Study of a Photovoltaic-Thermal Hybrid Collector with Juxtaposition of Thermal Energy Production Functions

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ABSTRACT

This work proposes a mathematical dynamic modeling of a PV-T bi-fluids collector prototype that will permit electricity production and preheating air and/or hot water production.
This study is realised in a bi-dimensional geometry according to some assumptions. The collector is discretized along the flow and the collector slope is taking into account in the radiative transfers equations. Thus, a TRNSYS software type is developed in order to describe the thermal and electric behavior and performance of this collector in dynamic conditions.
Then, an experimental study is presented on a test bench in situ on the PV/T air panel configuration (without water production option) which is integrated in a building roof.

KEYWORDS

Solar collector, Mathematical model, TRNSYS, photovoltaic

INTRODUCTION

The use of heat removal fluids permits to improve the electrical conversion efficiency by cooling the photovoltaic cells. Through hybrid solar collectors, the extracted heat can be recovered to obtain air preheating in air gaps at the back of PV modules and/or domestic hot water in tubes. These purposes make this kind of technology very attractive for solar applications such as in building and in industry. Hybrid air or water collectors were investigated in several theoretical and experimental analysis. Thus, Bergene et al (1995) presented a detailed steady-state modeling of a PV water hybrid collector. Hollick (1999) reported the experimental study of a solar collector composed of a solar panel stuck on a perforated and corrugated sheet steel. Then, Zondag (2002) investigated numerically and experimentally a hybrid Photovoltaic water collector in various dimensions. Starting from this study, Chow (2002) introduced an explicit dynamic model of a water PV/T collector adapted to simulation. Ji (2003) analysed the annual performance of a hybrid PV air collector integrated into a building facade. Later, Belusko (2004) proposed the modeling of a solar air collector with a metal corrugated absorber by comparing it to an unglazed solar collector. The aim of this study is to present a dynamic 2D thermal model of the PV/T hybrid bi-fluid solar collector using Trnsys software in order to optimize the behavior of such component in a building integrated configuration. Then, experimental studies are led in controlled limit conditions and in situ in order to validate the results of the simulation.

ASSUMPTIONS AND THERMAL ANALYSIS OF THE SYSTEM

The photovoltaic-thermal collector studied is shown schematically in Figure.1. It consists in a ribbed metal sheet absorber on which is fixed a PV plate through a thin adhesive layer. There is an air gap between the absorber and an insulation layer. In the rib covered by an insulation layer and being used for the mechanical resistance of metal sheets, some insulated pipes are integrated allowing the circulation of water. A thin absorber is welded to each tube. The prototype dynamic 2D model is composed of the Photovoltaic air collector model and the water collector model These models are based on a nodal approach according to some assumptions. The collector is segmented in the x-direction (along the flow) according to a step dx. The temperature at each node can be considered as a mean temperature. The slope of the collector is taking into account in the solar radiation evaluation. It is assumed that there is no heat flow through the insulation layer under the air gap. In this study, only a rib and two halves of solar panel are considered.

Nodal Approach

The layers constituting the system are represented by some nodes. The nodes T_c and T_e represent the sky and the ambient air temperatures, T_1 and T_9 are for the PV modules and the metal sheet. T_8 is for the base of the metal rib and T_7 and T_4 are for the inclined part of the rib. T_3 and T_{12} represent the insulation layer, T_5 and T_{10} are for the air in the gap, T_6 and T_{11} are the mean radiant temperature of the air gap. T_{19} is for the glass layer, T_{21}, T_{22} and T_{13} are for the insulation layer in the rib. T_{15} represents both the copper tube and the absorber. T_{14} is for the insulation layer under the tube, T_{20} is for the water in tube, T_{17} and T_{18} are for the radiative and convective temperatures of the confined air gap in the rib. T_{win} is the inlet water temperature and T_{fin} and T_{fin2} are the inlet air temperatures in the air gap. T_{iconv} and T_{irad} are for the interior air temperatures.

