Design of a flat-plate Photovoltaic-Thermal (PV-T) hybrid collector: modelling and experimental investigations

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Abstract

In this paper, the interest in the development of a single-glazed flat-plate photovoltaic-thermal (PV-T) collector is discussed. In order to evaluate the performances of a PV-T collector, a simplified 2D model has been used to simulate the thermal and electrical efficiency operating range according to the collector properties. Thus, key-parameters for performance improvements were identified and quantified. Based on those investigations a collector has been designed, built and tested. Improved assembling methods were used, focusing on both heat transfer between PV cells and fluid and on optical properties of materials.

At zero reduced temperature and based on the absorber area, a thermal efficiency of 79 % has been reached under PV operation for a corresponding electrical efficiency of 8.7 %. The overall energy efficiency is quite high (87.7 %) compared to results found in literature. Numerical simulations using TRNSYS software have been carried out. They were based on the parameters which were extracted from those experiments. They were carried out in order to compare the performances of four different systems for domestic hot water applications: PV-T collector, side-by-side (half PV module, half solar thermal collector), PV module and typical solar thermal. The considered total integrated area was 5m² for each configuration. The results of those investigations are presented in this paper and are very promising for the future development of PV-T collector.

1. Introduction

A solar cell is a device that converts the energy of sunlight (photon) directly into electricity (electron) according to the gap energy E_{gap} of the semiconductor material of the solar cell. The absorption of a photon with energy E_{photon} lower than the gap energy E_{gap} of the cell semiconductor material cannot create a light-generated carrier but is converted into heat. The absorption in a solar cell of a photon with energy E_{photon} greater than the gap energy E_{gap} of the semiconductor material creates a light-generated carrier but also residual energy (energy difference between E_{photon} and E_{gap}) which is converted into heat. Therefore the efficiency of solar cell is limited [1] and most of the absorbed radiation is converted into heat, no matter which semiconductor material is used. For example, a conventional photovoltaic cell made of mono-crystalline silicon reflects around 10 % of the incoming radiation whereas only 16 % of the incoming radiation is converted into electricity. In fact, most of the absorbed energy is wasted into heat as described in the Figure 1.

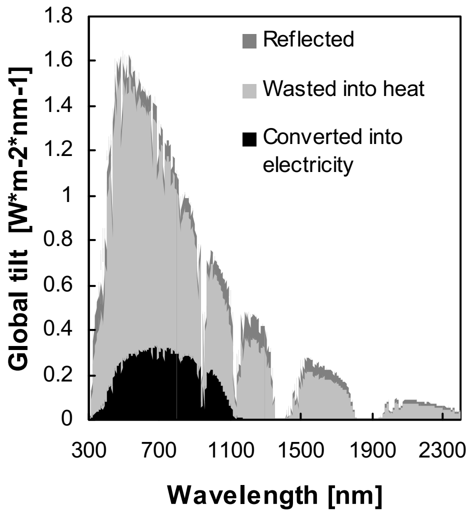

Fig. 1: Photo-conversion of a real single crystalline silicon solar cell. Spectral representation based on External Quantum Efficiency, I(V) and reflection measurements performed on a single crystalline silicon solar cell (Jsc=36.5 mA/cm², FF=0.75, Voc=0.6 V, η=0.164)

In this context, the development of hybrid components such as a PV-Thermal (PV-T) solar collector can offer a solution to valorise the produced heat of PV cells and modules in one single solar system. That contributes to solve the question of shortage of available roof surfaces for both PV and solar thermal.

A photovoltaic-thermal collector is a hybrid solar component in which PV-cells are localized at the level of the absorber plate of a thermal collector and heat up a water or air loop that can be valorised for domestic hot water, heat pump coupling, etc… [2]. In a glazed flat-plate PV-T collector (see Fig. 2), the presence of an additional glass cover reduces to some extent the optical performance of the PV module but increases strongly the thermal performances of the collector. As a consequence, the overall energy conversion is better compared to an unglazed collector. In the literature [2-4] the thermal efficiency of developed PV-T collectors under PV operating conditions are usually lower than 60%, whereas it is about 80% for a standard thermal collector and the thermal losses are also much higher than the losses of a standard flat-plate collector. The electrical efficiency of developed PV-T collectors at 25°C is usually about 12 % which is lower compared to pure PV-modules of same PV technology. This is due to the additional glass cover in front of the solar cells, leading to additional optical losses.

