

MATERIALS ASSESSMENT FOR PV-T MODULES THERMAL PERFORMANCE IMPROVEMENT

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ABSTRACT: Photovoltaic-thermal (PV-T) collectors integrate solar thermal and photovoltaic technologies into a single system, enabling simultaneous production of electricity and heat. The efficiency of PV-T collectors is directly linked to effective heat transfer through the system layers, which impacts overall thermal and electrical performance. This study evaluates the role of adhesives, the attachment media between the photovoltaic (PV) panel and the heat exchanger (HX); and insulating materials, which constitute the back-side of the PV-T panel, in optimizing heat transfer and improving the efficiency of PV-T collectors. Two small-scale prototypes were developed to test selected adhesives and insulations under real-world conditions. The investigation considers not only thermal performance but also economic feasibility, durability, and ease of manufacture. Final conclusions integrate experimental data with a one-dimensional Python simulation, identifying the most conductive adhesive and the most effective insulating material. The findings contribute to the development of a more efficient and cost-effective new PV-T collector design.

Keywords: Hybrid photovoltaic-thermal (PV-T) collector, adhesives, insulations, experimental testing, heat transfer modelling.

1 INTRODUCTION

Photovoltaic-thermal (PV-T) collectors combine solar thermal and photovoltaic technologies in a single panel, producing electricity and heat simultaneously. This hybrid technology may be used for diverse applications, such as pool heating, domestic hot water production, and heat production at low temperature for industrial processes (Herrando et al., 2014; Kalogirou & Tripanagnostopoulos, 2006). However, the temperature requirements of the final application also determine the most suitable PV-T collector type for each case (Herrando et al., 2014; Ramos et al., 2017). PV-T collectors usually have a photovoltaic (PV) laminate and an absorber or heat exchanger (HX), through which thermal energy is extracted.

This work aims to study the influence of different materials on the heat transfer along the PV-T collector, focusing on the impact of the attachment media between the PV panel and the absorber, as well as the back insulation of the PV-T modules.

PVT collector materials have direct impact on heat transfer through layers and, therefore, are related to the energy performance of the PV-T collector (Abdelrazik et al., 2018; Michael et al., 2015; Zhang et al., 2012). Thermal performance is conditioned by the heat transfer between the PV and the HX, as well as by keeping the PV-T panel isolated to avoid ambient losses (Herrando et al., 2019; Joshi & Dhoble, 2018). Moreover, PV panels reduce its performance ratio operating at high temperatures. Extracting heat to the heat exchanger also raises the electrical performance (Dubey et al., 2013; Rawat et al., 2017).

The final objective of the study is to assess the most adequate materials for a new PV-T collector design, in order to maximize the heat transfer through all the layers and, in consequence, its thermal and electrical efficiency. Economic and durability aspects will be additionally considered in the assessment, as well as each material's handling, especially for adhesives, in order to facilitate the PV-T collector manufacturing as much as possible.

2 EXPERIMENTAL SETUP DESCRIPTION

2.1 Prototypes

Two small-scale prototypes are prepared and evaluated in order to determine the suitability of the materials in terms of heat transfer and insulation performance.

A range of materials (both adhesives and insulations) have been reviewed and two sets have been selected for the testing. Apart from the costs, which have been used for both; application modes, ease of handling during manufacturing and thermal conductivity (ranged between 0.18 to 3.40 W/m·K) have been used as criteria for choosing adhesives, while insulations have been selected based on the thermal insulation properties (from 0.025 to 0.037 W/m·K), their physical characteristics and handling. **Table I** describes each prototype and its tested materials.

Each prototype consists of a PV panel with four test probes made of the material to be tested along with the absorber, each one sized 30x30 cm. Each prototype has the same layer structure (PV panel, adhesive, absorber, insulation and backsheet). **Figure 1** shows Prototype 1 disposition in detail.

Prototype 1 tests four back insulations, with the PV attached to the HX with the same adhesive, while Prototype 2 tests four adhesives, maintaining the same insulation. Both prototypes contain a glass-glass PV panel (unglazed PV with a laminated glass in place of the tedlar backsheet). The PV panel incorporates N-type and TOPCon cell technology, with 600 Wp of maximum power and a 22.21% of efficiency at STC.

