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The PHOTOTHERM project: full scale experimentation and modelling of a photovoltaic - thermal (PV-T) hybrid system for domestic hot water applications

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Abstract

Photovoltaic-Thermal (PV-T) hybrid collectors are a promising technology, representing an efficient exploitation of solar energy with which to fully optimize the surfaces of integration within the building envelope. In spite of sustained interest since the mid 70s, there are only few studies providing a statement on the actual utility of this technology for real usage scenarios.

In 2012, the project PHOTOTHERM was initiated with the aim of evaluating the real potential of covered water based PV-T collector coupled to a Solar Domestic Hot Water System (SDHWS).

In this paper, first results obtained in the frame of this project are presented. First the design and indoor performance of the selected PV-T prototypes are presented, and the full scale PV-T plus DHWS system installed at EDF R&D outdoor test facilities is described. The results of monitoring this test system are presented and discussed. Finally, an overview on the on-going work regarding PV-T collector and system simulation is presented as well as the next steps of the project.

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Keywords : Photovoltaic-thermal hybrid collector, domestic hot water, monitoring, dynamic modelling

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1. Introduction

Although a classic photovoltaic module may absorb 80 to 90 % of incident solar radiation, typically only 10 to 20 % of the incident energy is converted into electricity. The remainder is dissipated as heat and is lost. In this context, a covered hybrid Photovoltaic – Thermal (PV-T) module makes use of this absorbed radiation, producing electricity and acting as a heat source.

The hybrid PV-T collector concept has been developed since the mid 70s. They have gained increased attention in recent years as a result of a growing market for low-energy or positive-energy buildings. Indeed, these kinds of buildings require new active and multifunction envelopes that are able to cover the energy needs of the building, for example through the installation of building integrated photovoltaic (BIPV) systems. In this framework, PV-T collectors have the interest of producing domestic hot water and electricity simultaneously. Thus, these collectors represent an alternative solution to potential usage conflicts of building envelopes.

Theoretical, numerical and experimental studies of PV-T collectors are reviewed in [1] and [2]. Only a few of the reviewed studies entailed a complete R&D investigation, dealing with an innovative prototype development, a deep study of its behaviour in an experimental system, and its modelling both alone and in the global system.

In that context the PHOTOTHERM project was launched in 2012. A collaboration between INSA – Lyon and EDF R&D, the project runs until 2014. Its main objective is to provide a definitive statement on the real potential of a PV-T collector by evaluating accurately the performance of a single well-understood covered water based PV-T collector functioning as a part of a Solar Domestic Hot Water System (SDHWS). The PHOTOTHERM project will provide results regarding the monitoring and modelling of a full-scale SDHWS system using improved PV-T prototypes under real climatic conditions.

In this paper, preliminary results obtained in the framework of the project PHOTOTHERM are presented. First the design and indoor performance of the selected PV-T prototypes are presented. The full scale DHWS system using PV-T prototypes is then described and the results of monitoring are discussed. Finally, an overview on the on-going work regarding PV-T collector and system simulation is presented as well as the next steps of the project.

Nomenclature

| | | | |
|---------------|------------------|-----------------|---|
| ρ | density | Φ_{sw} | shortwave radiations |
| C_p | thermal capacity | Φ_{lw} | longwave radiations |
| V | volume | $\Phi_{conv,w}$ | conductive flux between the fluid and the exchanger |
| Φ_{conv} | convective flux | $\Phi_{flow,w}$ | heat flux linked to the flow of the fluid |
| Φ_{cond} | conductive flux | | |

2. Design of PV-T components under investigation

A full and accurate study of the component materials and manufacturing processes for hybrid PV-T modules was undertaken in a previous project (EDF R&D / INSA Lyon / Fraunhofer ISE). The outcome of this project was a high efficiency prototype, composed of a flat fractal heat exchanger [3] coated with an electrically insulating film laminated with 32 interconnected mono-crystalline silicon solar cells (mc-Si), encapsulant material and a low-refractive-index polymer film as front layer. The laminated PV-T absorber is then inserted into a collector housing with high transparency glass on the front and thermal insulation on the back (See Fig. 1).

