CIER 2017
31 Mayo – 2 Junio 2017
IX Conferencia Internacional de Energía Renovable, Ahorro de Energía y Educación Energética
… "El Caribe hacia el 100% con Fuentes Renovables de Energía"

Colectores solares fotovoltaicos-térmicos (PV/T): Características y modelado de prestaciones

Photovoltaic-thermal (PV/T) solar collectors: Features and performance modelling

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Resumen

Actualmente, las células fotovoltaicas (PV) presentan eficiencias eléctricas entre un 5–25%. Uno de los parámetros más importantes que afectan a dicha eficiencia es la temperatura de sus células: mayor temperatura, peor eficiencia eléctrica. La tecnología fotovoltaica/térmica (PV/T) es una solución para garantizar una adecuada conversión de la energía solar.

La tecnología PV/T genera energía eléctrica y térmica simultáneamente. Es adecuada para aplicaciones a baja temperatura (25–40ºC). Además se reduce el área total con respecto a colectores individuales y la eficiencia global es mayor. Se describe la instalación en una vivienda unifamiliar donde los colectores PV/T se integran con una fuente de calor geotérmica y con una bomba de calor para producir agua caliente sanitaria y calefacción.

Este trabajo tiene dos objetivos. Primero, se analizan las posibilidades de la tecnología PV/T. Segundo, se desarrolla un modelo de colector PV/T plano de agua en TRNSYS y se analiza su funcionamiento.

Palabras claves: Energía solar; colectores PV/T; modelado; TRNSYS.

Abstract

Currently, the electrical efficiency of photovoltaic (PV) solar cells ranges between 5–25%. One of the most important parameters that affects the electrical efficiency of a PV collector is the temperature of its cells: the higher temperature, the lower is the efficiency. Photovoltaic/thermal (PV/T) technology is a potential solution to ensure an acceptable solar energy conversion.

The PV/T technology produces both electrical and thermal energy simultaneously. It is suitable for low temperature applications (25–40 ºC) and overall efficiency increases compared to individual collectors. This paper describes an installation in a single-family house where PV/T collectors are coupled with a ground heat exchanger and a heat pump for domestic hot water and space heating purposes.

The aim of this work is twofold. First, the features of the PV/T technology are analyzed. Second, a model of a flat-plate PV/T water collector was developed in TRNSYS in order to analyze collectors performance.

Key words: Solar energy; PV/T collectors; performance modelling; TRNSYS.

Introduction

Social concerns about climate change are growing. Since the Copenhagen Climate Conference (1997), several countries began implementing energy policies to reduce the global warming gases and pollution. This, together with the rising price of fossil fuels and the drawbacks of nuclear power plants, makes the renewable energy a promising solution to mitigate the effects of the global warming and change the current power generation model based mainly on fossil fuels.

Solar energy is the most abundant and clean among the renewable energy technologies [1]. Moreover, solar energy is widely used in buildings which, in developed countries, are responsible for about 40% of the final energy consumption [2]. There are two main solar technologies used in buildings: photovoltaic (electrical energy generation) and thermal solar energy (sanitary hot water, space heating or cooling).

Currently, electrical efficiency of photovoltaic (PV) solar cells ranges between 5–25% [3]. One of the most important parameters that affect the electrical efficiency of a PV collector is the temperature of its cells: the higher temperature, the lower is the efficiency [4]. In fact, the photovoltaic conversion efficiency decreases linearly with the temperature of the PV cells [5]. To ensure an acceptable solar energy conversion at high temperatures, a cooling system might be integrated with the PV collector. In this sense, photovoltaic/thermal (PV/T) technology is a solution.

The reference Michael et al. [6] is a complete guide about PV/T systems. A PV/T solar collector is a combination of a PV solar collector and a thermal solar collector in a single unit to produce both electrical and thermal energy simultaneously. Avezov et al. [7] provides a detailed classification of PV/T collector types. The two main types are air and water PV/T collectors. The air PV/T collector can be subdivided in glazed/unglazed, single/double pass or channel flow and the water PV/T can be subdivided in glazed/unglazed, round/square/rectangular tube absorber, sheet and tube or channel flow.

The thermal efficiency of a PV/T collector is lower than efficiency of a typical thermal collector due to (1) a lower optical absorption of PV laminates compared to the typical thermal absorber plate, (2) the extra thermal resistance of the PV cells and (3) the fraction of the solar energy converted into electricity by the PV cells [6]. Moreover, the electrical efficiency of a PV/T collector may be even lower when compared to an efficiency of a PV collector if the cooling fluid temperature is not low enough to achieve the cooling effect. Thus, PV/T technology is constrained to low temperature applications such as floor heating systems (25–40ºC) to ensure the cooling effect of the PV cells [8]. Anyhow, PV/T collectors provide a cost saving compared to individual thermal and photovoltaic panels because some components are shared in a single unit. Moreover, total area is reduced and overall efficiency (electrical + thermal) increases compared to individual collectors.

