Modelling, Simulation and Experimental Study of a Hybrid Photovoltaic-Thermal Collector (PVT)

Carlos A. Figueiredo Ramos[1,2], Adérito N. Alcaso[1,2]
and Antonio J. Marques Cardoso[1]
[1]CISE – Electromechatronic Systems Research Centre,
University of Beira Interior, Calçada Fonte do Lameiro,
P – 6201-001 Covilhã, Portugal
[2]Polytechnic of Guarda, Guarda, Portugal
framos@ipg.pt, aderitona@ipg.pt, ajmcardoso@ieee.org

Abstract

Solar energy is among the renewable energies with the highest growth potential in the world. From this primary energy source, one can obtain electrical or thermal energy through different conversion methods, either using the photovoltaic panel or the thermal collector, respectively. The photovoltaic-thermal (PVT) collector is a hybrid solar device that combines, in the same equipment, an electrical energy production module (photovoltaic module) with a thermal energy production module (thermal module). However, the PVT does not have the same maturity as the photovoltaic panels or the thermal collectors that are independently available on the market. As an emerging equipment, it still needs to be further studied and developed, namely in its modelling, among other aspects. This work focuses on a numerical investigation of the PVT technology, with the goal of evaluating how computational mathematical models predict the operating scenarios of an experimentally studied PVT unit. As such, acquired experimental data was analised against simulations of energy and mass balances. The model was validated for the same conditions of the experimental tests, therefore determining the degree of agreement with the data acquired experimentally. A very good general agreement is observed between the simulated and experimental results.

Keywords
Photovoltaic-Thermal solar collector, Energy balance, Photovoltaic model, Mathematical models.

1. Introduction
The energy captured from the sun, solar energy, is one of those considered as renewable, from which electrical and thermal energy can be obtained through conversion devices. The hybrid solar collector, called photovoltaic-thermal collector (PVT), is an equipment that simultaneously produces heat and electricity by converting solar energy. Generically, the structure of the PVT is composed of photovoltaic (PV) and thermal modules together in a single device. The cooling of the solar cells by the thermal module fluid increases their efficiency, while at the same time there is heat absorption through the same working fluid, which can be used in other processes. The PVT performance can be evaluated through experimental and numerical tests. A flat plate PVT without coverage was used in the study, supported by an electrical and thermal systems infrastructure, which was properly instrumented in order to obtain climatic data (incident solar radiation, ambient temperature and wind speed), the mass flow rate of the thermal fluid, temperatures at various points of interest in the equipment, voltage, and current. The present work is based on the evaluation of a proposed mathematical model to simulate the behavior of the PVT, and thus be able to optimize its performance. This numerical model implemented in a MATLAB-Simulink environment takes into account thermal energy balances in each of the PVT components and the equivalent circuit of the solar cell. This model not only allows for the calculation of electricity and heat production, but also for understanding the general behavior of the collector, under different environmental and operational conditions. A very good overall agreement is observed between the simulated and experimental results, noting that the greatest difference between these values is around 2.3%. As a general conclusion, it can be said that the proposed model is a reliable tool for studying the performance of PVTs.

2. Literature Review

2.1 Solar Energy

The Sun is a huge nuclear reactor of continuous fusion, where the nuclear reactions taking place are at the origin of the energy emitted into space. However, only a small fraction of this energy reaches the earth's crust, which would still be more than enough to solve humanity's energy problems, if it were possible to use this energy efficiently. In fact, it would only be necessary to use about 0.01% of the solar energy that reaches the Earth to satisfy the total energy demand of the world (Duffie and Beckman 2006). The total amount of solar radiation, with its high value, contrasts with global energy consumption and fossil fuel reserves which, in turn, are expected to run out in the coming decades of the current century if their exploitation continues at the same rate (Lupu et al. 2018).

Solar radiation is concentrated in a range of short wavelengths of the electromagnetic spectrum and about half of the radiant energy emitted by the Sun is in the form of visible light, with the remainder in the form of ultraviolet and near infrared radiation. Most of the solar energy at the limit of Earth's atmosphere is in the wavelength range of 0.25 to 3 μm, while at the Earth's surface is mostly in the range of 0.29 to 2.5 μm. This difference in the wavelength range of solar radiation between the boundary of the atmosphere and the Earth's crust is due to atmospheric reflection of solar radiation, absorption by molecules in the atmosphere, Rayleigh dispersion (molecular dispersion) and Mie dispersion (dispersion by dust particles and air pollution) (Ramos 2022). In the Earth's crust, where ultraviolet, visible and near infrared radiation is observed, the maximum spectral density occurs for a wavelength of 0.55 μm (Duffie and Beckman 2006), which corresponds to a yellowish-green visible light.

2.2 Spectral Response

The global solar radiation that shines over a body on the Earth's surface, such as equipment for harnessing solar energy, is composed of direct solar radiation, which is received from the Sun directly without being dispersed by the atmosphere, by the diffuse fraction, which is originated by its dispersion in the atmosphere, and by the component reflected by the ground and by all existing bodies in the vicinity.

Depending on the material and technology used, solar cells have a different efficiency in converting solar energy into electrical energy. These cells have a spectral sensitivity that not only dictates their efficiency under different radiation conditions, but also defines the radiation range for which the operating efficiency is maximum. Can be observed that the range of solar radiation for which the solar cell reports the best performance does not overlap with the wavelength interval for which solar radiation is maximum (Coulson 1975). The range of wavelengths of the solar spectrum for which photovoltaic conversion takes place is between 0.3 and 1.2 μm, that is, essentially in the range of visible radiation and part of the near infrared radiation. Infrared radiation with a wavelength greater than 1.2 μm will heat the solar cell and consequently reduce its efficiency, but without generating electrical energy.

2.3 The Hybrid Photovoltaic-Thermal Technology

One of the drawbacks associated with PV technology is its reduced performance, requiring, therefore, large areas of implantation, which can be an important limitation for its greater globalization. Furthermore, and as is known, the incidence of solar radiation in solar cells based on silicon technology increases their temperature, thus reducing their electrical efficiency. The decrease of electrical efficiency with temperature is given by (Kalogirou and Tripanagnostopoulos 2006; Skoplaki and Palyvos 2009). The natural convection cooling of these cells by their surroundings may not be sufficient to reduce their temperature and obtain maximum performance. To overcome these inconveniences, one may consider the integration of the PV module with a thermal module in a single device, the PVT, in order to convert solar energy into electrical and thermal energy simultaneously.