Table I: Prototypes 1 and 2 description

Prototype 1 - Insulations		
Probe	Thickness (m)	Thermal conductivity (W/m·K)
1	0.025	0.037
2	0.025	0.032
3	0.025	0.025
4	0.030	0.025
Prototype 2 - Adhesives		
Probe	Thickness (m)	Thermal conductivity (W/m·K)
5	0.00013	0.16
6	0.00013	0.18
7	0.0002	1.5
8	0.002	3.4

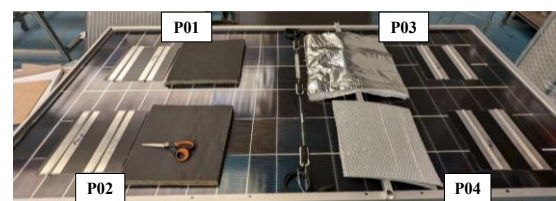


Figure 1: Prototype 1 design and assembly

2.2 Test procedure

In order to measure and analyse heat transfer performance, temperature sensors are placed in each prototype. Only heat transfer due to solar radiation is being taken into account; thus, thermal and electrical circuits are disconnected. Experimental tests are performed in Zaragoza, Spain (latitude 41.716), during winter months. Prototypes are tested under natural conditions, exposed to a quasi-constant solar in-plane irradiance between 300-420 W/m² (horizontal). Panels are placed in horizontal 120 cm height benches.

Pt100 temperature sensors are distributed in each layer to measure every prototype: two under the PV laminate, two between the absorber and the insulation for each probe, one in the back side of the insulation for each probe. Therefore, each prototype counts with 15 precision probes (described in **Figure 2**). An additional methacrylate layer is added to the probes to fasten the assembly of all the materials and ensure a proper contact between components.

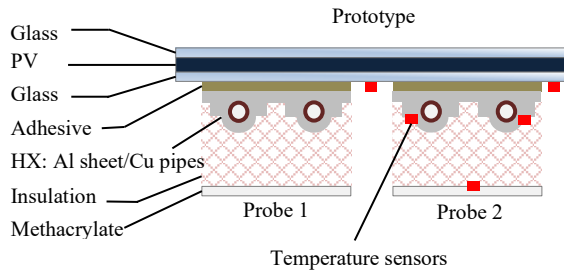


Figure 2: Prototype layers and temperature sensors distribution

Environmental data (irradiance, ambient temperature and wind speed) are also measured (see **Table II**) and registered with a frequency of 1 min in a PLC Modicon 241. Each test is performed at least for 2 days with similar weather conditions and 4 days in total. The test starts when the panel is exposed to sun and lasts at least one hour. The first 30-40 minutes of exposure are intended to allow the prototypes to acclimatize until they become stable. All temperature sensors measured the same value before exposing the panel to the sun.

Table II: Instrumentation and sensors

Physical property	Sensor model	Range	Precision
Temperature	Pt100	-50-400 °C	± 0.05 °C
Irradiance	Pyranometer, LP-PYRA-03 AC	0-2000 W/m ²	± 0.025 W/m ²
Wind velocity	4.3303.22.007, Thies Clima	0-50 m/s	± 0.3 m/s

2.3 One-dimensional simulation

One-dimensional model is developed using Python for simulating temperatures in each layer of the PV-T collector and prototypes. This simulation is intended to be validated with the experimental data, in order to implement it in a more complex model for estimating PV-T panel efficiency and both electrical and thermal productions.

Figure 3 shows the PV-T layer configuration and the energy flows considered.

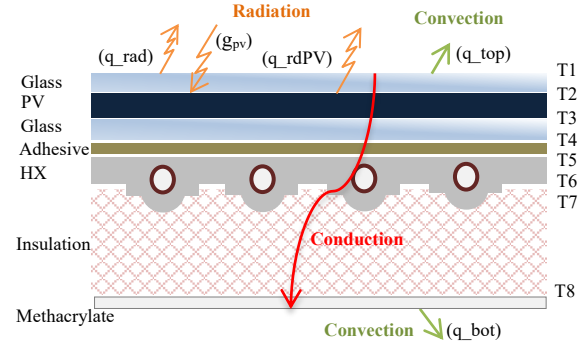


Figure 3: PV-T collector layers and energy flows

The PV-T collector model is developed under the following assumptions:

- radiation absorption in the glass layer and the collector frame is negligible; (Agarwal & Garg, 1994; Herrando et al., 2019)
- the ambient temperature is uniform around the collector and heat losses from the PV panel frame and the borders of each probe are negligible (Cristofari et al., 2009; Notton et al., 2005);
- the PV cells and the thermal absorber are in perfect thermal contact; (Herrando et al., 2019)
- solar irradiance and wind speed are uniform over the collector surface area. (Herrando et al., 2019)

The model is run under steady-state conditions (Herrando et al., 2019; Zondag et al., 2003). Energy conservation equation is used for defining heat transfer through layers. In addition, there is no fluid running into the copper tubes so there is no thermal energy generated and the electric circuit of the PV panel is disconnected, so there is no electricity production. Above all these assumptions, boundary conditions for these equations are detailed below:

Top Layer. The main losses on the top of the PV-T collector are due to forced convection caused by wind (q_{top} , see eq. (2)) and radiation from the glass to the sky (q_{rad} , see eq. (3)). The convective heat transfer coefficient depends on wind velocity (v_{wind}) and various expressions are given in bibliography for its estimation. In previous works (Bhattarai et al., 2012; Notton et al., 2005; Rejeb et al., 2015) for similar applications, validated with experimental data, expression showed in eq. (1) provided accurate values. Initially, the model is based on this experimentally obtained h_{wind} approximation, but has been adjusted according to the results of the tests. Hence:

$$h_{wind} = 4,2 + 2,9 \cdot v_{wind} \quad (1)$$

$$q_{top} = h_{wind} \cdot (T_{glass} - T_{amb}) \quad (2)$$

$$q_{rad} = \varepsilon_{glass, long\lambda} \cdot \sigma \cdot (T_{glass}^4 - T_{sky}^4) \quad (3)$$

where T_{glass} is the glass temperature in the above surface, T_{sky} is the sky temperature, which is calculated as $T_{sky} = 0.0552 \cdot T_{amb}^{1.5}$, with the ambient temperature (T_{amb}) in Kelvin, $\varepsilon_{glass, long\lambda}$ is the glass emissivity at long wavelengths and σ is the Stefan-Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}$ W/(m²·K⁴)) (Cristofari et al., 2009; Notton et al., 2005).

PV layer. The PV layer absorbs the fraction of the total solar irradiance (G_{inc}) that is not reflected by the glass (g_{pv}), calculated as:

$$g_{pv} = G_{inc} \cdot \tau_{g, short\lambda} \cdot \alpha_{PV, short\lambda} \quad (4)$$

where $\tau_{g,short\lambda}$ is the transmittance of the glass while $\alpha_{PV,short\lambda}$ is the absorptivity of the PV panel, both at short wavelengths (Tiwari & Sodha, 2006; Zondag et al., 2003).

The radiative heat flux emitted by the PV layer at long wavelengths, which is not absorbed by the glass, is lost to the environment. This radiative heat loss (q_{rdPV}) can be estimated as follows:

$$q_{rdPV} = \varepsilon_{PV,long\lambda} \cdot \tau_{g,long\lambda} \cdot \sigma \cdot (T_{PV}^4 - T_{sky}^4) \quad (5)$$

where T_{PV} is the temperature of the PV layer, $\tau_{g,long\lambda}$ is the transmittance of the glass and $\varepsilon_{PV,long\lambda}$ is the emissivity of the PV layer, both for long wavelengths (Tiwari & Sodha, 2006; Zondag et al., 2003).

Back insulation layer. The main loss in the back layer of the PVT collector is due to forced convection caused by wind (q_{bot} , see eq. (6)), calculated similarly to q_{top} :

$$q_{bot} = h_{wind} \cdot (T_{metha} - T_{amb}) \quad (6)$$

where T_{metha} is the temperature in the bottom side of the methacrylate layer.

Heat conduction. For every layer, it is considered perfect thermal contact, which allows a heat flow from the hottest layers to the coolest, in contact with the ambient. For every layer, heat conduction equation is defined as:

$$q_{layer,a} = \frac{k_a}{\delta_a} \cdot (T_{a,in} - T_{a,out}) \quad (7)$$

where k_a is the thermal conductivity coefficient of the layer, δ_a corresponds to the thickness of each layer and $T_{a,in}$ and $T_{a,out}$ relay to the temperatures in the top and the bottom of each layer. The top temperature of each layer is the bottom of the one above, due to the assumptions made previously.