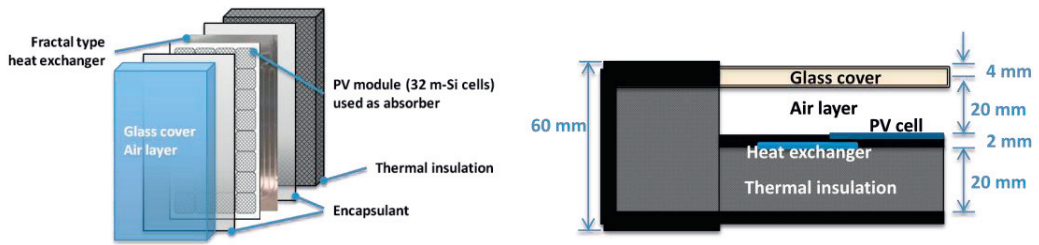


Fig. 1 : Elements and schema of the PV-T prototype

Solar thermal and PV components do not exploit the same range of radiation wavelengths and are not so complementary due to the temperature dependence of photo-conversion efficiency. In this context, an alternative PV cell lamination has been developed with increased optical and thermal performance [4,5]. This comprises a front layer with a low refractive index instead of a glass cover and a low UV absorbing layer instead of the conventional EVA material. mc-Si cells have been encapsulated and their electrical performance was characterised under standard operating configurations (EQE, I-V and reflection measurements). As a result of these changes, an increase of more than 2mA/cm² in generated current density was attained for the PV-T encapsulation module. Also, an increase in the solar absorption coefficient was achieved compared to equivalent mc-Si cells laminated as a conventional standard glass/EVA/mc-Si/EVA/Tedlar module.

3. Performance evaluation under controlled conditions

Thermal and electrical performance of the prototype was measured under controlled conditions according to EN12975 standards at the TestLab Solar Thermal Systems of Fraunhofer ISE. The collector was tilted with an angle of 45° and exposed to a constant average global irradiation. In order to take into account the radiation losses from the collector to the surroundings, the simulator is equipped with an artificial sky and a controlled wind speed blown in a parallel direction to the collector simulates the convection losses. The fluid flow rate was fixed at 72 kg/h per m² of aperture area. The average wind speed was 3 m/s, the ambient temperature fixed at 29 °C and the global irradiation reaching the collector was assumed to be constant at 958 W/m² [4]. The fluid inlet temperature was changed incrementally and outlet temperatures was measured as shown in figure 2.

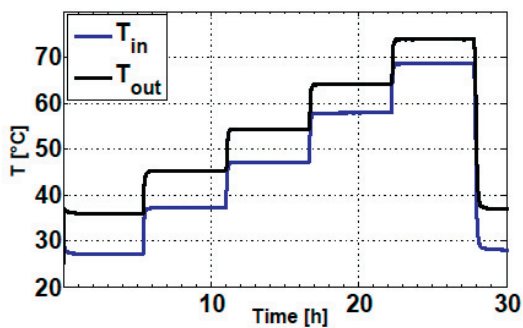


Fig. 2: Thermal experimental results of the PV-T collector at controlled conditions with PV operating in maximal power point.

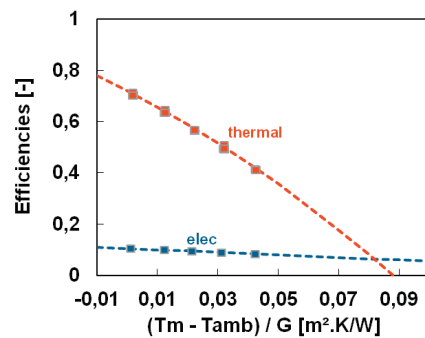


Fig. 3 : Thermal yield from the measurements

In these conditions, the prototype offered an unprecedented level of solar energy conversion efficiency: the experimental validation confirmed a thermal efficiency for domestic hot water of the PV-T module exceeding 70 % (Fig. 3), with a simultaneous electrical efficiency of 10.5 % [4]. These results showed a significant improvement of both thermal and electrical efficiency in comparison to other PV-T designs found in literature [1].

4. Monitoring under real conditions and preliminary results

The high component efficiencies reported for controlled conditions (Fig. 2b) are insufficient to assess the overall potential of the prototype. It must be evaluated as part of a complete system and real (varying) environment in order to make a statement on this PV-T collector technology. Additional experimental measurements in outdoor test conditions are essential to provide these data. A PV-T collector array was installed on the Building Envelope & Solar Technologies Laboratory (BESTLAB) at EDF R&D, coupled to a real domestic hot water system and monitored under an extended period. The solar array included six PV-T modules (1 m² each) oriented south with an inclination of 45° (Fig. 4), coupled to a domestic hot water system with simulated water consumption (average : 157 l/day at 55°C).