The main objective of this integration is to convert more energy per unit area, compared to independently installed PV modules and thermal collectors. The PVT is therefore a cogeneration equipment, in which the electrical and thermal modules form an equipment built in such a way as to transfer heat from the PV cells to a thermal fluid, resulting in the cooling of the cells and consequently in improvement of their electrical performance and extending its useful life. Recognizing the potential of this type of solar technology, the International Energy Agency (IEA) created a working group, "Task 35 - Solar PV/Thermal Systems", during the period from 2005 to 2007, in order to evaluate and increase knowledge of this type of technology and, at the same time, contribute to its introduction in the global market, as a quality and commercially competitive product. After this period, the IEA created a new group, called

"Task 60 - PVT Systems", with an expected duration of 2018 to 2020, with the aim of continuing the work of the previous group.

The types of solar technology are explained in Hofmann et al. (2010) and Ramos et al. (2019), where PVT types are distinguished. Thus, and taking into account applications from low to high temperature, PVT collectors can be classified as flat plate or concentration. Both types of collectors can use water or air as thermal fluid, or they can use these two fluids simultaneously. Flat plate PVTs may or may not have an additional glass cover in its construction, thus distinguished as PVT with and without coverage, respectively. The PVT with additional coverage will contain a layer of air between it and the PV module, thus increasing the temperature, due to the greenhouse effect, and therefore the thermal efficiency, to the detriment of the electrical efficiency of the PVT. On the other hand, the PVT without additional glass gives priority to electricity generation. PVT concentrators have as their main objective the concentration of solar radiation in a given area (receiver and absorber with thermal exchange fluid), through reflection devices (mirrors), in order to increase the amount of solar radiation shining on the PV cell (Coventry 2005; Smeltink and Blakers 2006). These collectors are used in situations where it is necessary to obtain high temperatures. The areas of application of PVT technology are, among others, space heating, water heating and drying (Said et al. 2018).

In the field of modelling and simulation of PVTs, the analytical model by Hottel and Willier (1958) for flat plate thermal collectors was applied by Florschuetz (1979) in PVT collectors, concluding that their behavior in terms of heat transfer can be considered identical to the first ones. Bergene and Lovvik (1995) proposed a model to analyse the performance of PVT collectors based on energy transfer analysis. Sopian et al. (1996) analysed the performance of an air PVT collector using a steady-state model. Zondag et al. (2002) developed numerical models for the behavior of PVT collectors, namely a dynamic three-dimensional (3D) model and three non-dynamic models in 3D, 2D and 1D. It was concluded from the study that for the calculation of efficiency curves the simplest model, a one-dimensional model, results satisfactorily. Sandnes and Rekstad (2002) developed an analytical model for PVT collectors, modifying Hottel and Willier's model for flat plate collectors, adding the additional effect of photovoltaic cells. They obtained a good agreement between the simulation and the experimental results.

3. PVT System Structure

The work presented herein took place at CISE | Electromechatronic Systems Research Centre, in its field GIRS-RES | Guarda International Research Station on Renewable Energies. Numerical analysis and experimental tests were carried out on a flat plate PVT without additional glass cover, where thermal fluid was a mixture of water and antifreeze fluid. Figure 1 shows the PVT in study, in its overall scheme (a) with the structure of the equipment and the partial schematic of the thermal module (b). In the PV module, the glass cover has low iron and the contact film between glass and solar cells is EVA (*Ethylene Vinyl Acetate*), and EVA+Tedlar (*Polyvinyl Fluoride*) under the cells. The tubes and thermal plate (absorber plate) are in copper, the latter painted with a selective coating where the cells are placed. In order to avoid heat losses, the sides and back of the PVT are thermally insulated.

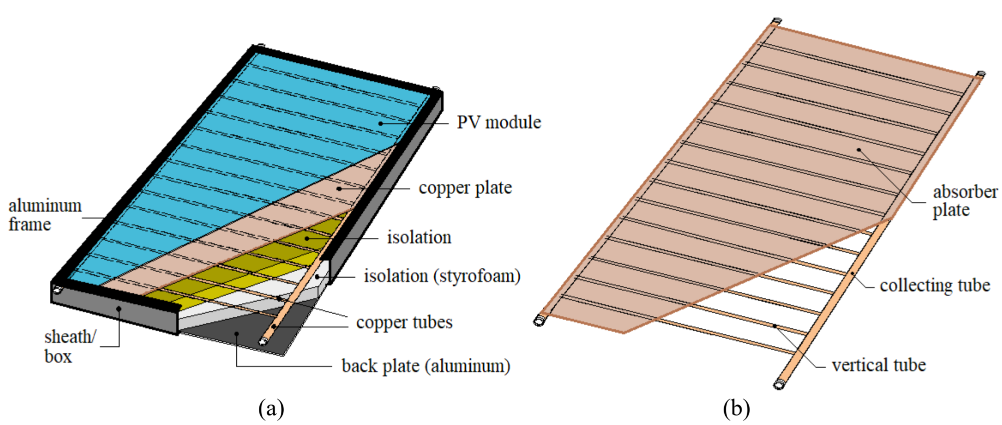


Figure 1. Scheme of the studied PVT: (a) overall scheme; (b) partial schematic of thermal module

The main characteristics of PVT are as follows: the PV cell technology is monocrystalline, the solar radiation reception area is 1.6 m^2, the maximum electrical power is 190 W, the current at maximum power and short-circuit current are, respectively, 5.2 and 5.6 A, the voltage at maximum power and open circuit are, respectively, 36.4 and 45.2 V and the maximum thermal power (for values of solar radiation of 1000 W/m^2 and wind speed of 0 m/s) is 629 W. From the data it is concluded that the PVT has a nominal electrical efficiency of 11.9%. The PVT was installed at an angle of 35º relative to the horizontal (site latitude Φ = 40.5425º) and was oriented towards the South (site in the Northern Hemisphere). Figure 2 shows the schematic of the PVT system together with the thermal and electrical subsystems, and the control and monitoring of all measured values. Real-time values were acquired at every second, with the aim of checking their variation over time.