Several authors have worked on PV/T modelling. Tiwari and Sodha [9] developed a thermal model of PV/T water collector and they found an analytical expression for the PV module and the cooling water temperatures validated experimentally. Dupeyrat et al. [10] developed a two-dimensional single glazed flat PV/T model to evaluate both electrical and thermal efficiency. Yazdanpanahi et al. [4] used a numerical model of a water flat plate PV/T collector to perform an energy and exergy analysis. The authors validated the model experimentally. Anderson et al. [11] used an extension of the Hottel-Whillier model to study the performance of a building integrated PV/T collector. Bilbao and Sproul [12] developed a detailed transient model of a water PV/T collector based on the electrical-thermal analogy. The authors studied the hourly performance of the system and its transient behavior.

Nevertheless, only a few models of PV/T solar collector are integrated in typical simulation programs for thermal energy system analysis in buildings. For instance, there are only two types of PVT model in TRNSYS [13]: type560 and type563. The first one is suitable to interact with simple buildings models while the second one is suitable to interact with detailed buildings models. Nevertheless, both types model an unglazed PV/T collector. In EnergyPlus [14] there is an object to model a water or air PV/T collector, but it does not give information about the temperature of each layer of the collector and it requires plant loop with a water thermal storage tank (if the fluid is water) or an outdoor air system (if the fluid is air) to be defined.

The aim of this work is to develop a new type of a flat-plate glazed water PV/T solar collector in TRNSYS. The model is used to evaluate the main features and limitations of a typical PV/T collector. This paper is divided into three main parts: (1) description of a real PV/T system application, (2) mathematical modelling of the PV/T collector and (3) analysis of the simulation results.

A real PV/T system application

An example of installation using PV/T technology is shown in Fig. 1. This installation is operating in the city of Leicester (UK) in front of the Institute of Energy and Sustainable Development (IESD) of De Montfort University.

A PV/T array of six PV/T collectors (Fig. 1 (a)) is coupled with a ground heat exchanger (Fig.1 (b)) and a water-to-water heat pump. An electric heater is installed to achieve the water set-point temperature. The system provides domestic hot water (DHW) and space heating (radiant floor) in a single-family house. The ground loop and the PV/T water circuit are both separated from the secondary circuit (DHW and heating circuit) by means of a flat-plate heat exchanger (Fig. 1 (d)). Figure 1 (c) shows the pipes (supply and return) that connect the ground heat exchanger with the heat exchanger of Fig. 1 (d).

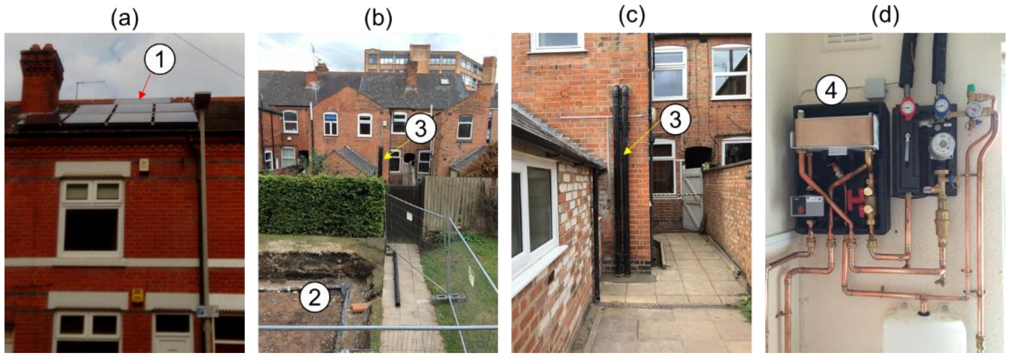

Figure 1. Thermal Installation located in Leicester that integrates PV/T technology with a ground heat exchanger and a water-water heat pump. (a) PV/T array, (b) back side of the house with the ground heat exchanger, (c) supply and return pipes that connects the ground loop with (d) the internal flat-plate heat exchanger that separates the secondary circuit (DHW and heating circuit) from the ground loop and the PV/T circuit. 1 – PVT collectors, 2 – Ground heat exchanger, 3 – Connection pipes, 4 – heat exchanger

The installation can operate in three modes:

(1) Charging ground from PV/T: the water circulates between the ground loop and the PV/T array. Thus, PV/T collectors are being cooled while the temperature of water is increasing.
(2) Charging hot water tank from PV/T: the water of the PV/T circuit is heated by the PV/T collectors to cool them at the same time. The hot water at the exit of the last PV/T collector of the array is used in the flat plate heat exchanger of Fig. 1 (c) to increase the temperature of the hot water tank inside the house.
(3) Charging hot water tank from ground by using the heat pump: The ground loop is used as cold source for the evaporator of the water-to-water heat pump. The heat pump produces the hot water required for the system and the electric heater is activated by a control system only if necessary.