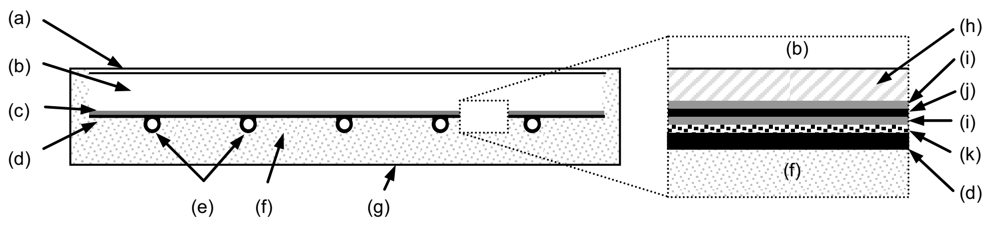

Fig. 2: Representation of a flat plate water PV-T collector. (a) collector glass cover; (b) air layer; (c) PV cells; (d) metal sheet; (e) metal tubes; (f) thermal insulation; (g) frame; (h) PV module glass; (i) EVA layer; (j) solar cell; (k) Tedlar layer + adhesive.

2. Analysis of PV-T performances

2.1 Modelling of thermal performance

In order to understand and to quantify the discrepancies in terms of thermal efficiency between a PV-T collector and a classical thermal collector, a simplified 2D model has been developed and used to simulate the thermal (and - in the case of PV-T – also the electrical) efficiency curves according to its parameters. The simple 2D model is based on the equations presented by Duffie and Beckmann [5] with modifications in order to take into account the photo-conversion and the specificities of PV-T collectors.

In fact, in the case of a PV-T collector, two different modes have to be described. In the open-circuit mode, the solar cells are not connected to a MPP-tracker and therefore the PV-T collector behaves like a standard thermal collector (η_{elec} = 0), and therefore it thermal efficiency is given by the equation (1) where $(\tau\alpha)$ is the effective transmission absorption product, U the thermal losses coefficient, G the incoming solar radiation and ΔT the difference between the absorber temperature and the ambient temperature.

Open-circuit mode :

$$\eta_{Th(oc)} = (\tau\alpha)_{eff(oc)} - \frac{U_{oc}\Delta T}{G} \; ; \; \eta_{Elec} = 0 \tag{1}$$

In the maximal-power-point mode, the solar cells are connected to a MPP-Tracker and therefore part of the incoming radiation is converted into electricity ($\eta_{elec} > 0$) and therefore can not be transferred into heat. That impacts the values of $(\tau\alpha)$ and U. Equation (2) describes the corresponding thermal and electrical efficiencies, where τ_c is the collector glass cover transmission coefficient, r_c the module packing factor, η_{ref} the cell reference efficiency, β the temperature dependence coefficient of the solar cell, T_{pv} the solar cell temperature and T_{ref} the solar cell reference temperature.

MPP-mode :

$$\eta_{Th(mpp)} = (\tau\alpha)_{eff(mpp)} - \frac{U_{mpp}\Delta T}{G} \; ; \; \eta_{elec} = \tau_c r_c \eta_{ref}\left(1 - \beta * \left(T_{pv} - T_{ref}\right)\right) \tag{2}$$

At the η_0 point, corresponding to a situation when the absorber temperature (assumed to be the PV cells temperature) is equal to the ambient temperature, the term with the thermal losses disappears and the equation (2) is modified, as presented in the equation (3), where α_c is the absorber plate absorption coefficient.

$$\eta_{th(mpp)} = (\tau\alpha)_{\mathrm{eff(mpp)}} = 1.01\tau_c\alpha_p - \tau_c r_c \eta_{ref}\left(1 - \beta * \left(T_{amb} - T_{ref}\right)\right) \tag{3}$$

The thermal losses coefficient needs also to be modified. In fact, based on the absorber temperature, the electrical and thermal efficiencies of PV-T collector are equal to the thermal efficiency in open-circuit mode.

$$(\tau\alpha)_{eff} - \frac{U\Delta T}{G} = (\tau\alpha)_{eff(mpp)} - \frac{U_{mpp}\Delta T}{G} + \eta_{Elec} \tag{4}$$

