Experimental Investigation of PV/T Collectors with Phase Change Material

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Abstract

In the current work we evaluate the experimental operation of two different types of photovoltaic-thermal collectors (PV/T) and their performance after adding a layer of phase change material (PCM) within the panel. Each PV/T collector selected has a heat absorber unit different in material and geometry and was tested under four different configurations: unglazed, unglazed with PCM, glazed and glazed with PCM. Results show a slightly variation in the electrical generation but a great difference in the thermal performance between glazed and unglazed configuration. The addition of PCM results in a better distribution of the heat production, generating up to 30% of maximum thermal values after removing sun exposure. No significant differences are found between heat absorber units for similar configurations.

Keywords: Solar energy, Photovoltaic-thermal (PV/T); Phase change material; Experimental study.

1. Introduction

The increase on the world energy consumption observed during last decades has forced society to investigate new technologies and energy resources. Traditional energy technologies imply the use of fossil fuels and other precious resources whose future availability is limited and entail the generation of pollution in terms of air, water, soil and climate. This fact, together with the hardening of the European Union's policies relative to gas emissions and energy efficiency[1], have encourage the development and use of renewable energies, as a clean, cheap and reliable alternative. However, in order to reach the level of maturity required to face fossil fuels, new technologies need further research. In this frame, solar technologies emerges as one of the most promising alternatives due to the abundant, inexhaustible and clean nature of the sun (Parida, Iniyan, and Goic 2011). Regarding the flat plate collector, solar technology is traditionally subdivided into two main groups: solar thermal (ST) and photovoltaics (PV).

Solar thermal collector was the first panel type investigated and their typical efficiency rounds 80% (Colangelo et al. 2016; Hossain et al. 2011). However, its use has been gradually cushioned due to the high installation costs and common hydraulic problems. Photovoltaic panels, on the contrary, present efficiency values ranged between 5–20% depending on the PV cell technology (Islam et al. 2016), but the PV market has undergone a great development in last decade which helped to reduce both production and installation costs while improving the technology. These efficiency values, however, can be penalized due to the temperature increment of the panel (M. J. Huang, Eames, and Norton 2006; Radziemska 2003), and is estimated to drop at rate of 0.45%/°C in case of crystalline silicon cells (Du, Darkwa, and Kokogiannakis 2013). To limit the PV cell temperature during operation, several solutions have been proposed including the use of a heat absorber piece to remove surplus heat (usually named PV/T collectors) or the incorporation of phase change material (PCM).

First PV/T (photovoltaic-thermal) panels were suggested in mid1970 (Hendrie 1979; Kern and Russell 1978; Martin Wolf 1976) with the only objective of removing heat from the PV laminate. The technology was afterwards developed to make use of the heat removed but it was not until 1990s that the hybrid technology became a viable commercial solution (Bergene and Løvvik 1995; Garg and Adhikari 1999). Common PVT collectors are based on heat absorber unit adhered to a PV laminate so they can generate both electricity and low-grade thermal energy

[1] European Commission, 2017. Energy Strategy 2020: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2020-energy-strategy

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during the daytime (Chow 2010; Michael, Iniyan, and Goic 2015). The combination of both systems on the same module lowers the thermal performance with respect to a thermal collector, but incorporates the electrical production with enhanced performance with respect to the individual PV due to the cooling effect provoked by the stream fluid. As a result, the PV/T system produces more energy per unit area compared to a PV module and a thermal collector adjacent to each other (Tripanagnostopoulos et al. 2005; Zondag et al. 2002). Each energy rate can vary depending on the PV/T features: existence of frontal cover, absorber geometry and material, PV cell type or fluid stream for example. Although this technology has been widely studied during last decade (Beaudin and Zareipour 2015; Besheer et al. 2016; Good 2016; Palaskar and Deshmukh 2012), the high upfront investment cost and the low efficiency rates compared to fossil fuel systems restrain their use. According to experts, the great breakthrough is yet to come, but highlight the necessity of further research to increase efficiencies and reduce costs.