Introducing environmental data (wind velocity, irradiance and ambient temperature) in the one-dimensional model, temperatures in each layer and heat fluxes between them are obtained. Conduction, convection and radiation can be studied as well as the heat and energy losses to the ambient. For comparing both experimental and simulated temperatures, only results from the moment the system has stabilized onwards are considered.

The model also included T_{cell} , the theoretical temperature of the PV cells (Hajji et al., 2014; Santos et al., 2022), calculated as:

$$T_{cell} = ((T_{NOCT} - 20) / 800) \cdot G_{inc} + T_{amb} \quad (8)$$

where T_{NOCT} is the nominal operating cell temperature, characteristic of each PV panel.

A statistics analysis is additionally performed in order to evaluate the numerical goodness of the simulation. The Percentage Error is calculated for the period in which panel temperature is already stabilized.

$$Percentage\ Error = \frac{|y_{exp} - y_{sim}|}{y_{exp}} \cdot 100 \quad (9)$$

Table III: Properties of the PVT collector layers

Layer Parameter		Wavelengths	Value	
Top layer	$\varepsilon_{g,short\lambda}$	Emissivity (-)	Short	0.05
	$\tau_{g,short\lambda}$	Transmittance (-)	Short	0.94
	$\varepsilon_{g,long\lambda}$	Emissivity (-)	Long	0.86
	$\tau_{g,long\lambda}$	Transmittance (-)	Long	0.06
PV layer	$\alpha_{PV,short\lambda}$	Solar absorption coefficient (-)	Short	0.95
	$\varepsilon_{PV,long\lambda}$	Emissivity (-)	Long	0.89

3 RESULTS AND DISCUSSION

Experimental tests have been conducted for **Prototype 1** and **Prototype 2** to analyse the influence of the four insulations and four adhesive materials on heat transfer with a glass-glass PV. The results obtained provide qualitative information on the performance of each test sample. Figures containing the results are discussed below. Temperatures of the probes are represented in Celsius. Each Figure contains the collector absorber temperatures of each probe, simulated (solid lines) and experimental (dashed lines), as well as environmental (T_{amb}) and cell (T_{cell}) temperatures.

3.1 PV temperatures comparison

Both experimental and simulated results have been analysed firstly considering only the PV layers, taking temperatures from the free PV area where there are no heat exchanger nor material probes. **Figure 4** and **Figure 5** show experimental and simulated PV panel temperatures, as well as ambient temperature and theoretical PV cell temperature.

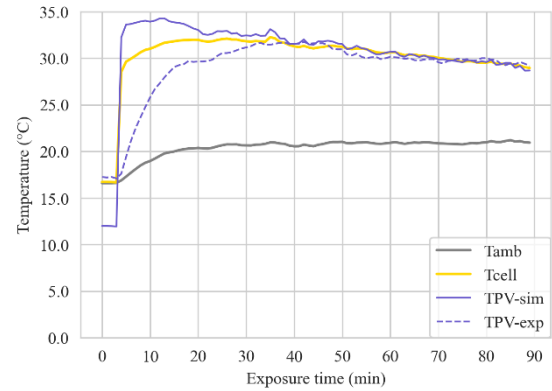


Figure 4: PV panel temperatures. Windless day

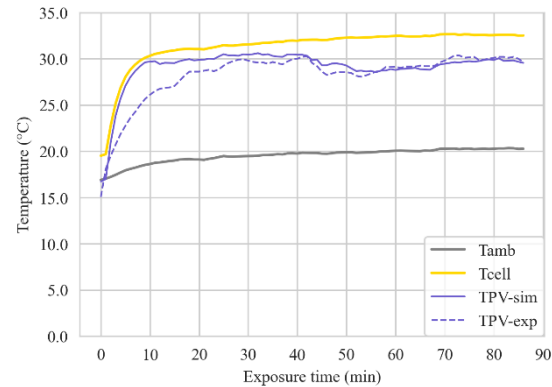


Figure 5: PV panel temperatures. Windy day

In these figures, simulated values do match experimental data, which means the one-dimensional simulation can reproduce experimental temperatures and heat transfer fluxes through the PV panel layers. However, it can be noticed that the simulated results do not match the first few minutes of the experimental tests, in which the panels are still acclimatizing. This is explained because the one-dimensional model has no inertia, unlike the experimental data, as it is performed under steady-state conditions.

