

Validation of the numerical model of a concentrated photovoltaic-thermal hybrid collector using TRNSYS

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Abstract. In a global climate context, an agreement has been reached to triple the world's renewable energy capacity and double energy efficiency by 2030. Solar energy is playing a key role in this process. In fact, solar systems, especially concentrated photovoltaic thermal (CPVT) systems, have received particular attention due to their efficiency and the diversity of their applications. The aim of the present work is to validate a numerical model for a CPVT hybrid collector, using TRNSYS simulations based on experimental results. Different simulations have been carried out for various solar irradiances, ambient temperatures, temperatures and flow rates of the heat transfer fluid in the collector. Thermal and electrical powers, considered as validation variables, were obtained. The results show good agreement between the model developed and the experimental results, with mean errors of 4.10% and 6.74% for electrical and thermal power, respectively. We conclude that the CPVT collector model on TRNSYS generates realistic result.

1. Introduction

In a global climate context, the progressive elimination of fossil fuels from the energy mix is essential. At parallel, efforts to deploy renewable energies must be stepped up in order to limit global warming to 1.5°C. As a result, an agreement has been reached to triple the world's renewable energy capacity and double energy efficiency by 2030 [1].

Renewable energies are still growing fast, with an installed capacity of 3 870 GW in 2023, of which solar power accounts for the largest share at 36.7% [2]. This renewable technology is one of the most dynamic. In fact, solar energy, has been attracting a great interest from the scientific community and industrial developers, because of its abundance, low carbon footprint and economic potential. According to July 2024 estimations, a total of 292 GW of solar capacity was installed during 2024, 29% more than at the same date in 2023. Analysis shows that the world will reach 593 GW of solar installations for electricity generation by the end of 2024 [3]. However, the installation of photovoltaic systems could be made less

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expensive and more beneficial by reducing the surface area of solar cells and taking advantage of the thermal energy lost during the conversion of sunlight. For this purpose, photovoltaic thermal systems (PVT) have become increasingly popular, thanks to their ability to produce electricity and heat simultaneously. This technology not only takes advantage of thermal energy recovery, but also reduces the temperature of PV cells. Hernando et al., (2023) [4] reviewed various experimental and numerical studies on PVT. The authors identified opportunities for performance improvement, sensor innovation and deployment as a power generation source. They estimated that the REmap (Renewable Energy Roadmap) reference emission curve could be reduced by more than 16% by 2030, putting PVT technology on the path to global decarbonization. However, the main problem being the low temperature of the thermal energy extracted limit the range of possible applications for a PVT, hence researchers have thought of integrating it with concentrating photovoltaics (CPV) to create a concentrating photovoltaic thermal system (CPVT) [5]. This innovative design is a combination of PVT and concentrating PV, offering the possibility of broadening the field of use while significantly reducing investment costs and the surface area dedicated to energy production. CPVT research focuses on several variants. Bellos and Tzivanidis (2019) [6] summarized in a study the various optical and thermal modifications to a parabolic-type CPVT collector. They found that there are many promising choices for designing these collectors to achieve high thermal performance and low cost. The authors developed a roadmap to guide future research and design of linear parabolic concentrator technologies. In an experimental study by Cabral et al., (2021) [7]. Outdoor electrical and thermal tests were carried out on a low-concentration collector based on a parabolic reflector geometry with a PVT receiver. The angle of incidence was modified on a daily basis. Overall electrical and thermal efficiencies of 8% and 59% respectively were obtained. Several researchers have investigated the possibility of integrating CPVT into buildings. Among them, Acosta et al., (2022) [8] compared a solar thermal plant with a hybrid LCPVT (*Low Concentrated Photovoltaic Thermal*) plant simulated in TRNSYS (*Transient System Simulation Tool*). The results showed that the specific energy yield of the LCPVT plant was up to 92% higher than that of the ST (*Solar Thermal*) plant, indicating that the hybridized version of the ST plant has a better yield/surface utilization ratio.