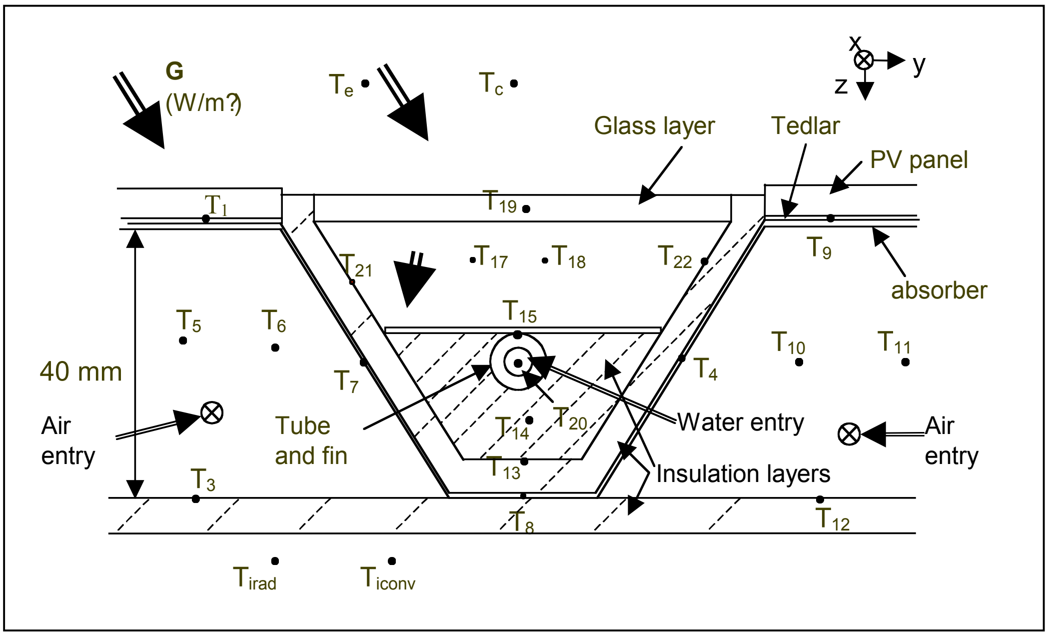


Figure 1: Cross section of the collector prototype

Modeling of the PV-T bi-fluids collector

The first part of the heat balance concerns the PV air collector, which consists in the air gap, the metal absorber, the Photovoltaic cells and the base of the rib. The equation at the PV modules node is given by Eqn.1, Chow (2003):

$$M_1Cp_1 * dT_1/dt = K_{1-e} (T_e - T_1) + K_{1-c} (T_c - T_1) + K_{5-1} (T_5 - T_1) + K_{6-1} (T_6 - T_1) + K_{7-1} (T_7 - T_1) + G\tau_{verre}\alpha_{cell} b_2 dx - G r_c \eta_{cell} b_2 dx$$

Where b_2 is the width of the PV panel, in meter, r_c is the ratio of cells area to aperture area (-) and η_{cell} is the temperature-dependent solar cell operating efficiency (-). L is the length of the collector, in meter and α_{cell} is the absorptance of photovoltaic modules (-), the solar radiation G is in W/m².

If q_{mf} is the air mass flow rate in kg/s and C_{pf} is the specific heat of air in J/kg.K, the air heat balance equation in the gap is given by Eqn.3:

$$M_5C_{p5}dT_5/dt + q_{mf}C_{pf}(T_5 - T_{fin}) = K_{1-5} (T_1 - T_5) + K_{7-5} (T_7 - T_5) + K_{5-3}(T_3 - T_5)$$

The Nusselt number Nu for forced convection in the gap can be obtained from this equation for fully developed turbulent flow in tubes or ducts, Petukhov (1970).

$$Nu = \{ (f/8) R_e P_r) / (1,07 + 12,7 (\sqrt{(f/8)}) (P_r^{2/3} - 1)\} (\mu / \mu_w)^{0,11})$$