Which corresponds to

$$U_{mpp} = U_{oc} - \tau_c r_c \eta_{ref}\beta G \tag{5}$$

For a given collector inlet temperature T_{in}, the heat removal factor can be calculated according to the equation (6)

$$F_R = \frac{\dot{m}C_p}{A_c U}\left[1 - \exp\left(-\frac{A_c U F'}{\dot{m}C_p}\right)\right] \tag{6}$$

where $\dot{m}$ is the collector flow rate, A_c the collector area, C_p the fluid heat capacity and F′ the collector efficiency factor, given by equation 7. As for a standard thermal collector, this collector efficiency factor depends on the absorber geometry. k_p and t_p stand for the thermal conductivity and the thickness of the metal sheet, W for the distance between two neighbouring tubes, D for the tube outer diameter and D_i for the tube inner diameter, h_{fi} is the heat transfer coefficient between metal tube and fluid (convection). In the case of a PVT collector, the collector efficiency factor also depends on the values of k_{si} and t_{si} which is the thermal conductivity and the thickness of the PV material and on the heat transfer coefficient between PV cells and metal plate (conduction) h_{pf}, see equation (7).

$$F' = \frac{1/U}{\dfrac{W}{U\left(D + (W-D)\dfrac{\tanh\left(\sqrt{\dfrac{U}{k_{si}t_{si}+k_p t_p}}(W-D)/2\right)}{\left(\sqrt{\dfrac{U}{k_{si}t_{si}+k_p t_p}}(W-D)/2\right)}\right)} + \dfrac{1}{h_{pf}} + \dfrac{W}{\pi D_i h_{fi}}} \quad (7)$$

Using the equations, the PV cell temperature can be extracted as described in the equation (8).

$$T_{PV} = (1-F_R)\left[\frac{G(\tau\alpha)_{eff}}{U} + T_{amb}\right] + F_R T_{in} \quad (8)$$

From these equations a whole thermal efficiency curve can be obtained. The calculation is grounded on the variation of inlet temperature while the other parameters are kept constant, using a double iteration loop to solve the set of equations. The Figure 3 presents the calculated efficiency curve of a selective flat plate collector and a PV-T collector.

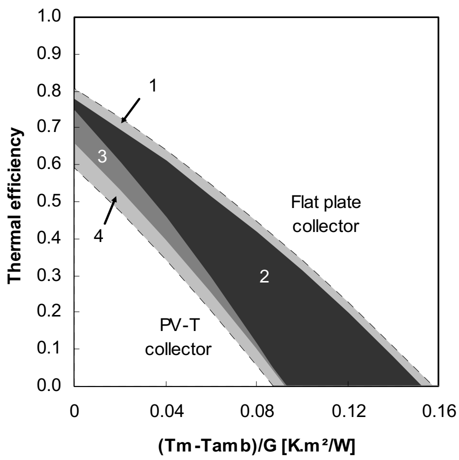

Fig. 3 Calculated thermal efficiency curve of a standard thermal collector (selective) and a PV-T collector (under PV operating conditions). Differences are mainly due to a lower absorption coefficient (1), higher emissivity (2), bad thermal contact (3) and conversion of radiation into electricity (4).

The results of those calculations show that, in opposition to our expectations, the conversion of a part of incoming radiation into electricity is not the main reasons to explain the differences in term of thermal efficiency. In fact, the PV plate emissivity, the absorption coefficient and the quality of the thermal contact between solar cell and cooling fluid are the main parameters affecting the thermal performance. In the part 2.2, we describe, according to those calculations, possible way of improvement of both thermal and electrical performances.

2.2 Ways of energy performance improvements

The various investigations that we led allow to identify important ways of improving the performance of the hybrid collector :

- Reduction of optical losses. This is possible by using a collector glass cover with increased solar transmission. Usually, for standard thermal collector, a low iron glass pane with a transmission of around 0.91 is used. By using a double sided coated Anti Reflection Coated (ARC) low iron glass cover with a transmission coefficient of, for example, 0.95, it can increase both thermal and electrical performance.

- Increase of absorption coefficient. In the case of standard PV modules, the absorption coefficient is optimized for the sensitivity range of the PV conversion (300-1100 nm for c-Si PV cells). However, in the case of PV-T collectors, the absorption coefficient is, for thermal reasons, relevant with respect to the complete range of the solar spectrum (300-2500 nm). Some investigation at the solar cell level and also in the different layer used to build the module could probably increase this coefficient.
- Heat transfer enhancement. The method of bonding the PV cells to the thermal absorber metal sheet can be improved. In fact, for most of the PV-T collectors described above, an additional adhesive layer between PV module and metal sheet is used. However, this leads to a low heat transfer rate between PV cell and metal sheet. In this case, the thermal conductance of this layer is estimated between 45 and 100 W/m²K [16]. In order to increase the heat transfer between PV cells and metal sheet a more advanced technique can be used for PV-T, the single package lamination [6-7].
- Reduction of thermal losses. It is possible to reduce the thermal losses of the PVT collector by applying low-e coating on the glass cover or on the absorber plate [8].