Fig.4 : Photos of the PV-T modules installed on the roof of BESTLAB

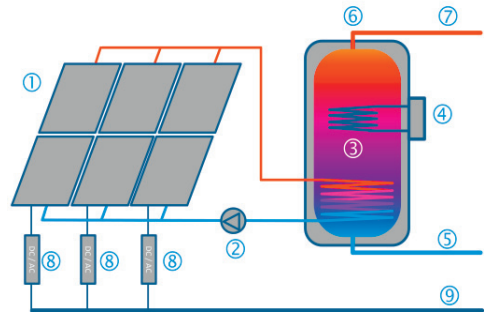


Fig.5 : Schema of the domestic hot water system. 1- PV-T collectors ; 2 – Pump (flowrate 4l / min; 3 - 300L water storage with delta T controller strategy 7/4°C ; 4 - Electrical auxiliary heating (nominal power 2.4 kW) 5 - Cold water inlet; 6 - Warm water out

In the installed system, the pump drives the circulation of glycolic water from the heat exchanger in the tank to the PV-T collectors, and micro-inverters inject electricity produced by the PV-T modules into the local grid (Fig. 5).

Weather data (total radiation on titled plan, ambient temperature and wind velocity), inlet and outlet fluid temperatures as well as module surfaces temperatures, flow rates, PV electric production and auxiliary heating consumption were monitored on a minute-wise basis since summer 2012.

Figures 6 and 7 present a sequence of data comprising measurements taken between 01/09/2012 and 10/09/2012. The electrical power and the solar global radiation on the plane of the PV-T modules are presented in figure 6. During the period of 13 days, a total PV energy of 29.5 kWh was produced for an average total radiation of 6 kWh/m²/day, equivalent to a mean electrical efficiency of 8.5 %. This rather low efficiency can be partially accounted for by losses in cabling from collectors to inverters (approx. 50 m), which were longer than for typical BIPV systems due to limitations presented by the experimental site.

Ambient air, and glycolic water inlet and outlet temperatures are presented in figure 7. It is observed that the set point temperature (55°) was achieved by the PV-T installation throughout the period except for the most cloudy days in the monitoring period (day 4 and 11). Nevertheless, the fluid temperature and consequently the PV-cells reach as high as 100 °C during sunny days, exceeding the acceptable limit of the PV material. Finally, the thermal energy during the studied period is estimated at 129 kWh, representing 36 % of the incoming solar energy.

For a better understanding of the system yield and to evaluate the effect of possible improvements in the system, a detailed numerical model was constructed and validated using the experimental data. In the following section, the first steps in the development of a new PV-T collector dynamic modelling are presented.

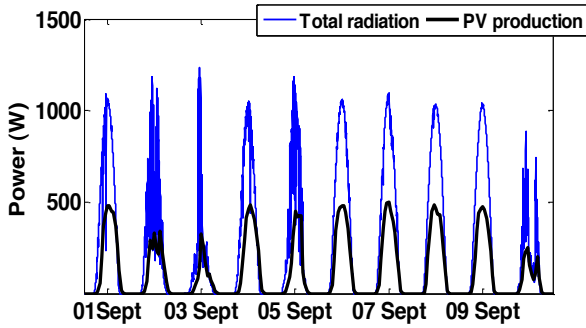


Fig. 6 : Measurements of PV power and solar radiations

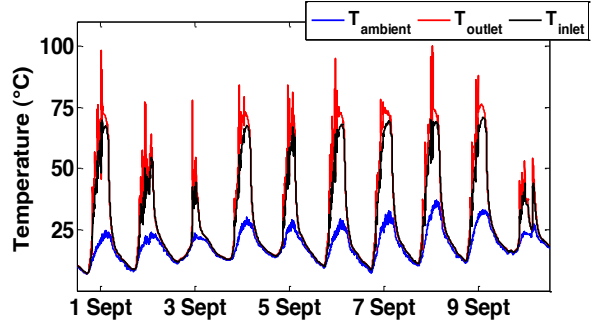


Fig. 7 : Measurements of inlet, outlet and ambient temperatures

5. PV-T dynamic modelling

Numerous PV-T models exist in the literature; the flat plate analytic model of [6], adapted to PV-T collectors by [7] appears to be the most widely used. This kind of model is used in steady state and dynamic modes despite the fact that they are derived from a consideration of the steady state regime. Despite this limitation, dynamic 3D models are implemented since the begin 2000 [8-12]. These models are based on thermal balance on one hand, and the thermal behavior of PV yield on another.

A finite volume model is implemented in the PHOTOTHERM project framework. For each control volume the thermal energy balance can be described as follows:

$$\rho C_p V \frac{\partial T}{\partial t} = \Phi_{conv} + \Phi_{cond} + \Phi_{sw} + \Phi_{lw} \tag{1}$$

Where ρ [kg/m³] is the density; C_p [J/(m³K)] is the thermal capacity of the considered control volume and V [m³] its volume. Besides, Φ_{conv} [W/m²] is the convective flux; Φ_{cond} [W/m²] designs the conductive flux; Φ_{sw} [W/m²] represents shortwave radiation and Φ_{lw} [W/m²] is the longwave radiation. These fluxes are defined in [6,9 and 10].