The use of phase change materials (PCM) as a way to regulate the temperature of the PV cells was introduced in 1978 (Stultz 1978) and since then, many works have focused on the benefits of this technology, from experimental (Ahmad Hasan et al. 2014; Klugmann-radziemska and Wcisło-kucharek 2017; Mahamudul et al. 2016) to numerical (M. J. Huang, Eames, and Norton 2007; Sarwar et al. 2011) point of view. This material is able to store thermal energy when it changes the phase during the warming, and releases it gets cold again and recover the initial state. This way, the use of this material can limit the maximum temperature reached on the PV cells if they exceed the PCM melting range. According to literature, the appropriate selection of PCM is essential for the success of the application. Factors like the PCM nature (organic, inorganic), melting point or total thickness directly condition the potential impact on PV performance. Its effect has been experimentally studied in controlled testing plants (A Hasan et al. 2010) or applied to buildings integration (BIPV) (Aelenei et al. 2014; Yin et al. 2013), and included in the International Energy Agency throughout the Annex 17 (International Energy Agency 2005) and the Task 42 of the Solar Heating & Cooling Programme (Rommel, Hauer, and Van Helden 2015).

The application of PCM to PV/T modules is less common than its use to PV of ST separated. Most of previous works tackle the combination with the PCM located in an external thermal energy storage (TES) (Lin et al. 2014; Ren et al. 2017; Yin et al. 2013). A few studies referred to cases with PCM directly inserted on the panel from the numerical approach (Malvi, Dixon-Hardy, and Crook 2011; Su et al. 2017) and experimental assessment (Besheer et al. 2016; Good 2016; Yang et al. 2018). All of them focused on sheet-and-tube copper heat absorbers, but no additional materials or configurations were explored.

With this work we aim to fill this gap and analyzed the effect of the same PCM on two types of PV/T modules: traditional sheet-and-tube copper and a roll-bond sheet aluminum heat absorber. Both models were experimentally addressed to evaluate the thermal and electrical performance with and without PCM. In the case of PV/T roll-bond aluminum absorber, glazed and unglazed configurations were considered in order to assess the influence of the cover into the PV/T performance.

2. Material & methods

2.1. Description of the prototype design and manufacturing

Two PV/T models were considering for the testing based in different heat absorber types: sheet-and-tube copper pipes and a roll-bond aluminium absorber. In the case of the aluminium, two configurations were explores, glazed and unglazed. Moreover, each model was investigated with and without PCM. Thus, a total of 6 PV/T panel models are analysed in this work.

Table 1: List of PV/T cases considered for the testing.

Case name	Absorber type	Frontal cover	PCM
Al PVT-1	Roll-bond, aluminium	NO	NO
Al PVT-1 + PCM	Roll-bond, aluminium	NO	YES
Al PVT-2	Roll-bond, aluminium	YES	NO
Al PVT-2 + PCM	Roll-bond, aluminium	YES	YES
EC PVT-2	Sheet-and-tube, copper	YES	NO
EC PVT-2 + PCM	Sheet-and-tube, copper	YES	YES

Sheet-and-tube copper absorber corresponds to the traditional model commonly employed in literature. For this case, the commercial ECOMESH panel was employed[2]. This hybrid panel contains a copper absorber, formed by a flat sheet and longitudinal tubes where the fluid flows. Second model was made based on a roll-bond absorber, developed by CGA technologies. The roll-bond sheet has two faces: one is flat to be in contact with the PV laminate and maximize the contact between surfaces, the other presents a wavy pattern with the fluid channels. In both models absorber pieces are located between the PV laminate, consisting on 60 polycrystalline cells with nominal power set at 270W, and the insulating layer, conformed by a 2.5-mm rock wool layer. Rest of absorber specifications are listed in Table 2.