PV/T mathematical model

The model presented in this work is an extension of the Hottel-Whillier method presented in Duffie and Beckman [15]. Figure 2 (a) shows the scheme of the modelled solar PV/T collector and Fig. 2 (b) shows how the heat flux is modelled.

The main assumptions of this model are listed below:

- The system is assumed to be in steady state condition.
- One-dimensional heat conduction is considered.
- The temperature of each layer of the collector is assumed uniform.
- The transmissivity of the EVA layer is 100%.
- Thermal losses by edges of the collector are disregarded.

The energy balance in the glass covering is:

$$\frac{t_c - t_g}{e_g/k_g + 1/h_{cr,c\rightarrow g}} - \frac{t_g - t_a}{\frac{1}{h_{cr,g\rightarrow a}}} = 0 \qquad (1)$$

Where t, e and k are the temperature in ºC, the thickness in m and the thermal conductivity, respectively and h_{cr} is the convective-radiant heat transfer coefficient in W m^{-2} K^{-1}. The subscripts a, c and g represent the ambient, the PV cells and the glass, respectively.

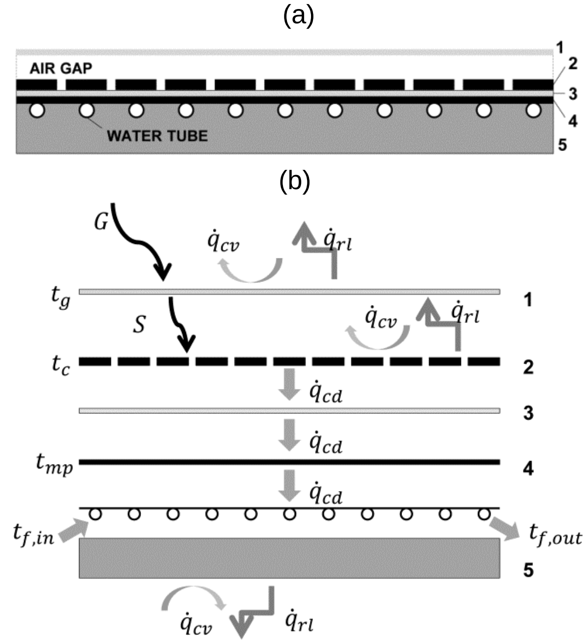

Figure 2. PV/T solar collector: (a) Compact view and (b) heat fluxes. Layers: 1-Glass cover, 2-PV cells, 3-EVA, 4-Thermal absorber, 5-Insulation.

The energy balance in the PV laminate is:

$$\beta_c S_c - \frac{t_c - t_{mp}}{\frac{e_{ev}}{k_{ev}}} - \frac{t_c - t_g}{\frac{e_g}{k_g} + \frac{1}{h_{cr,c\to g}}} - \eta_{el}\beta_c S_c = 0 \tag{2}$$

Where β_c is the packing factor, S_c is the radiation absorbed by the PV cells and t_{mp} is the mean temperature of the thermal absorber plate. The term η_{el} is the electric efficiency of the collector which is defined as [16]:

$$\eta_{el} = \frac{I_{mpp} V_{mpp}}{A_c G_{ref}} \left[1 - \beta_{ref}(t_c - t_{c,ref})\right] \tag{3}$$

The subscript ref represents the reference state given by the manufacturer and I_{mpp} and V_{mpp} represent the current and voltage at the maximum power point respectively. In this equation β_{ref} is the PV cell temperature coefficient.

The useful heat (Q_u) absorbed by the cooling water is defined as:

$$Q_u = \dot{m}_w Cp_w (t_{w,o} - t_{w,i}) \tag{4}$$

Where m_w is the water mass flow rate in kg s^{-1}, Cp_w is the specific heat of water in kJ kg^{-1} K^{-1} and $t_{w,o}$ and $t_{w,i}$ are the temperature of water at the exit and at the inlet of the collector.

