Energy performance of a low-cost PhotoVoltaic/Thermal (PVT) collector with and without thermal insulation

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Abstract. In this paper the performance analysis of a low cost/t tech PhotoVoltaic/Thermal (PVT) solar collector is presented. The unit under investigation consists of a commercially available flat-plate hybrid unit, based on the use of a polycrystalline PV module and a roll-bond aluminium absorber. The unit is not equipped with any back/frame insulation and glass cover/air layer. A one-dimensional finite-volume model is developed in order to analyse the collector performance. The computational domain is discretized along the longitudinal flow direction of the collector, and mass and energy balance equations are used. This paper is based on a previous work, where the standard PVT collector configuration, without any back insulation, is experimentally and numerically analysed. Here, a possible integration of back insulation layer is analysed numerically considering different insulation materials and thicknesses. In particular, the available experimental data is used in order to simulate the operation of the collector with different back insulation configurations. A comparison between standard and insulated configurations is performed. The performance is also analysed along the discretization direction for all considered configurations. Finally, a sensitivity analysis is performed in order to compare the performance of the several collector configurations as a function of the main design/operation parameters.

1. Introduction

In the recent period, the interest of scientist, policymakers and technicians has been more and more focused to the use of renewable energy sources. In this framework, one of most common renewable energy sources is the solar one, due to its intrinsic extensive availability and sustainability [1]. In this context, two technical solutions are conventionally adopted to produce electrical and thermal energy from the solar radiation. They consist of photovoltaic panels [2] and thermal collectors [3], respectively. These technologies allow one to produce separately electrical and thermal energy. However, the integration of both solutions in a one unit is also possible. In fact, a cogenerative solar collector, namely hybrid PhotoVoltaic/Thermal (PVT) collector [4], is designed to produce thermal and electrical energy at the same time. One of the advantages of a PVT collector is that this type of unit can produce a higher total energy output per unit of area with respect to solar thermal collectors or to photovoltaic panels [5], operating under the same conditions. Moreover, the lower the cell
temperature, the higher the electric efficiency of the PV panel [6]. In addition to this, in case the hybrid collector produces low temperature thermal energy, its efficiency may be higher compared to a PV panel operating under the same conditions of solar radiation, wind speed and air temperature. In particular, the electric performance is higher when the fluid flowing within the absorber operates between 20 and 50°C [7]. Furthermore, it is worth noticing that the performance of the PV cell is affected by the solar energy source available in a specific location [8].

PVT collectors are widely investigated in literature, in terms of experimental and numerical analyses. The investigation of an experimental installation integrating PVT collectors is performed by Tiwari et al [9]. In this study, water cooled flat plate PVT collectors arranged in a series configuration are evaluated calculating the annual energy gain, exergy flows, energy matrices and carbon credits. The authors developed a simulation model and validated it for the climatic conditions of New Delhi. The results outline an annual ratio of thermal energy to generated exergy of about 9.5 and an energy pay-back time analysis of 1.50 years, necessary to pay back the energy used to manufacture the unit. In a similar way, different heat transfer fluids and channels configuration of a PVT collector are studied by Su et al. [10]. In particular, dual channels configuration and combinations of water and air are investigated. The authors find that the best configuration is reached when water is used as heat exchange fluid for both channels with a mass flow rate of 0.15 kg/s, achieving a thermal and electrical efficiency of 76.4% and 7.8%, respectively. Furthermore, Khelifa et al. [11] studied a conventional sheet and tube PVT unit developing an experimental campaign and performing a simulation with a numerical model. The finite-difference method is used, in order to calculate the collector and fluid temperatures. The analysis shows that the PV cell temperature of the hybrid collector is 15–20% lower compared to the one of a conventional PV panel. In addition to this, the difference between the performance of flat plate PVT collector system, with and without glass cover, was investigated by Yazdanifard et al. [12]. Solar irradiation, Reynolds number, packing factor, collector dimensions and pipes configuration parameters are involved in the analysis of the collector performance.