It is significant to notice differences in the theoretical

temperature of the PV cells between windy and windless days. During windless or very low wind days T_{cell} matches both experimental and simulated PV temperatures once they are stabilized; however, this matching does not exist in windy days, where the T_{cell} is higher, due to the fact that T_{cell} definition does not take into account wind effect.

3.2 Insulating materials comparison

Small-scale tests were conducted for Prototype 1 in order to determine which insulation kept more heat inside the absorber.

Temperatures of the heat exchanger are represented for the four insulating materials (**Table I**). T_{1-exp} - T_{4-exp} correspond with the mean of both temperature sensors placed inside the **heat absorber** (see **Figure 2**) for each probe. **Figure 6** shows results for a test performed with windless weather conditions while **Figure 7** shows results obtained during a windy day.

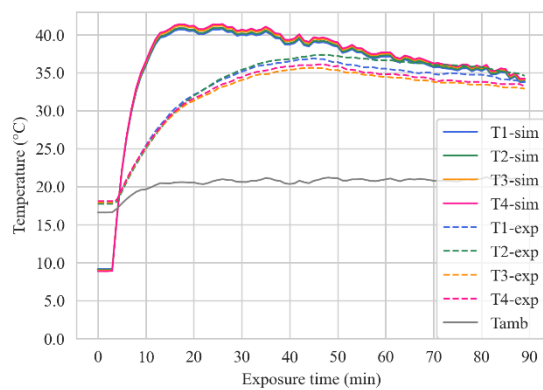


Figure 6: Prototype 1 heat absorber temperatures for each probe. Windless day

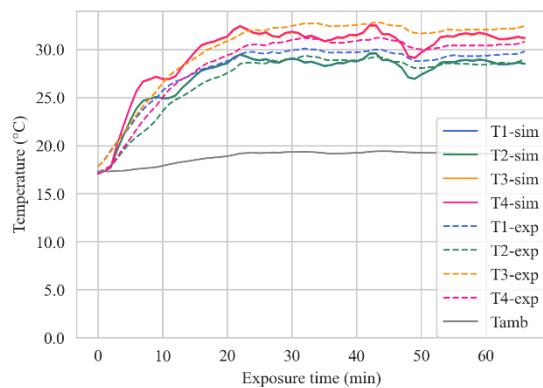


Figure 7: Prototype 1 heat absorber temperatures for each probe. Windy day

Experimental results reveal higher temperatures during windless days in probes 1 and 2, with a difference of 2,5 °C with probes 3 and 4; while this difference between probes is barely noticeable for simulated results.

On the contrary, on windy days (more than 4 m/s) probes 3 and 4 are the ones reaching higher temperatures during experimental tests. Moreover, temperature differences between probes are bigger (~ 5 °C). This can be explained because wind affects to the results and alters heat transfer depending not only on wind speed, but also direction and prototype orientation. Probes 1 and 2 are being penalized due to their orientation and location in the panel. Observing results from different windy days based

on wind direction and the location of the probes in the panel, it is conclusive that the assumption of wind speed being uniform over the collector surface area is not valid. A new model for wind speed over a flat-plate surface has been designed for recalculate the convective heat losses due to the wind in the entire surface of the PV-T collector, considering probes distribution and prevailing wind. This new convective heat transfer coefficient has been included as an enhancement of the first simulation approach. The results of this new model show two distinct curves for the probes facing the wind directly (1 and 2, more affected by the wind) and indirectly (3 and 4, less affected) (**Figure 7**). This differentiation fits better with the experimental data.

As in the PV temperatures, the one-dimensional simulation can predict quantitatively thermal changes, heat fluxes and layer temperatures, although simulated data do not reproduce the first minutes of experimental data, in which real temperature sensors have inertia and a period of acclimation. Moreover, the simulation is considerably sensitive to radiation and wind, whose changes are straight reflected on simulated results.

Overall, insulating materials contained in probes 1 and 2 have better heat performance, reaching higher temperatures during windless days.

3.3 Adhesive materials comparison

The following **Figure 8** and **Figure 9** show results obtained from adhesives small-scale tests (Prototype 2) for low and high wind speed respectively. Temperatures (T_{5-exp} - T_{8-exp}) represent the mean temperature inside the **heat absorber**, for each material (Probes 5-8, **Table I**).