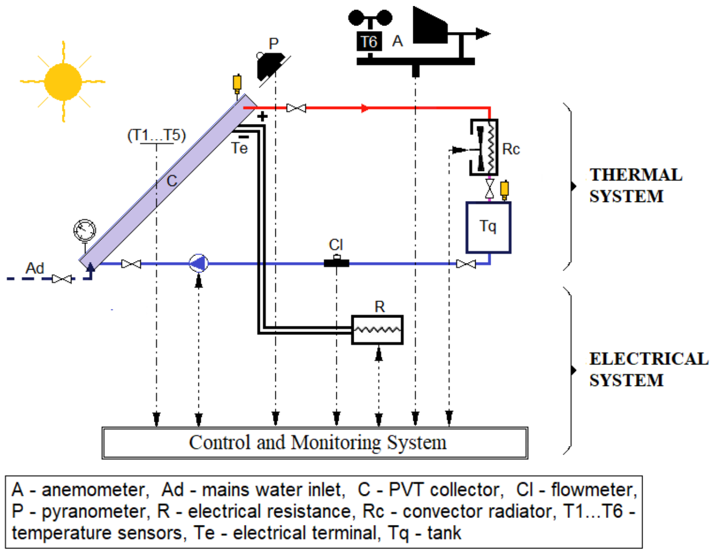


Figure 2. Scheme of the thermal and electrical subsystems of the PVT and of the system's control and monitoring

4. Mathematical Model of PVT

The mathematical model was developed with thermal balance equations in the different components of the collector for thermal part, assuming a uniform distribution of the thermal fluid inside the collector tubes, and for its electrical part it integrates a current source and a resistive load. The simulation was performed in the MATLAB-Simulink environment and the mathematical model will be later validated with experimental data. The respective instantaneous efficiencies of the PVT, namely the electrical and thermal efficiencies are obtained as follows, respectively, $\eta_e = P_e/(G.A) = (U.I)/(G.A)$ and $\eta_{th} = (\dot{m}.C\ (T_o\text{-}T_i)/(G.A))$, where P_e is the electrical power, U is the voltage, I is the electric current, G is the solar radiation, A is the solar cell area, $\dot{m}$ is the mass flow rate of the thermal fluid, C is the specific heat of this fluid, To and Ti are the outlet and inlet temperatures of PVT, respectively. The instantaneous total efficiency of a PVT is the sum of its electrical and thermal efficiency and can be defined by the following equation: $\eta_{total} = \eta_e + \eta_{th}$.

4.1 Considerations for Model Development

In this point, a mathematical model is developed for further simulation of the forced circulation PVT collector, based on the analysis of the energy balance, which includes photovoltaic conversion, thermal conduction, convection and radiation. The main heat exchanges, which result in gains or losses of heat for each component of the PVT collector, are due to the combined action of the basic phenomena of heat transfer, with some thermal phenomena resulting from the non-idealities of the electrical phenomena associated with resistive effects.

The energy balance is carried out in the various components of the PVT collector, namely in the glass cover, in the photovoltaic plate, in the thermal plate, in the tube, in the insulation layer and in the thermal fluid that circulates through the pipe. The EVA and Tedlar films will also have the same treatment, which, although they are very thin films and not considered in most works on the subject, have been shown to have an influence on the absorptivity and transmissivity of solar radiation. For the final model of the collector, the following assumptions will be considered, in order not to increase the complexity of the study, which will not significantly change the basic physical situation: the heat flow will be one-dimensional (except between the thermal plate and the tube, which will also have a 2D direction) and perpendicular to the surfaces of the various components of the collector; heat losses to the surrounding environment are essentially through the front and back surfaces, with negligible losses from the edges, mainly due to the large size of the collector and an effective thermal insulation; heat losses at the front and back of the collector are related to the same ambient temperature; the existence of dust on the surfaces that capture solar radiation is negligible, as well as the existence of shading; temperatures of the various components of the collector are assumed to be uniform; uniformity in the properties of the materials used and in their physical dimensions is assumed; it is considered that the temperature values of the parallel tubes, connected to the thermal plate, are equal and the mass flow rate in the tubes has an equal value in each one of them.

4.2 Heat Transfer Processes

The main energy balances associated with each component of the PVT collector are described below, where the conduction, convection and radiation terms are calculated by the usual and well-known equations corresponding to each of the heat transfer mechanisms (Ramos 2022). After presenting the figures with the energy balance schemes, the equations for the various components of the PVT collector are shown. In these equations the left side concerns the accumulated energy and the right side the input or output of energy flows.

Figure 3 presents the power balance for the glass cover component. This glass cover borders the environment in which it is involved on the front and is connected to the PV plate, on the back, by a thin layer of EVA adhesive.

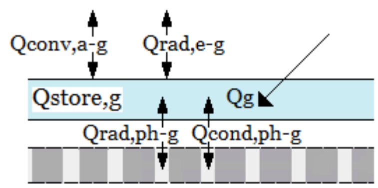


Figure 3. Power balance for the glass cover

Taking into account the Figure 3, the thermal power accumulated in the glass, $Q_{store,g}$, is the result of the solar radiation absorbed by the glass, Q_g, the heat transfer between the glass and the ambient air (convection heat transfer, $Q_{conv,a-g}$), the heat transfer with the surrounding environment (heat transfer by radiation, $Q_{rad,e-g}$) and the heat transfer with the photovoltaic plate (heat transfer by conduction, $Q_{cond,ph-g}$, and radiation, $Q_{rad,ph-g}$). The glass cover power balance equation will thus have the following form:

$$m_g c_g \frac{dT_g}{dt} = \propto_g G\, A_g + h_{conv,a-g} A_{a-g}\left(T_a - T_g\right) + h_{rad,e-g} A_{e-g}\left(T_e - T_g\right) + h_{ph-g} A_{ph-g}\left(T_{ph} - T_g\right) \quad (1)$$

where m_g, c_g, α_g and A_g are the mass, specific heat, absorptivity and area of the glass, respectively. The parameters T and h are the temperature and heat transfer coefficient, respectively, for each medium/component of energy balance. It should be noted that the temperature of the photovoltaic plate, T_{ph}, will correspond to the temperature of the solar cells, T_c and it is considered that the equivalent sky temperature, Te, will be equal to the ambient air temperature, Ta (Duffie and Beckman 2006; Chow 2003).
Figure 4 shows the power balance for the PV plate. The PV plate is bonded to the heat absorber plate by a thin layer of adhesive that is composed of an EVA and a Tedlar layer.