To obtain the glazed configuration, an additional glass layer was placed over the frontal side of the panel. The cover consisted on a 3.2-mm glass layer located and glued to the PV module, with a 12-mm air camera left between them. PCM was inserted between the absorber unit and the insulation layer with the help of several metallic bars placed across the PVT panel to ensure the PCM position during the experimental testing and the contact with the absorber.

Table 2: Specifications of absorbers of the PV/T models tested.

Magnitude	Units	EC model	Al model
Dimensions of collector	mm	1590x960	1420x940
Area	m^2	1.53	1.46
Absorber Material	-	Copper	Aluminum
Maximum operating temp.	ºC	150	85
Operating pressure	bar	2	4
Maximum pressure	bar	10	6
Pressure drop	bar	0.04	0.15
Nominal flow rate	l/h	120	100
Weight	kg	7	6
Water content	l	1.2	0.88

PCM selection and insertion

PCMs are components able to store thermal energy during the process of phase change. At ambient temperature the PCM remains in solid state, but when the temperature increases up to a particular value it changes into solid state, absorbing energy from the surrounded area. When applied to solar applications, PCM comply with particular requirements such us: ability to work for many cycles, chemical stability between 0 - 100ºC or small volume changes among others. Besides the general requirements, the suitability of a PCM is directly conditioned by the melting point selected. Attending to the fluid temperature inside PV/T panels, which may reach maximum values of 60-70ºC in extreme environmental conditions, we have established the phase change range suitable for this application between 45-50ºC.

Our objective with this PCM melting point selection is to store only the surplus heat generation over 45ºC and to prevent PV laminate from reaching excessive high temperatures. On this basis, we have selected the salt hydrate (inorganic PCM) C48, ClimSEL™ line of Climator Sweden, with a phase change temperature established at 48ºC (see Figure 1).

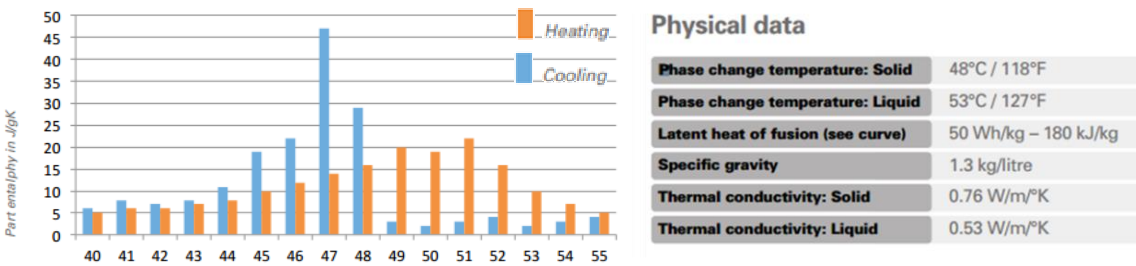

Figure 1: Inorganic C48 PCM technical sheet.

[2] Solar hybrid panel ECOMESH, EndeF Engineering SL. https://endef.com/en/products/

In order to prevent hybrid collector units from possible PCM leaks during the liquid state, PCM was added to the panel covered by an external enclosure. The material employed for the enclosure was aluminium foil pouches to favour the heat transmittance from the absorber to the PCM. A total of 16 kg was inserted in each panel, distributed in 32 pouches of 0.5 kg and 10 mm of thickness.

2.2. Description of the testing procedure

All PV/T units were tested in EndeF facilities, located in Zaragoza, Spain. Experiments were carried out in a testing bench with capacity for two solar panels. Hydraulic connection was set so that the heat exchange fluid flows in a close loop, crossing both panels on its way. Other components of the testing rig were: pump, hydraulic valves, an expansion vessel, heat dissipator and an electric board. Electrical production of the PVT prototype was generated in DC power and turned into AC power through the micro inverter located on the rear side of the panel, corresponding to the SMI-D480W-60-UL model, by Enecsys.