The fluid temperature evolution during its flow in the heat exchanger is calculated by

$$\rho_w C_{p,w} V_w \frac{\partial T_w}{\partial t} = \Phi_{conv,w} + \Phi_{flow,w} \tag{2}$$

Where $\Phi_{conv,w}$ [W/m²] is a conductive flux between the fluid and the heat exchanger and $\Phi_{flow,w}$ designs the heat flux linked to the flow of the fluid defined in [8, 9, 10, and 12].

One particular feature of this model is the implementation of a Voronoi tessellation centered on the branching points of the heat exchanger. This particular meshing is well-adapted to the fractal structure of the heat exchanger [13]. Finally, contrary to other works that apply the usual linear relation between PV production and temperature, a U-I model for each cell of the module has been implemented in our case. This method allowed mismatch effects linked to the temperature differences between the cells to be taken into account [14 - 16].

A preliminary validation comparing thermal outputs of the model to measurements in controlled conditions as presented in section 2 are shown in figure 8. The calculated outlet temperatures are observed to follow very closely to the measured data. The calculated outlet temperatures are generally less than the measured value by between 0.1 °C and 0.2°C, for a mean error of -0.16°C. Only outlet temperature at step temperatures transitions diverge punctually from about 1 °C.

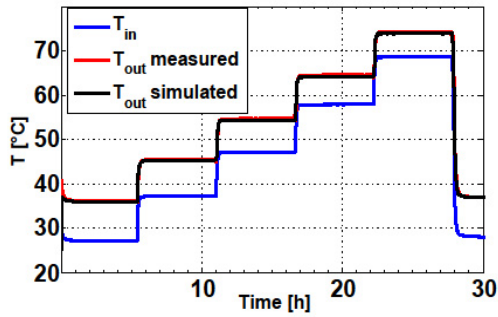


Fig. 6 : Thermal model results of the PV-T compared to measurement at controlled conditions and PV operating in maximal power point

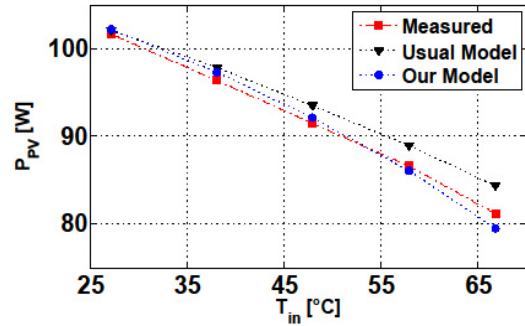


Fig. 9 : Electrical model and PV power results of the PV-T compared to measurement at controlled conditions at maximal power point

Finally, figure 9 shows the a model-data comparison for the maximal PV power for each inlet temperature in the same experimental conditions. The maximal power calculated by our model are close to the measurements; at the upper limit in inlet temperature a maximum difference of 1.7 W was observed (or 2 % relative error). This compares to a discrepancy of 3.1W, or 3.5 % for a conventional linear model.

These first results suggest that this dynamic 3D model offers an accurate description of the system. However, a validation under dynamic regime and real conditions must also be realized.

6. Conclusion and future work

A high efficiency PV-T prototype has been developed during a joint project between EDF R&D, the Fraunhofer ISE and the INSA-CETHIL. The PV-T system converts a majority of incident solar energy into useful electricity and recovered heat. Previous experimental measurements under controlled conditions showed an unprecedented performance of 80 % of thermal yield and 8.8 % of PV yield. The PHOTOTHERM project builds upon this research, with a complete R&D work of a functioning SDHWS system under outdoor experimental conditions.

The first days of monitoring of PV-T modules coupled with a domestic hot water system show that the prototypes present high performance in real climatic conditions, hitting 44.5 % of combined thermal and electrical efficiency. These first results confirm the measures realized under controlled conditions.

Finally, a dynamical component model is currently under development. It couples a 3D thermal model based on the heat balance and the Shokley diode equation to compute the module temperatures and to simulate the PV production. The experimental data for steady state conditions allowed a validation of the model in this regime, whereas the transient state model is still under development.

Once the model is validated, larger solar systems will be implemented and studied in order to elaborate optimal strategies for component interconnection and the management of the energy cogeneration versus building needs (heat and electricity).

Acknowledgements

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