This study focuses on validating the transient model of the CPVT collector, based on the experimental results of Gorouh et al [9]. Different simulations were carried out for various solar irradiances, ambient temperatures, temperatures and flow rates of the heat transfer fluid entering the collector. Thermal and electrical powers, considered as validation variables, were obtained.

2. Methodology

The study proposes a simulation model to predict the electrical and thermal power output of a CPVT module under real operating conditions. The schematic diagram of the CPVT is presented in Figure 1. The model calculates the electrical and thermal performance as a function of input parameters based on the actual operating conditions of the experimental study conducted by Gorouh et al. [9]. These experimental data were used to validate the model by comparing simulated results with measured thermal and electrical power outputs, thus ensuring full validation.

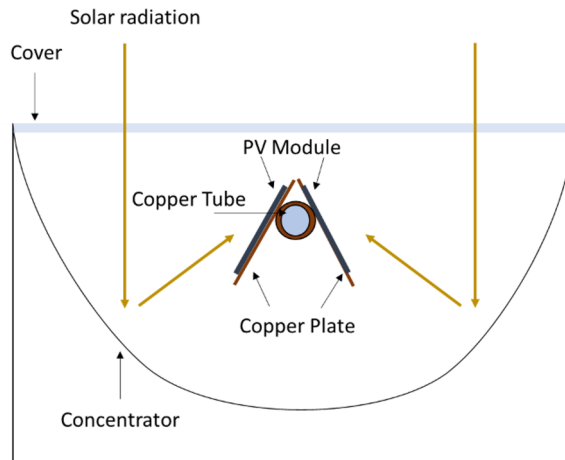


Fig. 1. CPVT diagram adapted from [9].

2.1. System simulation

The numerical simulation was conducted under TRNSYS (Transient System Simulation Tool), a simulation tool designed primarily for renewable energies and building sectors.

The system illustrated in Figure 2 consists of a CPVT collector and a pump to circulate the fluid. The collector modelled is that studied by Gorouh et al., (2021) [9], whose physical characteristics are: surface area of 0.644m^2 , covered with glass with a transmittance of 0.91. A parabolic concentrator with a reflectance of 0.92 reflects solar radiation linearly onto the receiver. The absorber consists of two copper plates and a copper tube between the plates, through which water is circulated as a heat transfer fluid. The plates are covered by a PV module based on monocrystalline cells.

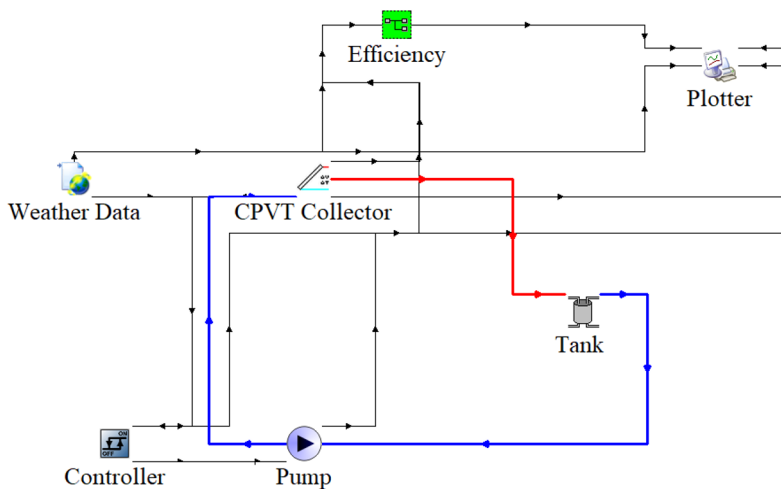


Fig. 2. System configuration in the TRNSYS simulation.

The collector was simulated using Type 50f on TRNSYS. A component developed to model hybrid concentrating solar collectors with heat losses as a function of wind speed and collector temperature. The model was developed by applying the energy balance and heat transfer equations to the different layers of the collector to obtain the thermal and electrical outputs, which are governed by the following equations:

- Geometric concentration ratio [10]:

$$C_R = \frac{A_{ap}}{A_{pVT}} \quad (1)$$

A_{ap} , A_{pVT} represent the aperture area and the absorber area respectively.