During the testing, data was continuously monitored in a PLC Modicon 241 and computationally registered for the postprocessing. The description of the main measurement instruments is included Table 3.

Table 3: List of sensors set on the testing bench.

Magnitude	Sensor model	Amount	Range	Accuracy
Temperature	Pt100, several brands	7	-50 - 400 ºC	± 0.05°C
Flow	Analogic DRG-L343, Kobold	1	1-30 l/min	± 3 % F.S.
Pressure	UNIK 5000, GE	1	0.7 – 700 bar	± 0.04 %
Irradiance	Pyranometer, LP PYRA 03 AC	1	0-2000 W/m2	0.025 W/m2
Current	HT-RS-0, Herten SL	2	0-10 V	±0.5 %

Experiments were carried out with natural irradiance during the summer season in Zaragoza (Spain). In order to obtain constant values of irradiance, the rig was manually oriented along the light hours with respect to the solar rays´ angle. The measurement period lasted from 11am to 5pm, reaching at two stable working points: first from 11am to 3pm and second from 3pm to 5pm. The working temperature of the PV/T unit was higher in the second stable point. Internal temperatures were monitored during the rest of the day to evaluate the effect of the PCM.

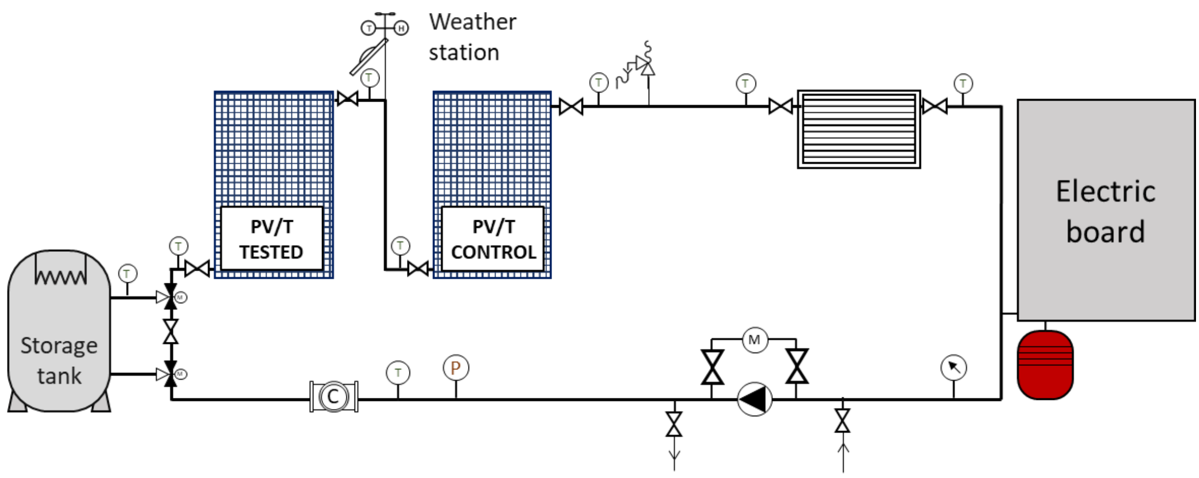

Figure 2: Hydraulic scheme of the testing bench.

2.3. Analytical considerations

Based on the information acquired by the different sensors and measuring equipment installed in the testing rig, the evaluation of several performance parameters was addressed.