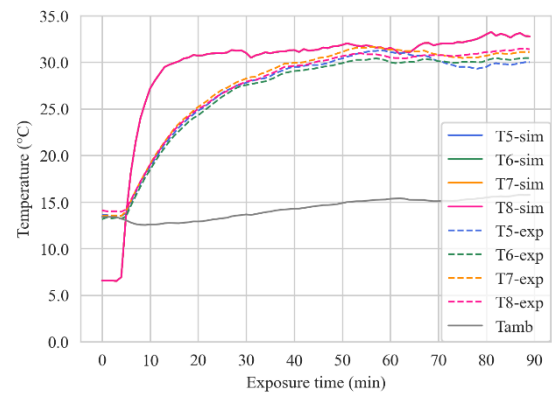


Figure 8: Prototype 2 heat absorber temperatures for each probe. Windless day

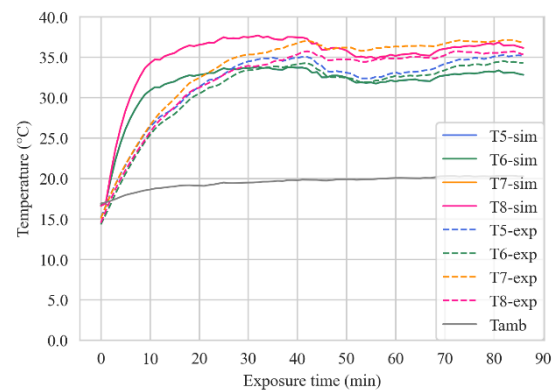


Figure 9: Prototype 2 heat absorber temperatures for each probe. Windy day

Figure 8 shows differences of less than 2 °C between probes during a windless day test, while for a windy day test in **Figure 9**, the differences of temperature between probes are higher, around 5 °C. As it happened with insulating material tests, temperature results on windy days are more affected by the wind depending on probe location, regarding the wind direction, in the adhesive's comparison tests.

Probe 7 and probe 8 reach higher temperatures in both tests. Probe 8 attaching media is a thermal paste with higher conductivity; however, its handling and applicability were a disadvantage against the double-face adhesive of probe 7.

As in the previous sections, the one-dimensional simulation can predict quantitatively layer temperatures and heat transfer, although simulated data do not reproduce the inertia of the temperature sensors. The simulation remains sensitive to radiation and wind, with the improvements included.

Overall, differences between adhesives during windless days, when results are not affected by probe location regarding

wind distribution above flat-plate, are not as significant as in the insulating material tests. Heat transfer depends on the thickness and thermal conductivity of materials, in particular for adhesives, where the thicknesses are very low, no appreciable differences are measured in the experimental tests. Other criteria, as ease of handling, prices, sustainability and lifetime are taken into account for choosing the ideal adhesive for the PV-T design.

3.4 Numerical assessment of 1D simulation

Percentage Error has been calculated in order to evaluate numerically the assessment of the one-dimensional model, comparing simulated results with the experimental values measured.

Table IV shows this indicator obtained for each scenario. In all the comparison tests, a Percentage Error of less than 8.0 % is obtained, so it can be concluded that the one-dimensional simulation is capable of predict reliable numerical data within that measurement range.

Table IV: Average Percentage Error values for each comparison test.

	Windless days	Windy days
PV	1.5 %	1.3 %
Prototype 1		
Probe 1	2.9 %	2.5 %
Probe 2	1.4 %	1.3 %
Probe 3	7.3 %	2.6 %
Probe 4	6.6 %	3.4 %
Prototype 2		
Probe 5	6.1 %	4.1 %
Probe 6	6.6 %	2.3 %
Probe 7	3.6 %	2.4 %
Probe 8	4.2 %	1.8 %

4 CONCLUSIONS

Following conclusion can be resumed from this work:

- The experimental study shows no significant differences between adhesives, but does show between insulations.
- Insulations in probe 1 and 2 are chosen because of the experimental results during windless days and its ease of installation and handling.

- Experimental results are highly dependent of the wind direction and the location of the probe in the panel. Forced heat convection in flat plate should be studied and taken into account in future studies or experiments.
- The one-dimensional simulation can reproduce experimental temperatures and heat transfer fluxes through the PV-T panel layers.
- The Percentage Error between simulated and experimental data remains under 8.0% in every comparison test.

5 ACKNOWLEDGEMENTS

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