In a similar study, the results outline a better overall energy efficiency of the PVT collector with glass cover compared to the unglazed one. Katiyar et al. [13] investigated a unglazed PVT collector in order to determine the thermal performance. In particular, a detailed steady state numerical model and an indoor solar simulator are used in the study. The model was developed to determine the thermal performance characteristics, as defined by solar thermal, and to perform an optimization of the collector design. The analysis shows that model accurately estimates the indoor experimental data, while for the outdoor thermal efficiency an accuracy of 0.9%.

As outlined by the literature review, there is a significant interest of the scientific community to numerical and experimental analyses of PVT collectors. However, the majority of the literature papers are focused on traditional PVT collectors with glass cover and thermal insulation. Conversely, a scarce investigation of low-tech flat plate PVT collectors is present in literature.

This paper deals with the investigation and the development of a finite volume model of an unglazed and not insulated flat plate PVT collector. The “Janus” PVT collector, manufactured by the Italian company AV Project Ltd., is selected in order to perform the analysis. The experimental investigation is performed on an outdoor installation, located at the Company headquarter in Avellino, Southern Italy, while the collector model is developed with Engineering Equation Solver (EES) software. This paper is based on a previous work [14], where a standard PVT collector configuration, without any back insulation, is experimentally and numerically analysed. In particular, the dynamic data measured by the experimental installation are compared to the numerical results carried out by the simulation. The thermal and electrical performance of the collector is evaluated along the discretized computational domain. Moreover, a sensitivity analysis of the PVT collector performance as a function of the different boundary/operating conditions is developed in order to complete the study.

Here, a possible integration of back insulation layer is numerically analysed considering different insulation materials and thicknesses. In particular, the available experimental data is used in order to simulate the operation of the collector with different back insulation configurations. In particular, a
comparison between standard and insulated configurations is performed. The performance is also analysed along the discretization direction for all considered configurations. Finally, a sensitivity analysis is performed in order to compare the performance of the several collector configurations as a function of the main design/operation parameters.

2. PVT collector description

A commercially available unit is selected for the investigation (Figure 1). An aluminium roll bond absorber and a PV polycrystalline module are used to manufacture the unit. The absorber integrates two separated supply circuits, allowing a uniform distribution of the cooling fluid. In particular, the roll bond absorber is equipped with 48 interconnected trapezoidal channels, each of them having a height of 1.6 mm and a width for the two parallel sides of 10.0 and 6.6 mm. The collector is 1644 mm high and 992 mm wide, while the net photovoltaic module area is equal to 1.44 m².

![Figure 1. Janus PVT collector: front and back of the collector (left), layout of the roll bond absorber channels (centre) and layout of the PV cells (right).](image)

The cross section of PVT unit, from the front to the rear, consists of: solar glass layer, Ethylene Vinyl Acetate (EVA) protecting layer, PV polycrystalline panel, a second EVA layer, a back-sheet of PolyEthylene Terephthalate (PET), butyl adhesive and roll bond aluminium absorber.

The standard Janus PVT unit does not include any glass cover/air and back/frame insulation layers. This configuration defines the most suitable collector application, consisting of low temperature heating in mild/hot climates.

3. Experimental installation

In order to investigate the PVT collector performance, an outdoor experimental installation is used. This installation was previously used by the authors in order to analyse the performance of the PVT unit [14] and to compare it with respect to a conventional PV panel [15]. In particular, the set-up integrates four Janus PVT collectors connected in parallel and other components, like water storage tank, connecting pipes, expansion vessel, safety valve, circulation pump. The technical specifications of the components are reported in [14] and, thus, are omitted here for reasons of brevity.