With R_e is the Reynolds number (-), P_r is the Prandtl number (-), μ_w and μ represent the dynamic viscosity of water and of air, in kg/m.s and f is a friction factor written as:

$$f = (0,79 \ln R_e - 1,64)^{-2}$$

The water heat balance equation in the tube is given by:

$$M_{20}C_{p20}dT_{20} /dt = K_{15-20} (T_{15} - T_{20}) + q_{mw}C_{pw}(T_{win} - T_{20})$$

The Nusselt number for fully developed turbulent flow is given by the Dittus-Boelter equation (Chow, 2003):

$$Nu_w = 0,023(Re_w^{0,8})(Pr_w^{0,4})$$

With q_{mw} is the water mass flow rate in kg/s and C_{pw} is the specific heat of water in J/kg.K and Nu_w is the Nusselt number for water (-).

TRNSYS INTEGRATION OF THE MODEL

A TRNSYS type representing an elementary volume of length dx of the bi-fluids solar collector was realised according to a zonal method. To obtain the global component, some elements of this type can be connected in series. The weather data, the inlet air and water temperatures and the time (dt) and the space (dx) data of discretization are used as inputs. The geometrical and thermal variables are parameters. The outputs permit to obtain the temperature at each node in dynamic conditions.

EXPERIMENTAL COMPARISON

Description of the experimental device

An experimental study was led in controlled conditions on a test bench at the laboratory in steady-state, Assoa et al (2005). Then, measurements in situ are currently in progress on a building roof at Total Energie society. They permit to obtain experimental values of various operating temperature in several preset points of the PV/T hybrid solar air collector in dynamic conditions.

The experimental setup consists in many instruments: air velocity transducers for air velocity measurement in the air gaps, thermocouples for the temperature measurement of the collector various layers, of the internal and external ambient air and of the air in the gap. An anemometer is used for the wind speed measurement and wind vane for wind direction measurement. Pyranometers are used for the solar global and diffuse radiations measurement. Then, the acquisition is realised using an Agilent HP 34970A data acquisiton system.

Photo 1: Model mounted in situ at Total Energie society (near Lyon-France)

Validation of simulation results

The tests carried out in steady state in controlled conditions provided the following results in Table 1, for a radiation G = 625 W/m² and a mean ventilation velocity V_{air} = 3.5 m/s. The water flow rate is 2l/h. The inlet air temperature is of 24.7°C and the inlet water temperature is of 25.5°C. The ambient temperature T_e is 36.3°C. The box is inclined of 15° and the collector length is 2.7m.

Table 1.
Comparison of simulation results and experimental results

Temperature node	Tsimulation (°C)	Texperimental (°C)
Air outlet Temperature	35.4	38.3
Water outlet Temperature	54	56
Glass layer	52.02	53.4

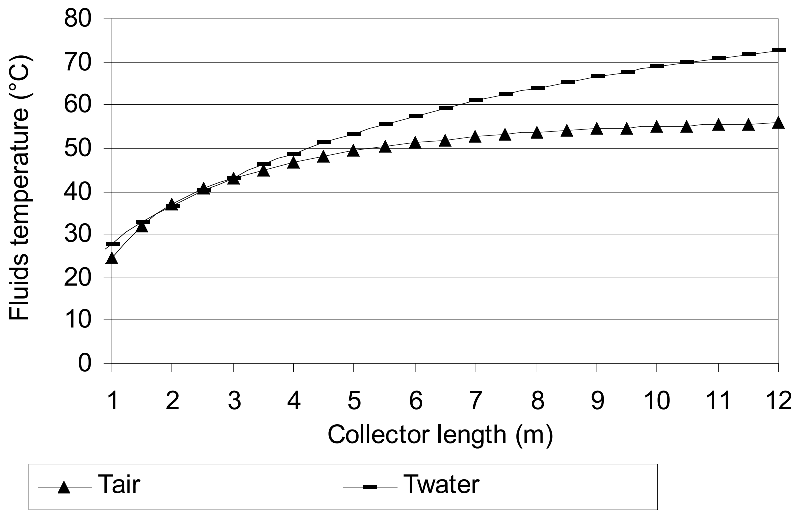
After comparison, the values obtained during the simulation are nearly close to the experimental values. The differences can be explained by the simplifying hypothesis used for the simulation and in particular by the fact that during calculations, the radiation was supposed uniformly distributed on all the surface of the collector, which was not checked during the tests carried out.

