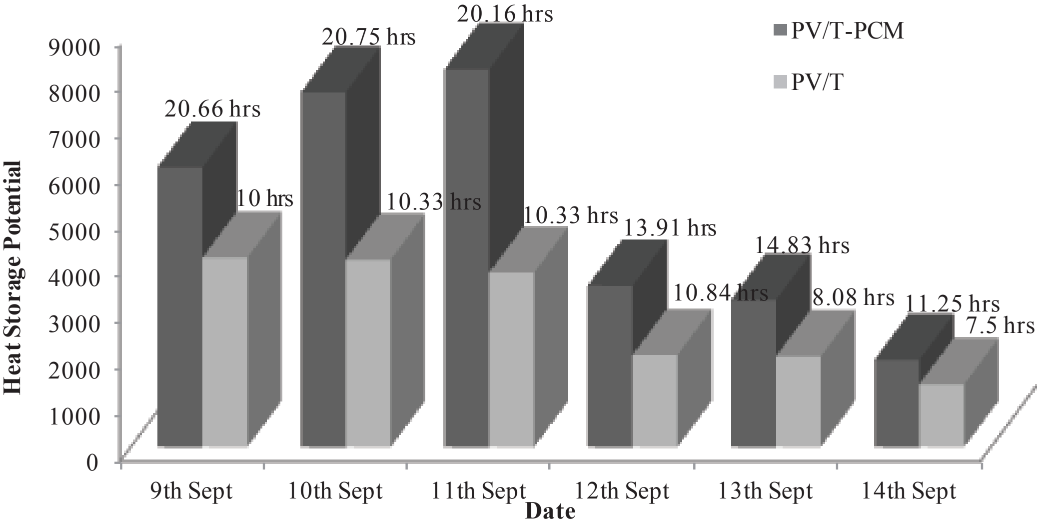

Fig. 6. Daily heat storage potential of PV/T-PCM and PV/T systems with the period of available heat against time

The PCM in the PV/T-PCM system extends the time for which the heat is available as it absorbs latent heat and charges during the day. The PV/T system allows for immediate availability of the heat gained by the system as the peak is at approximately midday when the simulated temperatures are at their highest. The PCM shifts the time for which the heat is used as the heat gain is stored until discharging of the PCM occurs.

3.2. Heat Storage Potential (HSP)

The heat storage potential (HSP) was calculated as

$$HSP = \int_{t=t_0}^{t=t_n} T_{inside\ container}\,dt - \int_{t=t_0}^{t=t_n} T_{water\ inlet}\,dt$$

HSP calculates the amount of heat transfer available to the water at the inlet. Under simulated conditions, HSP in the PV/T-PCM system can be seen to be up to 50% larger than the HSP of the PV/T system, as in Figure 6. This is due to the latent heat capacity of the PCM and its ability to charge and discharge under certain temperatures. Although, the values of HSP are not as high under maritime climatic conditions the amount of energy stored by the PV/T-PCM system still approximately 33% larger than the PV/T system.

For the first three days of the experiment when higher ambient temperatures are simulated [4], PCM increases the heat availability period by almost 100%, up to 20 hours; where the PV/T system has a heat availability period of just over 10 hours. During the latter days under ambient conditions, the period of available heat is reduced in both systems; this is due to the reduction in the heat input. However the PVT/-PCM system still allowed for an extended period of available heat of up to 14 hours compared to a system with no PCM of 8 hours, a 75% increase.

3.3. Water temperature

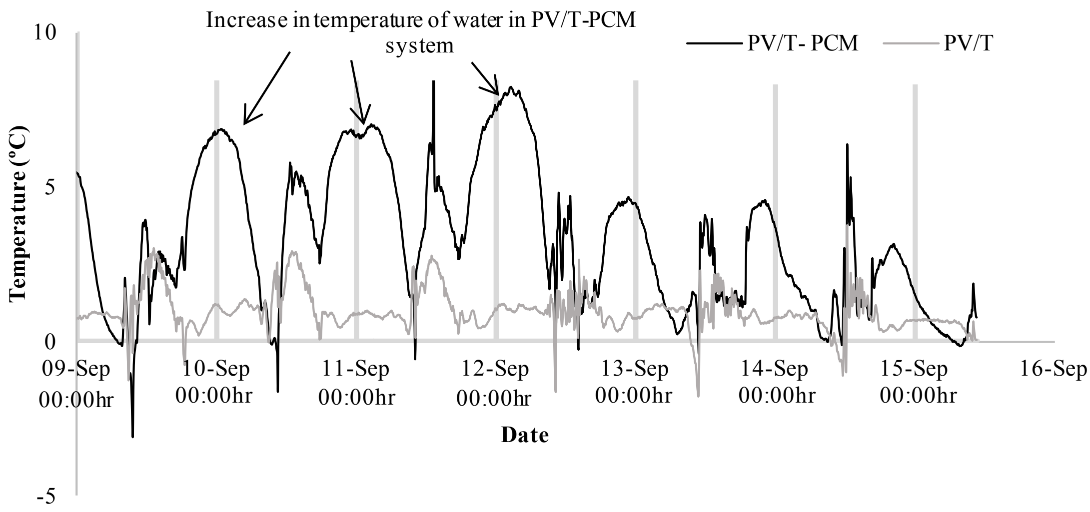

Fig. 7. Temperature differential of the water inlet and outlet in PV/T-PCM and PV/T

The temperature difference of the water in the PV/T compared to the PV/T system as illustrated in Figure 7 is a result of the charging and discharging of the PCM. The daily temperature variation of the water in the PV/T-PCM system shows the heat generated by the PV is being stored by the PCM during the day (approximately 11:00-18:00 hours) as there is little temperature difference between the incoming and outgoing water. As ambient temperature decreases the PCM discharges heat gained to the water as illustrated when the temperature of the water increases (approximately between 18:00-7:00).

The immediate availability of heat in the PV/T system can be seen as the temperature of the water peaks at approximately midday, allowing for no storage or extended time of availability. Although, the temperature of the water is not reaching the highs of PV/T-PCM system

The improvement in the potential of the PV/T-PCM system under simulated conditions is evident during the first three days of the experiment as the temperature difference between the inlet and outlet is reaching highs of approximately 8ºCcompared to that of maritime conditions reaching highs of approximately 4ºC[20].

4. Conclusion

The PV/T-PCM system has been shown to increase its heat storage potential compared to a PV/T system under simulated conditions. The time for which the heat was stored was nearly double that of a PV/T system under the same conditions. Similarly, the heat gain by the water in the PV/T-PCM system was approximately 6ºC degrees higher than that of a PV/T system.

The performance of a PV/T-PCM system can be seen to dramatically improve compared to a maritime climate like that of Ireland. In a higher temperature climate the heat storage potential increased by 100%. The amount of heat available to the systems has been shown to increase compared to that of a maritime climate. The length of time for which heat is available has been shown to increase by up to 100% compared to a system without PCM, thereby extending the potential time of use.

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