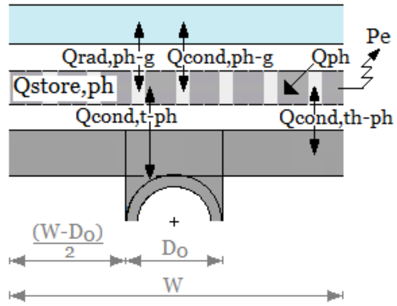


Figure 4. Power balance for PV plate

The thermal power accumulated in the photovoltaic plate, $Q_{store,ph}$, is the result of heat transfer by radiation, $Q_{rad,ph-g}$, and by conduction, $Q_{cond,ph-g}$, between the glass and the photovoltaic plate; of heat transfer by conduction between the photovoltaic plate and the thermal plate, $Q_{cond,th-ph}$ and the portion of this last plate that corresponds to the connection with the tube, $Q_{cond,t-ph}$; of the heat absorbed by the photovoltaic plate from solar radiation, Q_{ph}, and generated by the conversion of solar radiation that the photovoltaic plate receives, Pe. It should be noted that the components after the photovoltaic plate are considered opaque to infrared radiation (Duffie and Beckman 2006).
The energy balance equation for the PV plate is as follows:

$$m_{ph}c_{ph}\frac{dT_{ph}}{dt} = h_{g-ph}A_{g-ph}\left(T_g - T_{ph}\right) + h_{cond,th-ph}A_{th-ph}\left(T_{th} - T_{ph}\right) + h_{cond,t-ph}A_{t-ph}\left(T_t - T_{ph}\right) + \alpha_{ph}\tau_g G\, A_{ph} - \eta_{ph}\alpha_{ph}\tau_g G\, A_{ph} \quad (2)$$

where α_{ph}, A_{ph} and η_{ph} are the absorptivity, the area and the efficiency of PV module, respectively, and τ_g is the cover glass transmissivity. The term P_e is related to the electrical power generated by converting the solar radiation that reaches the photovoltaic plate and is dependent on the T_{ph} temperature and, consequently, on the efficiency of the photovoltaic module.

The power balance scheme for the thermal plate is shown in Figure 5. The thermal power accumulated in the thermal plate, $Q_{store,th}$, is the result of heat transfer by conduction between the photovoltaic and thermal plate, $Q_{cond,th-ph}$; of the heat transfer by conduction between the portion corresponding to the pipe connection and the thermal plate itself, $Q_{cond,t-th}$ and the heat transfer by conduction between the thermal plate and the insulation, $Q_{cond,isol-th}$.

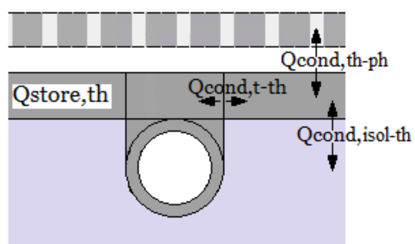


Figure 5. Power balance for thermal plate

The energy balance equation for the thermal plate is presented as follows:

$$m_{th}c_{th}\frac{dT_{th}}{dt} = h_{cond,ph-th}A_{ph-th}\left(T_{ph} - T_{th}\right) + h_{cond,t-th}A_{t-th}(T_t - T_{th}) + h_{cond,isol-th}A_{isol-th}(T_{isol} - T_{th}) \quad (3)$$

where A_{ph-th}, A_{t-th} and $A_{isol-th}$ are the contact areas between the photovoltaic and thermal plates, between the tube and the thermal plate and between the insulation and the thermal plate, respectively.
Figure 6 shows the power balance scheme for the tube. The heat flux from the PV plate transmitted to the metallic connection of the tube (and for the tube itself), is the result of the heat transmission through the absorber plate, $Q_{cond,t-th}$, and along the portion of this plate that corresponds to the connection with tube, $Q_{cond,\,t-ph}$. The heat flow from the metallic connection to the thermal fluid is carried out by conduction and by convection, Q_{w-t}. In terms of heat losses from the tube to the insulation, the term is $Q_{cond,t-isol}$.

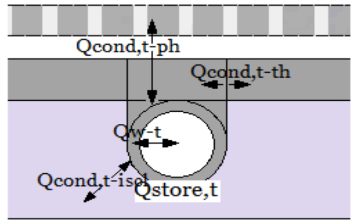


Figure 6. Power balance for tube

For the case of the tube physically connected to the thermal plate, the following energy balance equation will be obtained:

$$m_t c_t \frac{dT_t}{dt} = h_{th-t} A_{th-t}(T_{th} - T_t) + h_{isol-t} A_{isol-t}(T_{isol} - T_t) + h_{w-t} A_{w-t}(T_w - T_t) + h_{ph-t} A_{ph-t}\left(T_{ph} - T_t\right) \quad (4)$$

where m_t is the sum of the masses of the tube, the metallic connection of the tube to the thermal plate and the small portion of the thermal plate above this connection.

Figure 7 shows the power balance scheme for the insulation. The thermal power accumulated in the insulation layer, $Q_{store,isol}$, is the result of heat transfer by conduction between the pipe and the insulation, $Q_{cond,t-isol}$; of heat transfer by conduction between the thermal plate and the insulation, $Q_{cond,isol-th}$ and the heat transfer between the insulation and the environment, $Q_{,a-isol}$.