ANALYSIS OF SIMULATION RESULTS

A study was carried out using TRNSYS software on the prototype in order to permit the comparison of the collector thermal performances while varying its length L in natural and forced convection of water and air.

Influence of the length of the collector for natural convection

We assumed that the air velocity V_{air} is 0.4m/s, the water velocity V_w is 0.015 m/s, the solar radiation is G=625W/m², T_e=20°C and T_{fin}= T_{win}= 20°C.

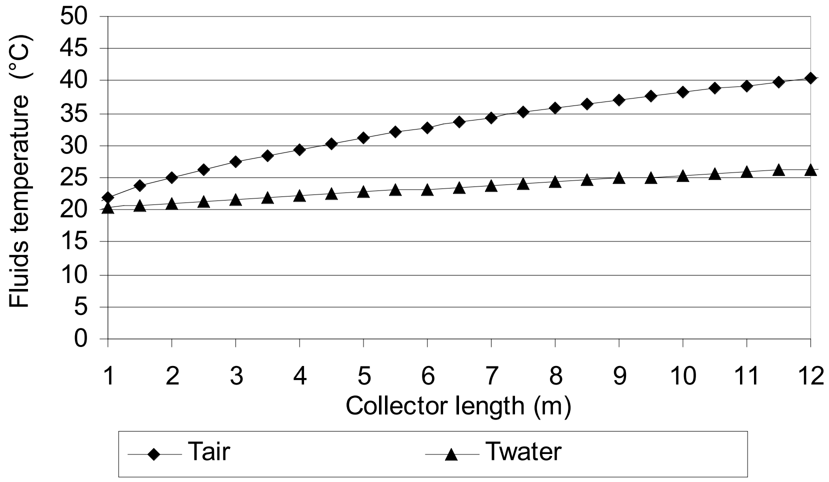


Graph 1- Temperatures of water and air according to the collector length

We can note in Graph 1, an important increase in water temperature on less than 10m of collector. For low lengths of collector, the water collector seems to permit to provide temperatures being able to reach approximately 80°C in natural convection.

Influence of the length of the collector for forced convection

For forced ventilation, we assumed that V_{air}= 4,1m/s, V_w= 0,3 m/s, G=625W/m², T_e=20°C and T_{fin}= T_{win}= 20°C.



Graph 2- Temperatures of water and air according to the collector length

As expected in Graph 2, for a higher velocity of water in tube, the water outlet temperature is very low. As for the temperature gradient of air reaches nearly 20°C on 10 m approximatively of collector. The analysis of these graphs shows that for a low collector length and a mean radiation it is possible to obtain satisfying thermal performances.

CONCLUSION

A mathematical model of the PV/T bi-fluids hybrid collector presented was developed according to simplifying hypothesis. The experimental study carried out confirmed the values obtained during simulation. A parametric study permitted to find the awaited tendencies concerning the temperature of the fluids according to the collector length and the flow regime. The results show that a low water velocity seems to be adequate to obtain a collector adapted to moderate temperature applications so to domestic hot water production. Moreover, it is noticed that low collector lengths seem to be adequate to obtain satisfying thermal performances. It would be interesting thereafter to continue the experimental confrontation in dynamic conditions. Next step already engaged is obviously the consideration of the electric conversion phenomena in the model of the PV-T collector. The serie of in situ measurements are still in progress for the PV/T air panel configuration (without water production option). This project is supported by the French Ministry of Equipment and the ADEME (National Agency of Environment and Energy Management).

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