3. Experimental development and testing of an improved PV-T collector

Based on the experimental investigations, the modelling and numerical simulations done in the part 2, a PV-T collector has been developed. The investigations concerning material aspects and challenges in the development of PVT collectors that were carried out in our project are described in reference [6,10] .The absorber plate was made of two PVT panels having each 18 pseudo square sc-Si PV cells connected in series. The total surface area of the absorber was 1.27 m². The ratio between the solar cell active area and the full absorber surface (packing factor) was 0.67 and the absorber absorption coefficient was measured around 0.94 (use of improved PV module materials). The heat transfer coefficient between PV cells and plate (conduction) h_{pf} was estimated to be around 700 W/m²K.

A single glazed flat plate PV-T collector was built using this PV-T absorber. The front cover was 4 mm thick low-iron glass with an anti-reflective coating. The thermal insulation on the back of the absorber is 60 mm thick and the edge insulation is 40 mm thick. The performance of this PV-T collector was measured at the indoor solar simulator test facility of Fraunhofer ISE. The efficiency values presented in the Figure 4 are based on the absorber surface area. In the Figure 5, the thermal efficiency curve of the developed collector is compared to the thermal efficiency curves of a typical PVT collector and a standard thermal collector.

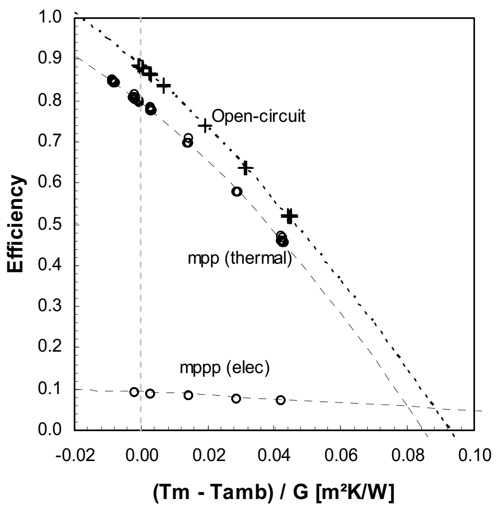

Fig. 4 Thermal efficiency curve measurements using an indoor solar simulator of the newly developed PV-T collector, under PV operation conditions (circle) and without PV extraction (cross)

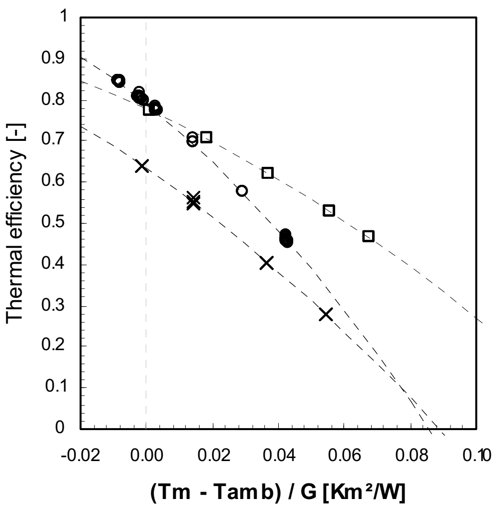

Fig. 5 Thermal efficiency curve measurements using an indoor solar simulator of the newly developed PV-T collector under PV operation conditions (circle), an existing PV-T collector under PV operation (cross) and a thermal collector with selective absorber (square)

The thermal efficiency at zero reduced temperature was measured at 79 % under PV operation with a corresponding electrical efficiency of 8.8 %, leading to a high overall efficiency of 88 %. These experimental results indicate a significant improvement of both thermal and electrical performance in comparison to previous work on PV-T collector concepts [2-4]. The optical performance of the experimental collector reaches values which are as high as good solar thermal only collectors. However, the heat loss coefficient of this collector is significantly higher than those of a highly efficient flat plate collectors, but still in the same range as some less efficient solar thermal only collectors on the market.