The installation is equipped with a measurement system, based on the adoption of a multifunction data logger, PV regulator/inverter system, PT100 thermoresistances, K type surface thermocouples, pyrometer and a flowmeter [14, 15]. In particular, the thermocouple sensors are used to measure PVT bottom side and ground temperature while the thermoresistances are used to measure the inlet/outlet temperature of the collector system. As concerns the PV part, a SolarEdge inverter unit was adopted. The component consists of a highly efficient single-phase inverter coupled with a power optimizer allowing a real time monitoring of the PV panels operating parameters.

4. Numerical model of the PVT collector

The PVT collector under investigation is simulated by a 1-D finite volume model. The adopted model is based on the discretization of the PVT collector along the fluid direction (longitudinal axis) in n
equal finite volumes, determining \( n+1 \) computational domain nodes. In Figure 2, the layers of the PVT unit and the discretization are shown.

A model previously developed by the authors [14] is used and modified in order to perform the analysis presented in this study. In particular, for the scope of this work, the model is modified in order to estimate the performance of the PVT collector when an insulation layer is integrated on its back side. The developed model calculates the thermodynamic parameters of the fluid flow, layers temperatures, thermal and electrical powers along the longitudinal direction by solving mass and energy balance equations applied to each element of the computational domain. The model is developed with Engineering Equation Solver (EES) software.

![Figure 2. Computational domain discretization [14].](image)

The model is based on several assumptions: steady-state, thermodynamic equilibrium, negligible kinetic and gravitational terms in energy balances, constant thermal conductivity of solid materials, uniform solar radiation distribution and absorption, uniform temperature distribution in each solid material along cross direction, linear variation of the fluid temperature between the inlet and outlet of each elementary domain. Only for the insulation layer, a linear variation of the temperature along its height is adopted, due to the thickness of this layer that is significantly higher compared to the other ones. In this way, a suitable insulation temperature may be used for a correct calculation of the heat transfer with the surrounding environment.

With the respect to the model developed in reference [14], where nine energy balance equations are used to calculate the temperature within the layers, here, additional two energy balance equations are implemented in order to calculate the temperature inside the insulation layer and the one of the layer-air interface.

The mean temperature and pressure values, calculated between the inlet and outlet of the finite volume, are used to evaluate the fluids properties, while the equations proposed by Incropera and DeWitt [16] are used to calculate the local convective heat transfer coefficients and fluid pressure drop. Finally, manufacturer data regarding geometric and thermal properties of the layers are used to complete the model [14]. Moreover, in the simulation, 20 finite-volume elements are used, a value that allows an acceptable trade-off between linearization error and computational time.

5. Results
In this study, previously collected experimental data are used [14]. Total solar radiation, ambient air and ground temperature, PVT inlet/outlet water temperature, PVT bottom side temperature and water flow rate were measured using a sampling time of 1.00 minute (Figure 3). The flow was set to 5.00 l/min, thus, to 1.25 l/min per each collector. This condition was assumed because: i) no devices are installed that may cause a non-uniform flow distribution among the four PVT collectors, ii) the fluid distribution circuit is hydraulically balanced.

The data reported in Figure 3 are analyzed and compared with the ones obtained by the model in the previous work of the authors [14]. The experiments were performed under Italian climatic...
conditions, nevertheless in the sensitivity analysis the effect of the solar radiation on the collector performance has been investigated. In this study, the same experimental data reported in [14] are used as in order to simulate the operation of the collector equipped with different back insulation configurations and to perform a comparison with the results achieved by the simulation of the standard configuration. Rock wool, polyester and polyurethane foam with different thicknesses are used in order to perform the comparison. In particular, a thickness of 3.0, 5.0 and 7.0 cm is adopted, while a thermal conductivity of 0.018, 0.030 and 0.035 W/(m K) is adopted for the polyurethane foam, polyester and rock wool, respectively. All the nine configurations of materials and thicknesses were investigated.

The performance of the unit is also analysed along the discretization direction for all considered configurations for fixed operating conditions of: 30.0 °C inlet fluid, 25.0 °C air temperature, 30°C ground temperature, 1000 W/m² solar irradiation, 1.25 kg/min mass flow rate. Finally, a sensitivity analysis is performed in order to compare the performance of the several collector configurations as a function of the main design/operation parameters.