The instantaneous heat power generated by each prototype was calculated form the flow rate of the fluid, $\dot{m}$, the specific heat of water, c_f, and the thermal leap of the fluid in its path across the panel ΔT, as given en Eq. (1). Based on this heat power, we define the instant thermal efficiency of the PV/T panel as indicated in Eq. (2). With A_G as the gross area of the photovoltaic laminate, sized in 1.56 m^2, and G the amount of solar irradiation measured by the pyranometer in W/m^2 attached on the rig.

$$\dot{Q} = \dot{m} \cdot c_f \cdot \Delta T \quad (1)$$

$$\eta_{th} = \dot{Q} / (A_G \cdot G) \quad (2)$$

Attending to the electrical part, electrical output (W_p) was directly measured during the experiments through the use of a current isolator. From this data, cell efficiency was calculated as defined in Eq. (3), considering the irradiance capture by the PV laminate (Irradiance x PV area).

$$\eta_{PV} = \frac{W_p}{(I \cdot A)} \quad (3)$$

In order to directly compare all PV/T models, a general PV/T efficiency was defined transforming the energy quantities into primary-energy. To that end, we employ the conversion coefficient η_{power} previously used in literature to transform electrical energy into thermal equivalent value and usually established in 38% (B. J. Huang et al. 2001; Ji et al. 2007; Kamthania and Tiwari 2014). The overall PV/T performances is therefore define as indicated in Eq. (4).

$$\eta_{tot} = \eta_{th} + \eta_{PV}/\eta_{power} \quad (4)$$

3. Results & Discussion

Environmental conditions corresponding to the testing days of each prototype are shown in Figure 3.Solar radiation was ranged between 800-1000 W/m^2 during the testing period and environmental temperature did not differ from each other more than 10ªC.

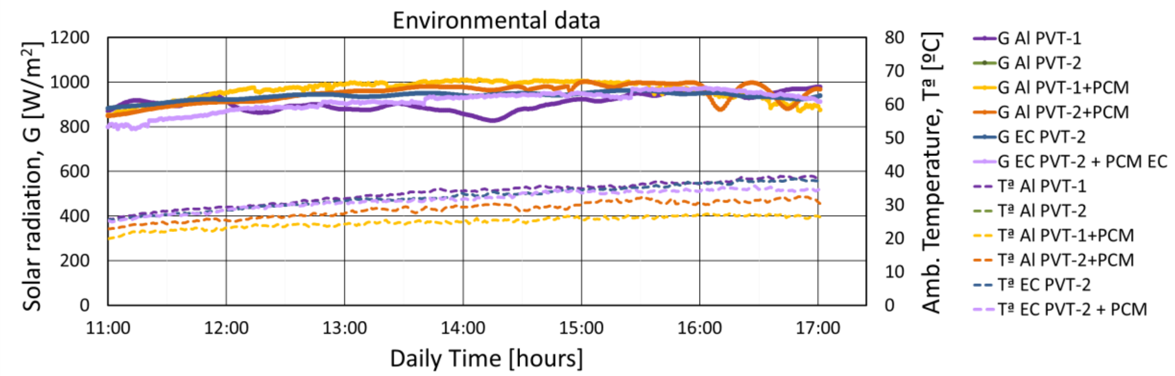

Figure 3: Environmental conditions on testing days.

Instantaneous heat power generated in each PV/T case throughout the testing day is shown in Figure 4. Based on this data, no significant differences are found with regard to the absorber type, with indicates similar thermal behavior for the two absorbers here considered.

In the case of the aluminum absorber, there is a noticeable difference between glazed and unglazed configurations. As expected, higher thermal power was generated in those cases with glass cover on the front side, reaching up to exceed in a 60% the generation of unglazed units. This difference becomes bigger when the working temperature of the panel increases at the secondary stable point, due to rise on thermal losses given on the unglazed units. At this point, the glazed cases reach to exceed the unglazed production in a 140%.

The incorporation of the PCM did not lead to a significant improvement on the thermal performance, but provoked some alterations on the heat power generation. First, the addition of 32 kg of PCM lead to increment the thermal inertia of the whole, which slowed down the temperature changes given on the panel, both in the beginning and the changing between stable points. Second, during the period between 12am to 3pm, cases without PCM reached to a stable point with quasi-constant heat power generation. However, cases with PCM showed a slow increment though time, reaching in some cases to higher values than the same model without PCM. Finally, the most relevant effect of the PCM is found at the end of the testing when the radiation is cut. At this moment, cases without PCM quickly recovered the initial state of null generation while cases with PCM exhibit a period of heat production, as a result of the energy releases in the PCM phase change. The amount of thermal energy releases is greater in the glazed configurations rather than the unglazed one, probably because the higher working temperature reached on the glazed cases allowed PCM to store more energy.