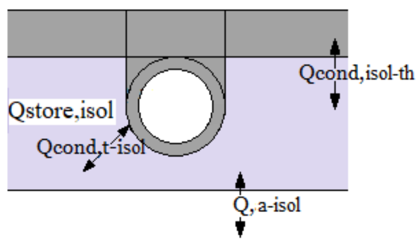


Figure 7. Power balance for insulation

In this case, the following energy balance will be obtained:

$$m_{isol} c_{isol} \frac{dT_{isol}}{dt} = h_{cond,th-isol} A_{th-isol}(T_{th} - T_{isol}) + h_{cond,t-isol} A_{t-isol}(T_t - T_{isol}) + h_{a-isol} A_{a-isol}(T_a - T_{isol}) \quad (5)$$

It should be noted that heat transfer by radiation, which may occur on the back surface of the PVT, itself a shaded surface, is not relevant and is therefore not considered. This simplification is due to the fact that the temperature difference between this surface and the surroundings is very small.

Figure 8 shows the power balance scheme for the thermal fluid inside the tube. The thermal power accumulated in the fluid, $Q_{store,w}$, is the result of the heat transfer between the tube and the fluid, Q_{w-t}, and the thermal power gained by the fluid, between the inlet and outlet of the tube, Q_w.

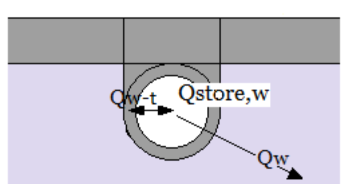


Figure 8. Power balance for thermal fluid

For the fluid in the tube, the power balance will be:

$$m_w c_w \frac{dT_w}{dt} = h_{t-w} A_{t-w}(T_t - T_w) + \dot{m}_w c_w (T_{w,o} - T_{w,i}) \quad (6)$$

where $T_{w,o}$ and $T_{w,i}$ are, respectively, the fluid temperatures at the outlet and inlet of the tubes connected to the thermal plate. The temperature T_w is the arithmetic mean between the temperatures $T_{w,o}$ and $T_{w,i}$. The parameters $\dot{m}_w$ and c_w are the mass flow rate and the specific heat of the fluid, respectively, at a temperature that will be the value of the arithmetic mean between the temperatures $T_{w,o}$ and $T_{w,i}$.
With regard to the EVA and Tedlar films, the same thermal analysis of the energy balance was carried out as for the components previously seen. In existing works by various authors on PVT, these very thin films are normally not analysed, considering them to have almost total transmissivity, which in practice could be considered a normal simplification. The thermal analysis of these films will therefore be carried out in order to be able to compare with works that do not consider them.

4.3 Electric Model

The electrical model for a PV module is derived from circuit theory and the general diode equation, where the simplified circuit of a cell consists of a diode and a current source, connected in parallel. This model being used by several authors (Liu and Dougal 2002; Xiao et al. 2004; Sera et al. 2007; Dondi et al. 2007; Villalva et al. 2009) as it does not have a high associated error and offers less complexity. Thus, the solar PV cell may be mathematically described by the current-voltage equation of a diode, Equation (16), where I_{PV} is the cell current, I_{PH} is the photocurrent, generated by the incident radiation which is directly proportional to solar radiation, Io is the saturation current inverse of the diode, q the charge of the electron (1.602 x 10-19 C), U_{PV} is the cell voltage, *a* the ideality constant of the diode, K is the Boltzmann constant (1.381 x 10-23 J/K) and T is the junction temperature (in Kelvin).

$$I_{PV} = I_{PH} - I_0 \left[e^{\frac{q\,(U_{PV})}{aKT}} - 1 \right] \quad (7)$$

This model, which considers only one diode and the equivalent loss resistances, is used by several authors (Xiao et al. 2004; Carrero et al. 2007; Yi-Bo et al. 2008), who consider it a simplified and adequate model for the described situation.
In order to be able to test the electrical load of the PVT, the system is connected to a resistance with a value corresponding to the U/I ratio of the maximum STC power.

4.4 Numerical Model

The PVT collector model schematic is presented in Figure 9. The test conditions used are the parameters G (solar radiation), Ta (ambient temperature) and Vwind (wind speed).

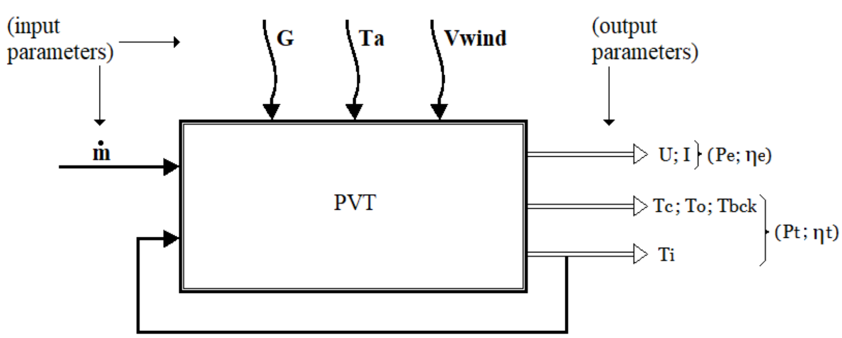


Figure 9. Modelling scheme of the studied PVT collector

For outputs values, there are the electrical parameters, U (voltage) and I (current), and the thermal parameters, Tc (cell temperature), To (PVT output temperature), Tbck (posterior temperature of the PVT) and Ti (PVT inlet temperature). The later temperature, Ti, together with the mass flow rate, $\dot{m}$, will be the control parameters of the PVT performance (Khalili et al. 2020; Sahlaoui et al. 2021).

5. Results and Discussion

5.1 Experimental Results

The tests were performed under dynamic state conditions, except in the case of the thermal fluid mass flow rate, where at certain times a constant operating value was imposed to analyse the impact of dynamic behaviour parameters. The experimental results represented below were obtained for a mass flow rate of the thermal fluid of $\dot{m}$=0.014 kg/s, for the best performance conditions of the PVT. In fact, the relationship between the electrical, thermal and overall performances of the PVT as a function of the parameter $\dot{m}$ show that this value $\dot{m}$=0.014 kg/s reflects the best performance, corresponding to the maximum value of efficiency (Ramos 2022). During the experimental tests, ambient temperature (Ta) values ranged from 25.3 to 37 °C, solar irradiance (G) from 244 to 1024 W/m² and wind speed (Vwind) from 0 to 4 m/s. Figure 10 presents the experimental results of PVT temperatures together with the meteorological values as a function of time.