Alternatively, the useful heat is defined as follows:

$$Q_u = A_c\left[\xi - U_L(t_{mp} - t_a)\right] \tag{5}$$

Where A_c is the collector area in m^2, ξ is the heat flux to the thermal absorber in W m^{-2}, U_L is the overall heat loss coefficient in W m^{-2} K^{-1} and t_a is the ambient temperature in ºC. The mean temperature of the thermal absorber plate (t_{mp}) is an internal variable of the collector and cannot be measured. An expression of Q_u as a function of measured variables is:

$$Q_u = A_c F_R\left[\xi - U_L(t_{w,i} - t_a)\right] \tag{6}$$

The flow rate factor F_R is calculated from this expression:

$$F_R = \frac{\dot{m}_w Cp_w}{A_c\, U_L}\left[1 - exp\left(-\frac{U_L\, A_c\, F'}{\dot{m}_w Cp_w}\right)\right] \quad (7)$$

F' is the flat plate collector efficiency and it is obtained from:

$$F' = \frac{1/U_L}{W\left[1/(U_L[D_o+(W-D_o)F])+1/C_b+1/(\pi\, D_i\, h_{cv,w})\right]} \quad (8)$$

Where D_o and D_i are the outer and inner pipe diameter in m, W the is separation between pipes in m ,C_b is the bound conductivity in W m^{-1} K^{-1} and $h_{cv,w}$ is the convective heat transfer coefficient inside the water pipe. F is the fin efficiency factor which is defined as:

$$F = \frac{\tanh(m[(W-D)/2])}{m[(W-D)/2]} \quad (9)$$

Being:

$$m = \sqrt{\frac{U_L}{k\, \delta}}$$

Where k is the thermal conductivity of the pipe in W K^{-1} m^{-1} and δ is the plate thickness in m.

On the other hand, the calculation of the U_L concerns the convective and radiative heat exchange between the top and bottom side thermal absorber plate and the ambient. Figure 3 shows the R network of the PV/T collector.

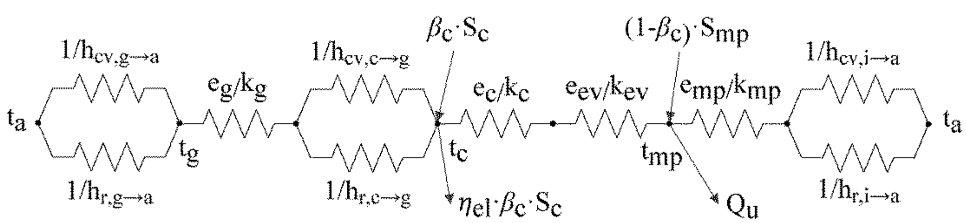

Figure 3. R network of the PV/T solar collector shown in Fig. 1.

The U_L coefficient is calculated as follows:

$$U_L = \left(\frac{1}{h_{cr,g\to a}} + \frac{e_g}{k_g} + \frac{1}{h_{cr,c\to g}}\right)^{-1} + \left(\frac{e_c}{k_c} + \frac{e_{ev}}{k_{ev}}\right)^{-1} + \left(\frac{e_i}{k_i} + \frac{1}{h_{cr,i\to a}}\right) \quad (10)$$

Where h_{cr} is the convective-radiative heat transfer coefficients in W m^{-2} K^{-1}, e is the layer thicknesses in m and k are the thermal conductivities in W m^{-1} K^{-1}. The subscripts g, a, c, ev, and I refer to the glass, the ambient, the PV cells, the EVA and the insulation layers.

The heat flux absorbed by the thermal absorber plate is calculated as follows:

$$\xi = (1-\beta_c)S_{mp} + U_p(t_c - t_{mp}) \quad (11)$$

The term S_{mp} is the amount of solar radiation absorbed by the thermal absorber plate. Equation 12 gives the expression for the solar radiation absorbed by a flat surface from the application of the isotropic sky model:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \frac{1+\cos(\beta)}{2} + \rho_g I (\tau\alpha)_g \frac{1+\cos(\beta)}{2} \quad (12)$$

Where I_b, I_d and I are the beam, diffuse and total radiation over horizontal surface respectively, ρ_g is the ground reflectivity, β is the tilt angle of the collector. The terms $(\tau\alpha)$ are calculated as follows:

$$(\tau\alpha)_b = \frac{T(\theta_1=0°)\ \alpha_p}{1-(1-\alpha_p)R(60°)}\left(1-b_0\frac{1}{\cos(\theta_1)}-1\right) \tag{13}$$

$$(\tau\alpha)_d = \frac{T(\theta_1=0°)\ \alpha_p}{1-(1-\alpha_p)R(60°)}\left(1-b_0\frac{1}{\cos(59.7-0.1388\beta+0.001497\beta^2)}-1\right) \tag{14}$$

$$(\tau\alpha)_g = \frac{T(\theta_1=0°)\ \alpha_p}{1-(1-\alpha_p)R(60°)}\left(1-b_0\frac{1}{\cos(90-0.5788\beta+0.002693\beta^2)}-1\right) \tag{15}$$

Where θ_1 is the angle of incidence, α_p the absorptivity of the thermal absorber plate and b_0 is the incidence angle modifier. T and R are the transmittance and the reflectance of the glass respectively and both are function of the reflectivity and the transmittance of the glass [16]. Due to fact that the absorptivity of the PV cells and the thermal absorber plate are different; the solar radiation absorbed by the PV cells (S_c) is different from that absorbed by the thermal absorber plate (S_{mp}).