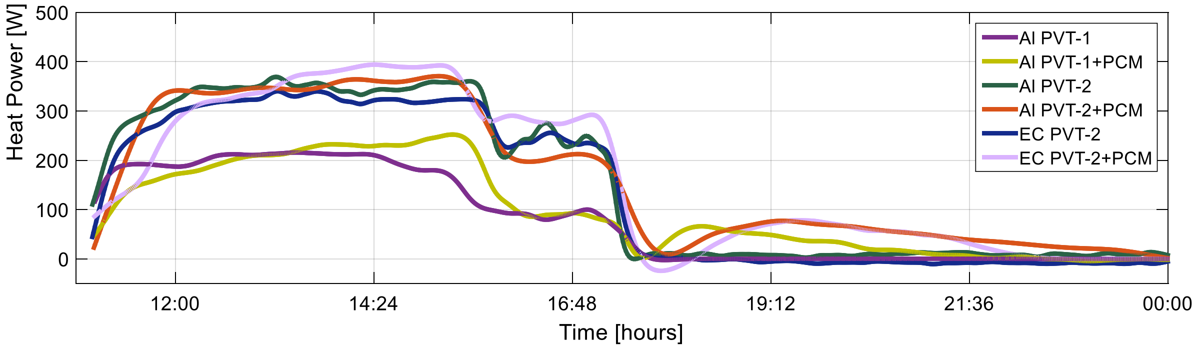

Figure 4: Daily distribution of heat power generation.

The melting point of the PCM varied from one case to other, because of its dependency on the operation temperature of the panel. Most of them however, reached the phase change temperature (48ºC) when changing from the first stable point to the second. PV/T working temperature during the second stable point surpassed 60ºC for all cases, which ensure the melting of the PCM attached to the absorber.

Total thermal energy generated for each case during the period of testing is shown in Figure 5. In this graph, values in bold refer to the total generation in Wh, including the period with sun radiation (from 11am to 5pm) and the period without it (from 5pm on). The deviation between glazed and unglazed configurations on the thermal production is easily visible here, as well as the PCM contribution to the total generation. No great differences are found between glazed models, even considering the disparity of absorber types.

The heat production resulting from the PCM was accounted for 135 Wh for the Al PVT-1 case, 263 Wh for the Al PVT-2 and 198 Wh for the EC PVT-2. PCM inclusion allowed to generate up to 30% of maximum thermal power values obtained during sun exposure in the unglazed case, and up to 25% in the glazed case.