4. TRNSYS PV-T system simulation

TRNSYS simulations [9] were carried out for a solar domestic hot water system for different configurations (thermal collector, PV array and optimized PV-T collectors).

The Figure 6 describes the domestic hot water system (DHW) used for PV-T and respectively solar thermal system. For side by side installation, only one collector is simulated (2.5m²) with a 2.5m² standard PV module. For a fully PV-T installation, a 5m² PV-T collector is simulated.

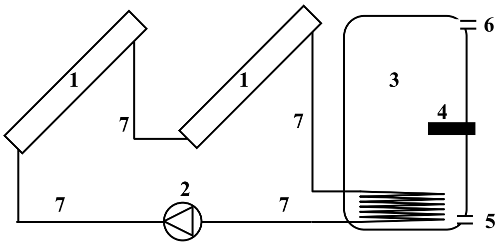

Fig 6: DHW description. 1. collector; 2. pump with controller; 3. 200L water storage; 4. Auxiliary heating (55% of tank height from bottom); 5. cold water inlet flow (15°C); 6. outlet flow (60°C); 7. collector loop piping;

TRNSYS simulations were carried out using parameters extracted from experiments. Paris (France) weather data were used and a daily consumption of 125 litres/day of hot water at 50°C was assumed for a whole year period. Both, yearly thermal and electrical output are presented in the Figure 7 and 8.

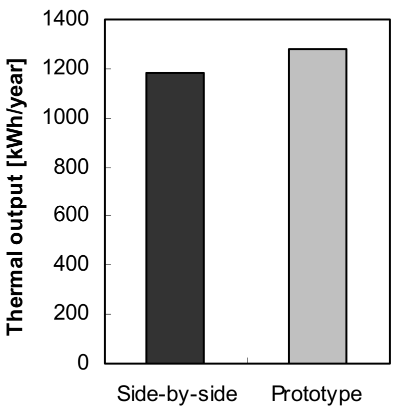

Fig. 7. Thermal energy yield (TRNSYS) of both PV-T and side-by-side systems in Paris (France).

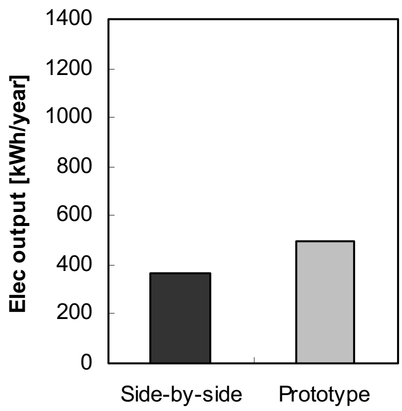

Fig. 8. Electrical energy yield (TRNSYS) of both PV-T and side-by-side systems in Paris (France).

The investigations show that the system with hybrid PV-thermal collectors built in this project has a better overall performance than side-by-side installations. We therefore expect that PV-T systems will receive more importance in the future, especially when further improvements are implemented.

5. Conclusion

For conventional photovoltaic modules, 80 to 90 % of the incoming radiation is absorbed by the module whereas only approximately 8 to 16 % is converted into electricity, depending on the PV-technology. In fact, most of this absorbed energy is wasted into heat. In this context, the development of hybrid components like PV-Thermal (PV-T) solar collectors can offer a solution to use the produced heat of PV modules. In a PV-T collector, PV cells operate as a thermal absorber and heat up a water or air circuit that can be used for domestic hot water, heat pump coupling, etc…

Based on a simple thermal and electrical 2D model, the thermal and electrical efficiency of such a collector was simulated according to the collector properties and key-parameters for performance improvements, like heat transfer between solar cell and fluid or emissivity were defined and quantified. Based on those investigations a collector has been built with improved assembling methods focusing on both heat transfer between PV cells and fluid and on optical properties of materials. Thermal and electrical measurements on this developed PV-T collector were carried out in the indoor testing facility with solar simulator. At zero reduced temperature, a thermal efficiency of 79 % has been reached under PV operation for a corresponding electrical efficiency of 8.7 %. The overall efficiency is quite high (87.7 %) compared to results found in literature.

TRNSYS simulations of PV-T solar system (DHW) were carried out. The investigations show that hybrid PV-thermal system using our PV-T collector can have a better overall performance than side-by-side installations. And additional possibilities exist for further improvements. Some of them may even be achieved quite easily as, for example, increasing the packing factor. Therefore we believe that PV-T systems will receive more importance in the future, especially when identified improvements will be implemented.

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