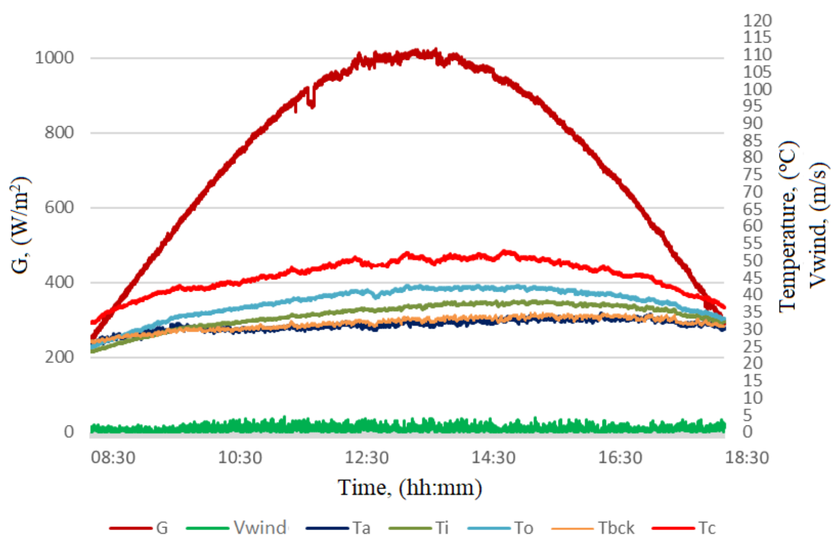


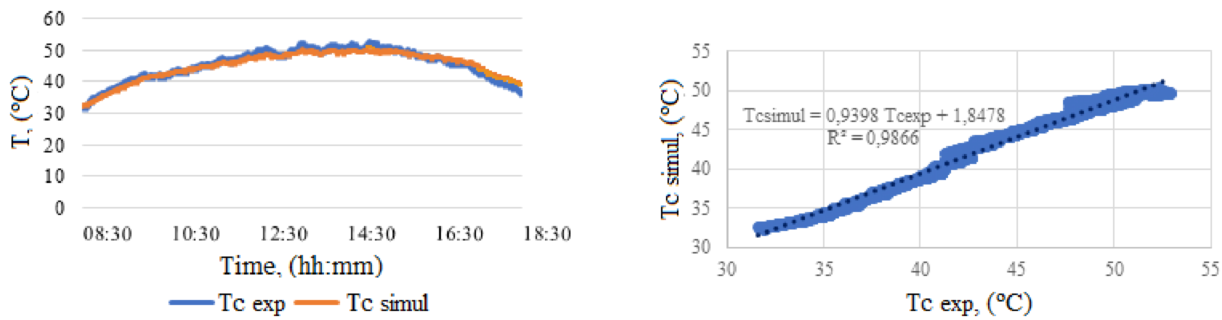
Figure 10. PVT collector temperatures and meteorological data

It can be observed that the temperature profiles have the same trend. Additionally, the highest temperature values are from the photovoltaic component of the PVT, Tc, which reaches a maximum of 53 ºC. The other parameters measured were the ambient temperature, Ta, the inlet and outlet thermal fluid temperatures of PVT, Ti and To, respectively, and the PVT back temperature, Tbck.

5.2 Validation

Validation is done considering several parameters, namely the values of the temperatures Tc and To and the values I and U, as using these make it possible to obtain other parameters that characterize the PVT performance.

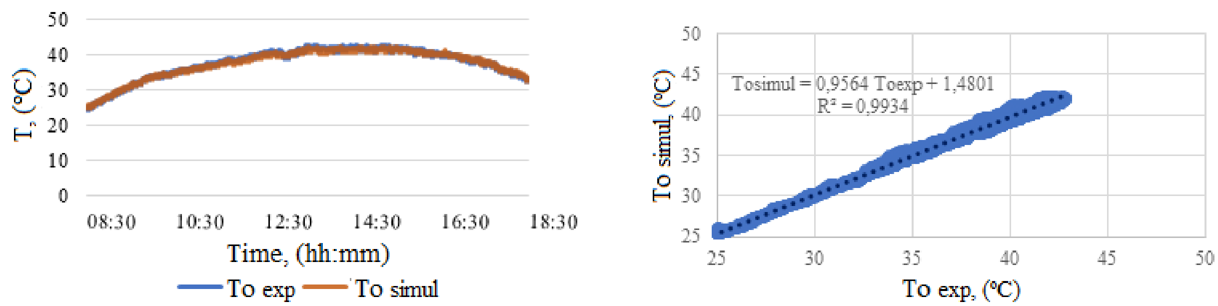
Figure 11 (a) shows the comparative result between the values of the experimental temperatures of the photovoltaic module (Tc exp) and the temperatures obtained by simulation (Tc simul) for the solar cells. Good overall agreement is observed between both results. For the same temperatures under analysis, Figure 11 (b) shows a good degree of concordance, through the linear regression study, where a strong correlation coefficient is observed.



(a) (b)

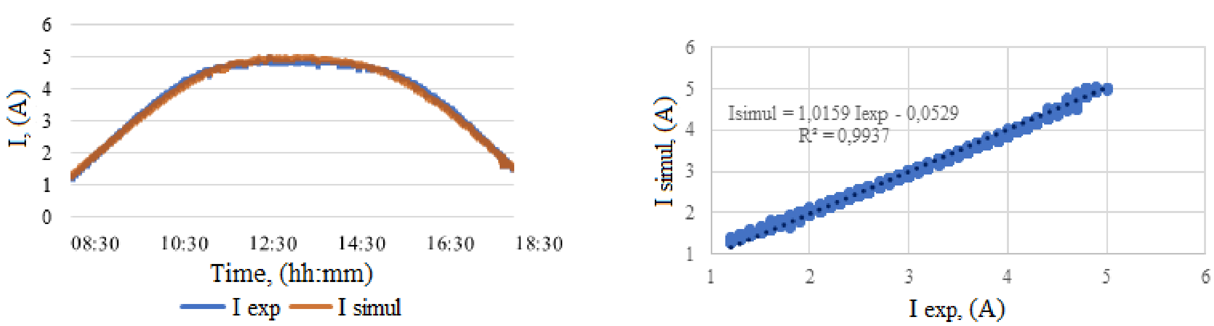
Figure 11. Comparison between experimental and simulated values of cell temperature, Tc: (a) over time; (b) correlation

A similar analysis can be performed on the results of Figure 12 (comparison between experimental and model values, of temperature To), Figure 13 (comparison between experimental and model values, of current I) and Figure 14 (comparison between experimental and model values, of voltage U). In all the figures presented, it can be observed that there is generally a rather strong agreement between the experimental and simulated results. It is observed that the greatest difference between these curves has a value of around 2.3%. This is a smaller value than the one observed in Ramos (2022) which was 2.5%. This is due to the fact that in the present work a more comprehensive mathematical model is considered, also considering the thin films of EVA and Tedlar in the energy balance of the PVT components.