Finally, the thermal efficiency of the PV/T solar collector is defined as follows:

$$\eta_{th} = \frac{Q_u}{A_c\ G} \tag{15}$$

Where G is the total radiation on the collector surface in W m^{-2}.

Results and discussion

The thermodynamic performance of the PV/T collector for a typical summer day (9 July) in the city of Leicester (52,63º N, -1,13º W) has been studied. The parameters required for the PV/T model developed in this work are shown in Table 1. Most of them have been taken from the manufacturer catalogue of Solar Angel [17].

Table 1. Parameters of the case study PV/T solar collector.

Parameter	Value	Parameter	Value
Length of the collector (L)	1,63 m	Wind velocity (v)	1 m s^{-1}
Breadth of the collector (b)	0,986 m	PV cell absorptivity (α_c)	0,9
Separation between pipes (W)	0,1 m	Thermal absorber thickness (e_c)	0,001 m
Density of cooling fluid (rho)	1000 kg m^{-3}	Distance PV cell to glass	0,01 m
Specific heat of cooling fluid (Cp_w)	4,19 kJ kg^{-1} K^{-1}	Thermal absorber emissivity	0,09
Insulation conductivity (k_i)	0,035 W m^{-1} K^{-1}	Glass emissivity (ε_g)	0,84
Insulation thickness (e_i)	0,05 m	Maximum power point current (I_{mpp})	8,1 A
Glass conductivity (k_g)	1 W m^{-1} K^{-1}	Maximum power point voltage (V_{mpp})	30,4 V
Glass thickness (e_g)	0,003 m	PV cell temperature coefficient (β_{ref})	0,0045 K^{-1}
Thermal absorber thickness (δ)	0,001 m	Radiation of reference (G_{ref})	1000 W m^{-2}
Packing factor (β_c)	0,90	Collector tilt angle (β)	45º
Outer pipe diameter (D_o)	0,010 m	Ground reflectance (ρ_g)	0,2
Inner pipe diameter (D_i)	0,009 m		

The results are shown in the following order: (1) Effect of the cooling water mass flow rate on the temperature of the glass, the PV cells, the thermal absorber plate, the temperature of the water leaving the collector and the thermal and electrical output for a fixed temperature of the cooling water at the inlet, (2) temperature analysis of the first and the last PV/T in an array (3) electrical and thermal efficiency for an array of PV/T collectors.