![Figure 3. Experimental measurements [14].](image)

### 5.1. Comparison between different configurations based on the use of experimental data

A comparison between model data with and without insulation is performed in terms of outlet temperature for all the insulation configurations. However, only the case of one insulation thickness is here shown for sake of brevity, while the other comparisons are reported in terms of mean values. In Figure 4 the difference of outlet fluid temperature between insulated and not insulated PVT unit for an insulation thickness of 5.0 cm is reported.
As expected, the temperature increase in case of polyurethane foam is the highest, while for the other two insulation materials this increase is lower. This is achieved because the thermal conductivity of polyester and rock wool is higher compared to the polyurethane foam. The increase of temperature ranges between about 0.6 to 1.2°C, while the mean values are 0.869, 0.879 and 0.906°C for rock wool, polyester and polyurethane foam, respectively.

The variation of the insulation thickness only slightly affects the temperature increase. In fact, in case of 3.0 cm the mean values are 0.824, 0.840 and 0.880°C and in case of 7.0 cm are 0.890, 0.898 and 0.918°C for rock wool, polyester and polyurethane foam, respectively. Therefore, as expected higher the thickness of the insulation and better the insulation material are, higher the outlet temperature is. However, the effect of the material is higher in case of lower thickness of the insulation.

5.2. Comparison along discretization direction

The performance of not insulated and insulated PVT collector is compared along the discretization domain for all configurations in terms of fluid outlet temperature, thermal and electrical power, under fixed boundary conditions: 30°C for fluid inlet and ground temperature, 25°C for air temperature, 1000 W/m² for solar radiation, 1.25 kg/min for collector flow rate. In Figure 5 and 6 the fluid temperature and thermal power increase is shown in case of a thickness of 5.0 cm. The fluid temperature along the collector length significantly increases in case of insulation. Obviously, the highest temperature increase is achieved in case of polyurethane foam, however such increase is not significantly different with respect to the one achieved for other materials. In addition, the temperature increase is almost linear due to heat exchange occurring within the collector. The mean temperature increase is 7.22·10⁻³, 7.27·10⁻³ and 7.40·10⁻³ °C/cm in case of rock wool, polyester and polyurethane foam, respectively. The increase of thermal powers follows the trends of the temperature ones. A significant variation of the thermal power can be achieved in case of insulation. The increase varies from 26% for the first domain element to 33% for the last one, while the mean increase is about 30% for all the insulation materials. This occurs because the positive effect of the insulation material is higher for the last domain elements. In fact, the thermal power decreases along domain, thus, the fluid temperature the end part of the collector increases in case of insulation material. Furthermore, the analysis reveals that in case of all insulation configurations the decrease of electrical power production along the is negligible, thus the plot of the trends are omitted. Similar results are achieved in case of other insulation thicknesses.

Figure 4. Outlet fluid temperature difference between insulated and not insulated PVT unit, insulation thickness 5.0 cm.
The mean increase of fluid temperature and thermal power along the collector length for all the insulation configurations is reported in Table 1. Here, it is clearly shown that the effect of the thickness and insulation material is relatively scarce. This is due to the fact that independently by the insulation layer the reduction of the thermal losses is almost the same.

**Table 1.** Operation and performance parameters of the sensitivity analysis.

| Insulation material | Thickness [cm] | Mean fluid temperature increase along the collector [°C] | Mean thermal power increase along the collector [W/m²] |
|---------------------|----------------|----------------------------------------------------------|------------------------------------------------------|
|                      | polyurethane foam | 3.0 | 5.93 | 7.0 |
|                      | polyester | 0.568 | 0.583 | 0.587 |
|                      | rock wool | 0.563 | 0.580 | 0.620 |
|                      | not insulated | 0.568 | 0.583 | 0.580 |

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**Figure 5.** Fluid temperature increase along the discretization domain, insulation thickness 5.0 cm.