(a) (b)

Figure 12. Comparison between experimental and simulated values of fluid temperature at the outlet of PVT, To: (a) over time; (b) correlation



(a) (b)

Figure 13. Comparison between experimental and simulated values of electric current of PVT, I: (a) over time; (b) correlation

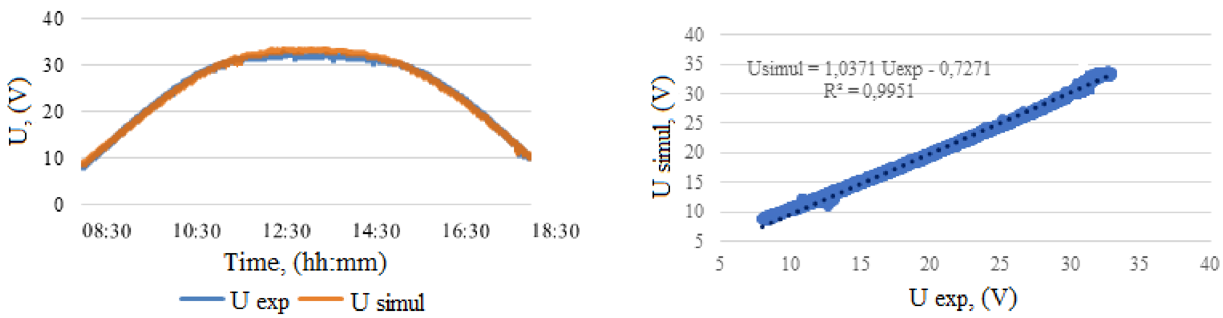


Figure 14. Comparison between experimental and simulated voltage values of PVT, U: (a) over time; (b) correlation

Based on the analysis carried out, it can be stated that the proposed model constitutes a trustworthy tool to study the behaviour of a PVT collector with a similar constitution to the one considered in this work.

6. Conclusion

The general objective of this work was the validation of a mathematical model developed for the global study of a type of PVT collector, namely a PVT without additional glass, in real scale and with a liquid thermal fluid. Inherent to the objective, a contribution to a better design of these types of hybrid collectors is pursued. The numerical model, with thermal energy balances and solar cell equivalent circuit, was implemented in a MATLAB-Simulink environment. The proposed model was validated with an excellent degree of agreement between data acquired experimentally, in real conditions, and simulated data, verifying that the highest value of the difference between these data was 2.3%, at some moments of the day. Thus, it can be ensured that the model is reliable in its application to the study of this type of PVT analysed, and it can even be verified that it can be adapted to other types of PVT.

Acknowledgements

This work was supported by the Portuguese Foundation for Science and Technology (FCT) under Projects UIDB/04131/2020 and UIDP/04131/2020.

References

Bergene, T. and Lovvik, O. M., Model Calculations on a Flat Plate Solar Heat Collector with Integrated Solar Cells, *Solar Energy*, 55, pp. 453-462, 1995.

Carrero, C., Amador, J. and Arnaltes, S., A Single Procedure for Helping PV Designers to Select Silicon PV Module and Evaluate the Loss Resistances, *Renewable Energy*, vol. 32, nº. 15, pp. 2579-2589, 2007.

Chow, T. T., Performance Analysis of Photovoltaic-Thermal Collector by Explicit Dynamic Model, *Solar Energy*, 75, pp. 143-152, 2003.

Coulson, K. L., *Solar and Terrestrial Radiation: Methods and Measurements*, Academic Press, New York, 1975.

Coventry, J. S., Performance of a Concentrating Photovoltaic/Thermal Solar Collector, *Solar Energy*, 78, pp. 211-222, 2005.

Dondi, D., Brunelli, D., Benini, L., Pavan, P., Bertacchini, A., and Larcher, L., Photovoltaic Cell Modelling for Solar Energy Powered Sensor Networks, *Proc. 2nd Int. Workshop Adv. Sens. Interface (IWASI)*, pp. 1-6, 2007.

Duffie, J. A. and Beckman, W. A., *Solar Engineering of Thermal Processes*, 3rd Edition, John Wiley & Sons, 2006.

Florschuetz, L. W., Extension of the Hottel-Whillier Model to the Analysis of Combined Photovoltaic/Thermal Flat Plate Collectors, *Solar Energy*, 22, pp. 361-366, 1979.

Hofmann, P., Dupeyrat, P., Kramer, K., Hermann, M. and Stryi-Hipp, G., Measurements and Benchmark of PV-T Collectors According to EN 12975 and Development of a Standardized Measurement Procedure, *Proceedings of Eurosun 2010*, Graz, Austria, September 28-October 01, 2010.

Hottel, H. C. and Willier, A., Evaluation of Flat-Plate Solar Collector Performance, *Transactions of the Conference on the Use of Solar Energy*, vol. 2, University of Arizona Press, Tucson, Arizona, 1958.

Kalogirou, S. A. and Tripanagnostopoulos, Y., Hybrid PV/T Solar Systems for Domestic Hot Water and Electricity Production, *Energy Conversion and Management*, 47, pp. 3368-3382, 2006.