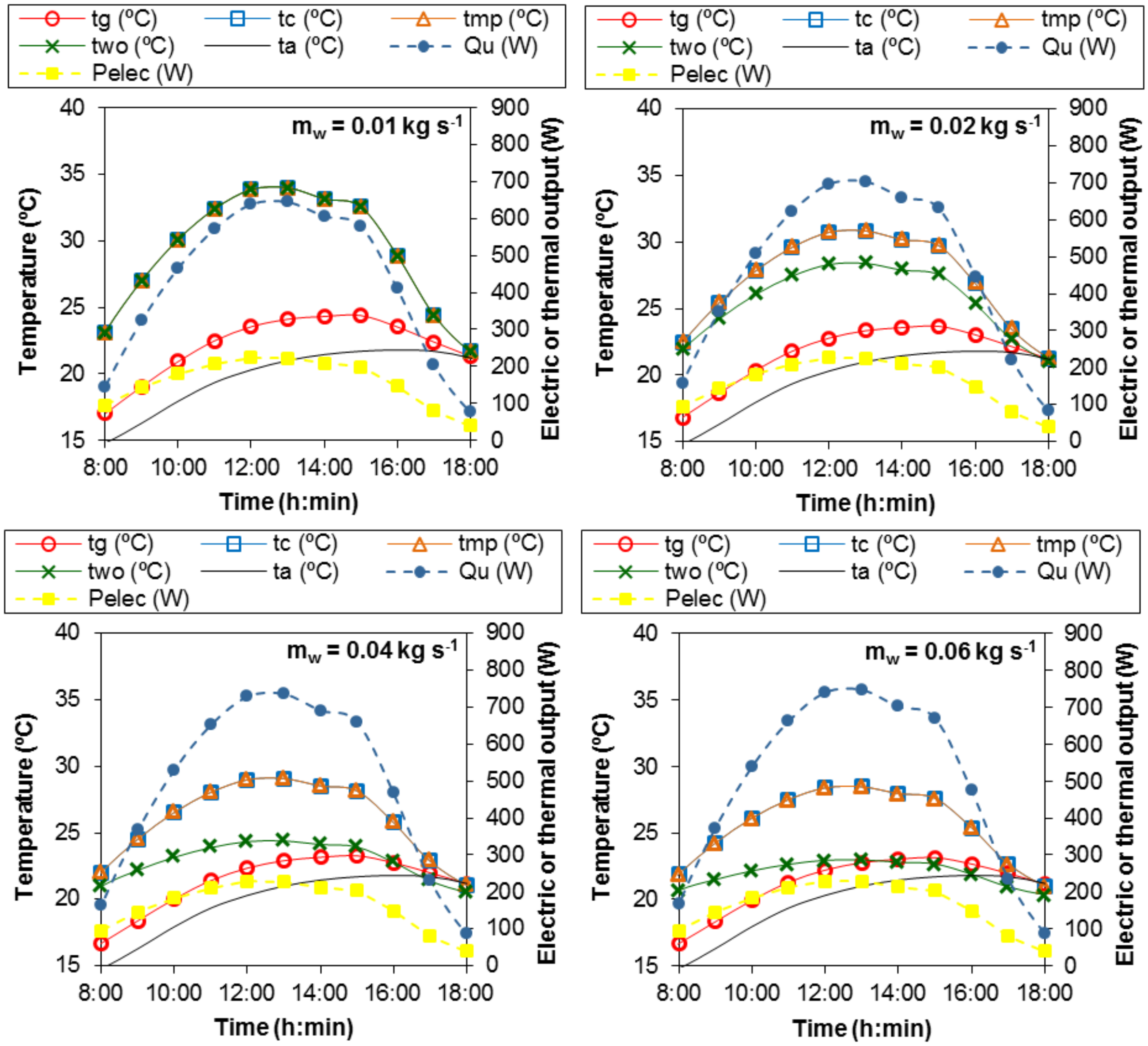

Figure 4. Hourly temperature analysis of the PV/T solar collector from 8:00 to 18:00 for a typical summer day (9 July) in Leicester and for different water flow rates. The temperature of the cooling water at the inlet is set to 20ºC.

Figure 4 shows the temperature analysis of the PV/T collector for different cooling water mass flow rates and for a fixed temperature of the cooling water at the inlet (20ºC). The results analysis shows that:

(a) The higher cooling water flow rate, the lower the temperature of the PV cells. If the water mass flow rate increases from 0,01 to 0,02 kg s^{-1}, the temperature of the PV cells decreases 3,0ºC at the maximum solar radiation point. However, the temperature of the PV cells decreases only 1,7ºC when the mass flow rate is increased from 0,04 to 0,06 kg s^{-1}.

(b) The temperature of the water leaving the PV/T collector increases when the mass flow rate is reduced. For instance, at the maximum solar radiation point, its value is 33,1ºC and 22,8ºC for a mass flow rate of 0,01 and 0,06 kg s^{-1}, respectively. Depending on the application, a control system must be used to achieve the water temperature set-point at the exit of the PV/T collector.

(c) The temperature of the glass covering is slightly affected by the variation of the water mass flow rate. For instance, at the maximum radiation point, this temperature is 24,1ºC for a water mass flow rate of 0,01 kg s^{-1}, while it is 23,0ºC for a water mass flow rate of 0,06 kg s^{-1}.

(d) The thermal output of the collector increases with the water mass flow rate. Nevertheless, this effect becomes weaker as the water flow rate reaches high values. For instance, at the maximum radiation point, the thermal output is enhanced by 59 W when the water flow rate changes from 0,01 to 0,02 kg

s^{-1}, while it increases only 11 W when the water flow rate changes from 0,04 to 0,06 kg s^{-1}. On the other hand, the electric output increases by 0,64 W and 3,3 W when the water flow rate changes from 0,01 to 0,02 kg s^{-1} and 0,04 to 0,06 kg s^{-1}, respectively.

Fig. 5 shows the PV/T array analyzed in TRNSYS for a typical summer day (9 July) in Leicester. The collectors are connected in serial mode. The water mass flow rate is set to 0,04 kg s^{-1} and the temperature of the water at the inlet of the first PV/T collector of the array (PV/T-1) is set to 20 ^{o}C.