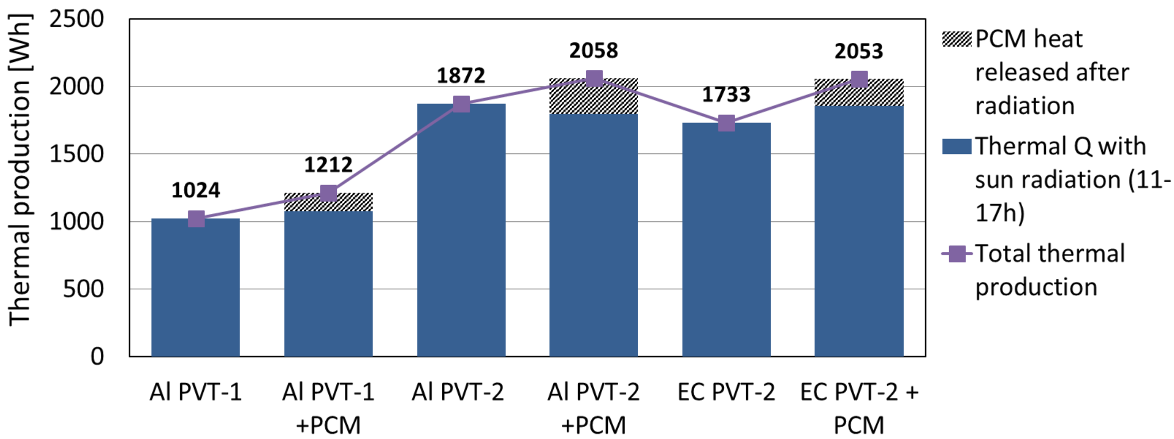

Figure 5: Total heat generated during the measurement period (11am- 5pm)

Besides the daily generation, we also have also evaluated the instantaneous electrical and thermal power generated in each case. To that end, we have calculated the average output during the stable period from 12am to 3pm and the respective efficiencies calculated from Eqs. (2) and (3). Graphical results are shown in Figure 6.

Electrical output was similar for all PV/T cases and it was ranged between 200 and 220 W. Electrical efficiencies, however, showed small differences and presented higher values for the unglazed configurations. This result is in concordance with previous studies found on PV/T (Besheer et al. 2016; Daghigh, Ruslan, and Sopian 2015) which underline the improvement on the electrical generation for the coverless panels. Efficiency values ranged 13-15%, which is in line with the typical efficiency given to the commercial p-Si cells in photovoltaic solar panels (Han et al. 2017; Hermann 1998; Islam et al. 2016).

Thermal output presented more differences between PV/T cases than the electrical part. As previously indicated, maximum values were found for the glazed configurations, which reached to work with a thermal efficiency much greater than the unglazed cases. This difference of the efficiencies is enlarged for higher working temperatures, where the capacity of the glass cover to reduce thermal losses is highlighted. In all cases, thermal efficiency values were lower than expected for typical PV/T panels (Al-Waeli et al. 2017; Zondag 2008), which suggest some thermal limitations on the test bench. Results are valid for establishing a comparison between models but further experiments are needed to fully characterize the thermal response.

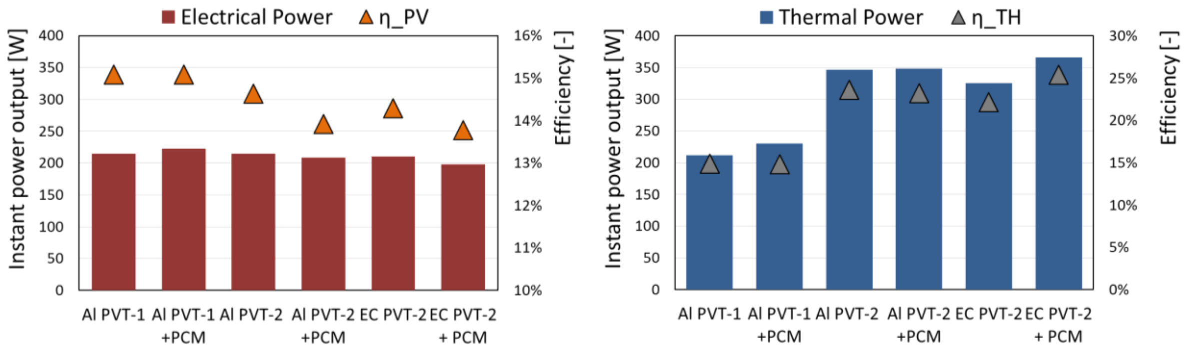

Figure 6: Electrical (left) and thermal (right) power and efficiencies during first stable period.

With the aim to compare the general performance of different PV/T cases, overall efficiency was estimated following the definition exposed in Eq (4). Values are shown in Figure 7. It should be noted that these performance values do not consider the heat generated by the PCM after the sun radiation, but only the efficiency ratios measured during the first stable period.