Khalili, N. N. W., Othman, M., Bakar, M. N. A. and L. Abdullah, L., Modelling of a Single Passage Air PV/T Solar Collector: Experimental and Simulation Design, *Processes*, 8, 763, pp. 1-18, 2020.
Liu, S. and Dougal, R. A., Dynamic Multiphysics Model for Solar Array, *IEEE Trans. Energy Convers.*, vol. 17, nº. 2, pp. 285-294, 2002.
Lupu, A. G., Homutescu, V. M., Balanescu, D. T. and Popescu, A., A Review of Solar Photovoltaic Systems Cooling Technologies, *IOP Conference Series: Materials Science and Engineering*, 444, 082016, 2018.
Ramos, C. A. F., Alcaso, A. N. and Cardoso, A. J. M., Photovoltaic-Thermal (PVT) Technology: Review and Case Study, *Proceedings of the 4th International Conference on New Energy and Future Energy Systems*, Macau, 12 pp., July 21-24, 2019; *IOP Conference Series: Earth and Environmental Science*, vol. 354, 012048, 2019.
Ramos, C. A. F., *Numerical and Experimental Study of a Photovoltaic-Thermal Solar Collector*, PhD dissertation (in Portuguese), Dept. Electromechanical Eng., Beira Interior University, Covilhã, Portugal, 2022.
Sahlaoui, K., Oueslati, H. and Mabrouk, S. B., Thermal and Electrical Performance Evaluation of Hybrid Air PV/T Collector - Numerical Analysis and Experimental Study, *International Journal of Sustainable Energy*, DOI: 10. 1080/ 14786451.2021.1884076, 2021.
Said, Z., Arora, S. and Bellos, E., A Review on Performance and Environmental Effects of Conventional and Nanofluid-Based Thermal Photovoltaics, *Renew Sustain Energy Rev*, 2018.
Sandnes, B. and Rekstad, J., A Photovoltaic/Thermal (PV/T) Collector with a Polymer Absorber Plate. Experimental Study and Analytical Model, *Solar Energy*, vol. 72, pp. 63-73, 2002.
Sera, D., Teodorescu, R. and Rodriguez, P., PV Panel Model Based on Datasheet Values, *Proc. IEEE Int. Symp. Ind. Electron. (ISIE)*, pp. 2392-2396, 2007.
Skoplaki, E. and Palyvos, J. A., On the Temperature Dependence of Photovoltaic Module Electrical Performance: A Review of Efficiency/Power Correlations, *Solar Energy*, 83, pp. 614-624, 2009.
Smeltink, J. F., Blakers, A. W., 40 kW PV Thermal Roof Mounted Concentrator System, *4th World Conference on Photovoltaic Energy Conversion*, Waikoloa, Hawaii, May, 2006.
Sopian, K. S., Yigit, H. T., Liu, H. T., Kakac, S. and Veziroglu, T. N., Performance Analisys of Photovoltaic/Thermal Air Heaters, *Energy Conversion and Management,* 37, pp. 1657-1670, 1996.
Villalva, M. G., Gazoli, J. R. and Ruppert, E., Comprehensive Approach to Modelling and Simulation of Photovoltaic Arrays", *IEEE Transactions on Power Electronics*, vol. 24, nº. 5, pp. 1198-1208, 2009.
Xiao, W., Dunford, W. G. and Capel, A., A Novel Modelling Method for Photovoltaic Cells, *Proc. IEEE 35th Annual. Power Electron. Spec. Conf. (PESC)*, vol. 3, pp. 1950-1956, 2004.
Yi-Bo, W., Chun-Sheng, W., Hua, L., Hong-Hua, X., Steady-State Model and Power Flow Analysis of Grid-Connected Photovoltaic Power System, *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, pp. 1-6, 2008.
Zondag, H. A., Vries, D. W., van Hendel, W. G. J., van Zolingen, R. J. C. and van Steenhoven, A. A., The Thermal and Electrical Yield of a PV-Thermal Collector, *Solar Energy,* 72, pp. 113-128, 2002.

Biographies

Carlos A. Figueiredo Ramos received the Mechanical Engineering diploma and the MSc degree in Industrial Engineering, both from the University of Coimbra, Coimbra, Portugal. He received the PhD degree in Industrial Engineering and Management, from the University of Beira Interior (Portugal). He is a PhD Researcher at CISE - Electromechatronic Systems Research Centre (http://cise.ubi.pt). Currently he is a professor at the Polytechnic of Guarda, Guarda, Portugal. His research interests include renewable energies, energy systems and environmental sustainability.

Adérito Neto Alcaso was holds a degree in Electrical and Computer Engineering from Technical University of Lisbon, Lisbon (Portugal) a MSc in Automatic Systems and a PhD in Electrical Engineering both from University of Coimbra, Coimbra (Portugal). He is a PhD Researcher at CISE - Electromechatronic Systems Research Centre (http://cise.ubi.pt). Currently he is a Professor at the Polytechnic of Guarda, Guarda (Portugal). His main research interests are related to electronic power systems for renewable energies and electrical drives.

António J. Marques Cardoso (StM'89, AM'95, SM'99) received the Dipl. Eng., Dr. Eng., and Habilitation degrees from the University of Coimbra, Coimbra, Portugal, in 1985, 1995 and 2008, respectively, all in Electrical Engineering. From 1985 until 2011 he was with the University of Coimbra, Coimbra, Portugal, where he was Director of the Electrical Machines Laboratory. Since 2011 he has been with the University of Beira Interior (UBI), Covilhã, Portugal, where he is Full Professor at the Department of Electromechanical Engineering and Director of CISE - Electromechatronic Systems Research Centre (http://cise.ubi.pt). He was Vice-Rector of UBI (2013-2014). His current research interests are in fault diagnosis and fault tolerance in electrical machines, power electronics and drives. He is the author of a book entitled Fault Diagnosis in Three-Phase Induction Motors (Coimbra, Portugal: Coimbra Editora, 1991), (in Portuguese), editor of a book entitled Diagnosis and Fault Tolerance of Electrical Machines, Power Electronics and Drives (IET/SciTech, UK, 2018) and also author of more than 500 papers published in technical journals and conference proceedings. Prof. Marques Cardoso currently serves as Editor-in-Chief of the MDPI journal Machines, and Associate Editor of the IEEE Transactions on Industry Applications, IEEE Transactions on Power Electronics, IEEE Journal of Emerging and Selected Topics in Power Electronics, IEEE Open Journal of the Industrial Electronics Society, IET The Journal of Engineering, as well of the Springer journal Electrical Engineering and the International Journal of Systems Assurance Engineering and Management.