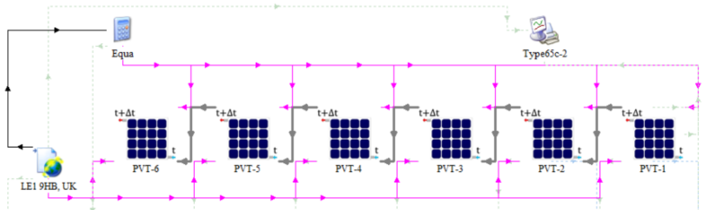

Figure 5. Simulation environment in Simulation Studio (TRNSYS) for an array of six PV/T collectors.

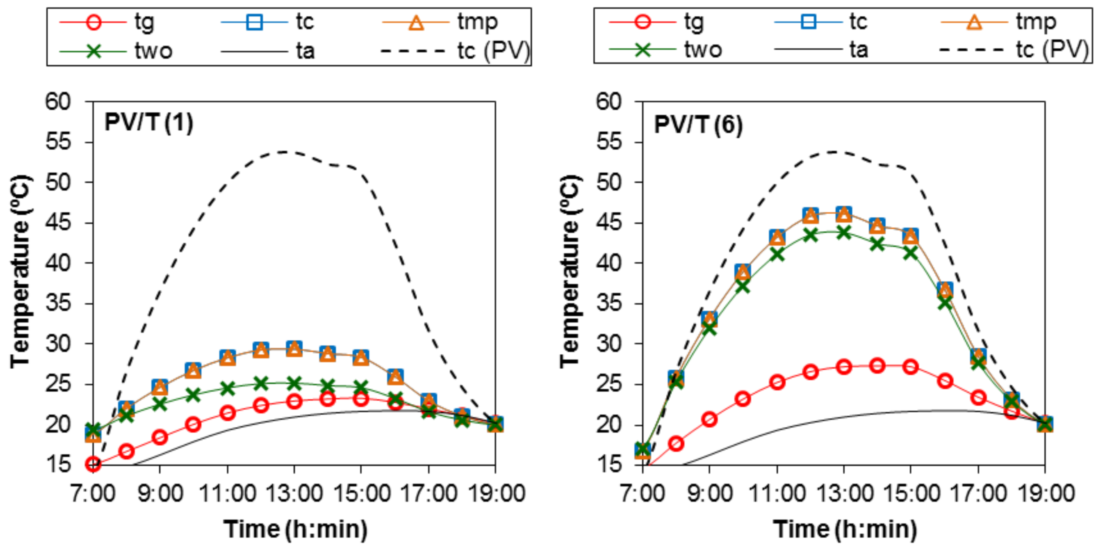

Figure 6. Hourly temperature analysis for the first and the last PV/T solar collector (PV/T-1 and PV/T-6 respectively) of the PV/T array for a typical summer day (9 July) in Leicester from 8:00 to 18:00. The temperature and the flow rate of the cooling water at the inlet of the first PV/T collector are set to 20 ^{o}C and 75 L $h^{-1}m^{-2}$.

Figure 6 shows the temperature analysis for the first and the last PV/T solar collector of the PV/T array illustrated in Fig. 5. Figure 7 (a) shows the electrical efficiency and Fig. 7 (b) shows the thermal efficiency. We observe that:

(a) At the point of maximum solar radiation, the temperature upgrading is 5,2^{o}C (20/25,2^{o}C) and 2,9^{o}C (40,9/43,8^{o}C) for the PV/T-1 and PV/T-6, respectively. Hence, the thermal efficiency of the PV/T collectors decreases as the temperature of the cooling water at the inlet increases (see Fig. 7 (a)).

(b) When the maximum radiation occurs, the temperature of the PV cells is 29,4^{o}C and 46,2^{o}C for the PV/T-1 and PV/T-6, respectively. Therefore, we achieve a higher water temperature at the exit of the PV/T array by adding PV/T collectors to the series connection, but the electrical efficiency of the array is penalized (see Fig. 7 (b)).

(c) As we add PV/T collectors in series to the array, the temperature of the water leaving the last PV/T collector of the array increases, but its electrical efficiency approaches the electrical efficiency of a typical PV collector. In the case that the electrical efficiency is a constraint of the system, there is a maximum temperature of the water at the exit of the last PV/T collector of the PV/T array. Thus, there is a maximum number of PV/T collectors that can be connected in series.