According to the overall efficiency, glazed configurations presented the best energy performance of the PV/T tested, despite the electrical benefits found in the unglazed aluminum cases. No relevant differences were found between cases with different absorber and the inclusion of the PCM did not seem to provoke changes on the overall efficiency. This assumption is based on the idea that deviations of 2% in the overall performance are not considered significant to assess differences.

Although the inclusion of the PCM did not directly affect to electrical and thermal efficiencies, it did allowed to redistribute the heat from the sun peak hours to the end of the day. As a result, a significant amount of heat it generated without any income of sun radiation. Moreover, the redistribution of the heat entails some benefits that are not directly reflected on the thermal or electrical performance. First, the PCM works as a storage element that can allow to reduce the thermal storage tank present in all PV/T installation, decreasing the initial investment of the end user. Besides that, it contributed to cushion the maximum working temperatures found in the PVT panel during sun exposure. This effect may be very beneficial in warm locations, since it prevents PV modules from overheating and contributes to extend the lifespan of PV/T panels.

In the authors‘ view, further studies focussig on the long-term PCM effect are needed to completely assess the benefits of this technique. With this in mind, an PV/T installation with PCM inserted is projected to take place in the south of Spain by next months to analized in depth the effect of this type of material on PV/T solar panels.

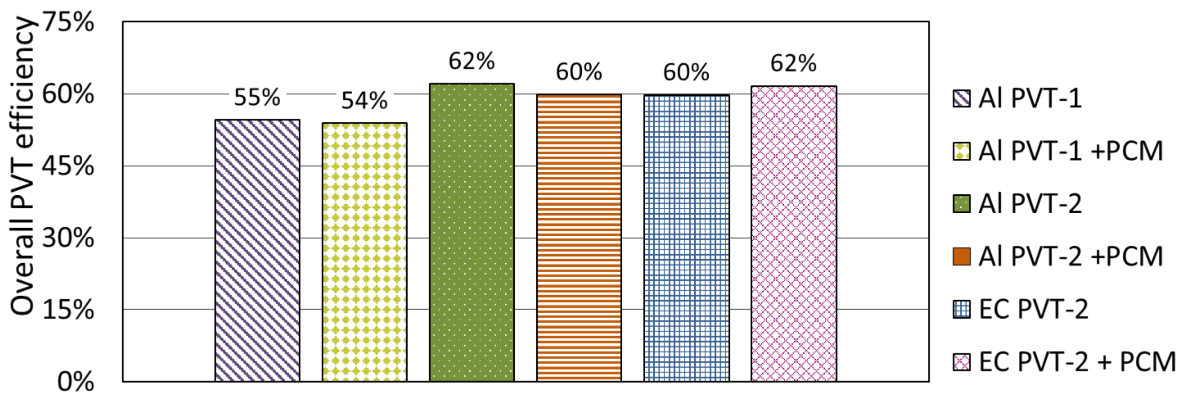

Figure 7: Overall performance measured during stable period.

4. Conclusions

In this work we evaluate the experimental performance of six PV/T panels. Two cases were carried out based on traditional sheet-and-tube copper heat absorber, glazed model with and without PCM, and the other four on roll-bond aluminum absorbers, glazed and unglazed, with and without PCM.

Result indicated similar energy production for the glazed configurations, independently of the absorber type. Greater differences were found between the glazed and unglazed configurations, where the coverless presented slightly better electrical efficiencies but meaningful lower thermal performance. This differences become greater with the increase on the working temperature, which mostly penalizes the unglazed PV/T models.

The addition of PCM did not lead to a direct improvement on the PV/T efficiency, but provoked a reallocation of the heat generation from the peak sun hours to the end of the day. This characteristic entails other benefits for the PV/T installation, such as reduction of the required storage volume or protection of prevention of the PV laminate from overheating. The long term effect of this protection would be the lifespan enlargement of the photovoltaic module and the whole PV/T installation, although further studies are needed to ensure that benefit.

5. Acknowledgment

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