**Figure 6.** Thermal power increase along the discretization domain, insulation thickness 5.0 cm.
5.3. Sensitivity analysis: comparison for different operating conditions

The investigated operation and performance parameters are reported in Table 2.

| Selected operation parameters | Investigated parameters                      |
|-------------------------------|-----------------------------------------------|
| solar radiation and mass flow rate | outlet temperature, thermal and electrical efficiency |

However, only some results are plotted for reasons of brevity because the differences between the thicknesses is negligible. The effect of solar radiation for a thickness of 5.0 cm is discussed in Figure 7. The analysis shows that the outlet fluid temperature increase ranges from 0.45 to 0.72°C. In particular, the increase is higher in case of higher solar irradiation values which determine higher temperatures within the collector. For a fixed solar radiation, the increase of outlet temperature is higher in case of polyurethane foam, nevertheless for all insulation materials all the values are close to each other.

![Figure 7. Effect of solar radiation on outlet temperature, insulation thickness 5.0 cm.](image)

The adoption of an insulation layer significantly affects the thermal efficiency, especially in case of scarce solar radiation (Figure 8). In case of 100 W/m² and insulated PVT, the efficiency is still negative, because insulation layer does not completely prevent the cooling of the fluid. It is worth noting that the thermal efficiency increase is scarcely affected by the adopted insulation material.
Furthermore, the analysis revealed that the electrical efficiency slightly decreases when an insulation layer is adopted (Figure 9), according to the temperature increase and PV cell performance. In fact, for all the materials the electrical efficiency drop ranges from $3.9 \cdot 10^{-4}$ to $5.5 \cdot 10^{-4}$. Similar results are achieved for the other adopted thickness values.

The analysis reveals that the effect of the mass flowrate on the performance of the insulated collector compared to standard one is more significant in case of low flow rates 0.25-0.75 kg/min. This occurs for all the investigated performance parameters, as shown form Figure 10 to Figure 12. It is worth noting, that lower the fluid flowrate, higher are the temperatures within the collector and thus higher is the positive effect of the insulation on the thermal performance of the unit. The opposite occurs for the electrical performance.
Figure 10. Effect of mass flowrate on outlet fluid temperature, insulation thickness 5.0 cm.

Figure 11. Effect of mass flowrate on thermal efficiency, insulation thickness 5.0 cm.
Figure 12. Effect of mass flowrate on electrical efficiency, insulation thickness 5.0 cm.

6. Conclusions
In this paper the performance of a not insulated low cost PVT collector is compared with one achieved in case of back insulation. Three different insulation materials are considered with three different thicknesses. Experimental data is used as boundary conditions to perform the simulation and to compare the results. The performance is analysed along the discretization direction for all considered configurations. The study is completed with a sensitivity analysis, performed in order to compare the performance of the several collector configurations as a function of solar radiation, mass flow rate and fluid inlet temperature operating parameters. The results show that:
- using the experimental data as boundary conditions, the calculated increase of temperature ranges between about 0.6 to 1.2°C, while the mean values are 0.869, 0.879 and 0.906°C for rock wool, polyester and polyurethane foam, respectively;
- the thermal power increase varies from 26% for the first domain element to 33% for the last one, while the mean increase is about 30% for all the insulation materials and 5.0 cm insulation thickness;
- varying the solar irradiation conditions, increase of the outlet fluid temperature with respect to the not insulated PVT configuration ranges from 0.45 to 0.72°C;
- under nominal operation conditions, the thermal efficiency of the insulated units ranges between 27.1 and 27.5% for the investigated insulations, which is about 4% higher than the value achieved with no insulation. The electrical efficiency is about 13.7%, lower of 0.05% compared to the value achieved without insulation.

The study reveals that significant improvement of the PVT thermal efficiency could be achieved in case of the adoption of an insulation layer. However, the magnitude of this one is not significantly affected by the insulation material used and its thickness.

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