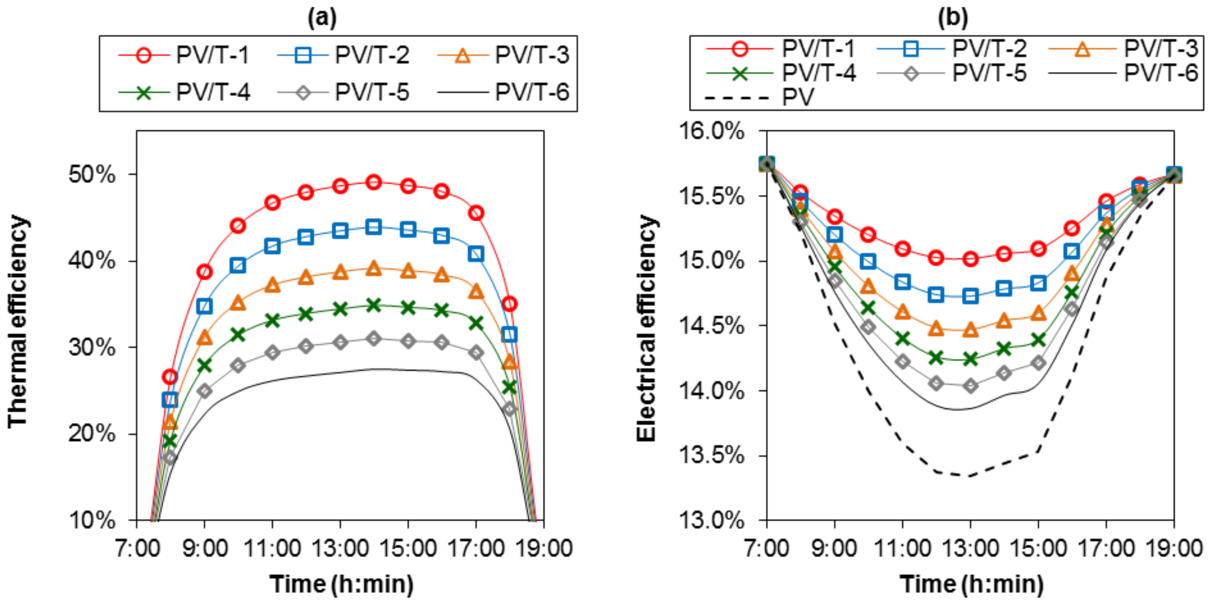

Figure 7. Hourly analysis for a typical summer day (9 July) in Leicester: (a) electrical and (b) thermal efficiency for each PV/T collector that integrates the PV/T array. The temperature and the flow rate of the cooling water at the inlet of the first PV/T collector are set to 20 ºC and 75 L $h^{-1}m^{-2}$.

Conclusions

This paper analyses the features and the modelling of PV/T solar collectors. The main capabilities and limitations of PV/T technology have been discussed. Moreover, a new TRNSYS type for a PV/T water collector has been developed. In this work the developed PV/T model is used to: (1) analyze the effect of the cooling water mass flow rate on the temperature of each layer of the PV/T collector, (2) analyze the behavior a PV/T array connected in series in terms of temperatures and electrical and thermal efficiencies.

The simulations were done by means of a new weather meteorological file for Leicester (UK) developed by the Institute of Energy and Sustainable Development (IESD) of the De Montfort University.

The main conclusions are:

(1) The solar PV/T technology is useful when electricity and heat are required simultaneously, but only for low temperature heating applications. If the temperature of the cooling water entering the PV/T collector is too high, the electrical efficiency may be even lower than that for a typical PV solar collector.

(2) A real installation which includes PV/T technology in a single-family house in the city of Leicester was described. This installation demonstrates the possibility to couple PV/T solar water collectors with geothermal sources, heat pumps and low temperature heating systems.

(3) The temperature of the PV cells decrease as the water mass flow rate increases. Nevertheless, the cooling effect by increasing the flow rate becomes weaker once high flow rates are reached.

(4) The analysis of a PV/T array demonstrates that there is a maximum recommended number of PV/T collectors connected in series. The temperature of the water leaving the PV/T array increases as more PV/T collectors are added in series, however the electrical efficiency of the last PV/T collector in the array approaches the electrical efficiency of a typical PV collector.

(5) The useful heat and the thermal efficiency of the first PV/T collector of the array is the highest; the temperature of the water leaving the last PV/T collector of the array is the highest, but both the useful heat and the thermal efficiency of this last collector are the poorest.

Acknowledgements

Antonio Atienza-Márquez acknowledges the Spanish Ministry of Education the financial support of the predoctoral contract FPU 15/04514.

The author also wish to thank the Dr Ivan Korolija, Prof. Richard Greenough, Prof. Alberto Coronas and Prof. José Manuel Cejudo for the opportunity to take a placement in the Institute of Energy and Sustainable Development (IESD) at De Montfort University in period between July and September 2015.

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