- Thermal power [11]:

$$\dot{Q}_{th} = \dot{m}_f C_{pf} (T_{f,out} - T_{f,in}) \quad (2)$$

Where \dot{m}_f , $C_{p,f}$, $T_{f,in}$ and $T_{f,out}$ represent the mass flow rate, the specific heat, the inlet and outlet temperature of the fluid respectively.

- Electrical power [10]:

$$P_{el} = I A_c C_R \eta_{opt} \eta_{pv} \quad (3)$$

I , A_c , η_{opt} and η_{pv} are the direct irradiation, the cells area and the optical efficiency respectively.

with:

$$\eta_{pv} = \eta_{ref} [1 - \beta_{pv} (T_{cell} - T_{ref})] \quad (4)$$

Where η_{pv} , η_{ref} , β_{pv} , T_{cell} and T_{ref} represent the PV modules efficiency, the PV modules standard efficiency, the temperature coefficient of PV cells, the average and reference PV cell temperature respectively.

- Thermal efficiency:

$$\eta_{th} = \frac{\dot{Q}_{th}}{I A_{ap}} \quad (5)$$

- Electrical efficiency:

$$\eta_{el} = \frac{P_{el}}{I A_{ap}} \quad (6)$$

- Global efficiency:

$$\eta_{global} = \eta_{th} + \eta_{el} \quad (7)$$

2.2. Experimental data

To validate the numerical model, the CPVT collector was configured on TRNSYS using the same physical properties as those employed by Gorouh et al. [9] Different simulations were carried out for various solar irradiances, ambient temperatures, temperatures and heat transfer

fluid flow rates entering the collector. The experimental measurements and simulation parameters are shown in the table 1.

Table 1. Experimental measurements and simulation parameters during the day.

Time (h)	Irradiations (W/m ²)		T_amb (°C)		T_in (°C)		Flow rate (Kg/s)	
	Exp	Sim	Exp	Sim	Exp	Sim	Exp	Sim
9:00	598	594.7	22.2	22.2	49.7	49.7	0.0498	0.0498
10:00	771	774.2	23.7	23.7	52.2	52.2	0.0493	0.0493
11:00	897	896.5	24.4	24.4	53.6	53.6	0.0495	0.0495
12:00	967	966.4	24.9	24.9	54.6	54.6	0.0490	0.0490
13:00	967	966.4	24.6	24.6	54.6	54.6	0.0503	0.0503
14:00	905	902.9	25.3	25.3	55.1	55.1	0.0508	0.0508
15:00	788	786.2	25.6	25.6	54.5	54.5	0.0503	0.0503

3. Results and discussion

3.1. Thermal power

Table 2 shows the thermal output values obtained experimentally by Gorouh et al [9] and those calculated using our numerical model, with the corresponding relative error values. taking into account variations in solar radiation, ambient temperature, heat transfer fluid inlet temperature and fluid flow rate.

Table 2. Experimental and numerical results for thermal power during the day.

Time (h)	Thermal power (W)		Error (%)
	Experimental	Simulated	
9:00	238	302.8	27.13
10:00	399	413.2	3.44
11:00	504	501.6	0.58
12:00	560	550.5	1.74
13:00	560	549.8	1.86
14:00	511	506.6	0.92
15:00	378	422.1	11.49

Figure 3 illustrates the evolution of the panel's experimental and numerical thermal output as a function of the time of day. The graph shows good agreement between the experimental results and the predictions of the model developed, closely following the solar radiation profile. The average deviations observed are of the order of 6.74%, with a minimum deviation of 0.58%. However, it is important to note that, according to the authors in [9], the measured thermal power does not always exactly follow the solar radiation profile at certain times, notably sunrise and sunset. These discrepancies are mainly due to one-off measurement errors during these periods.

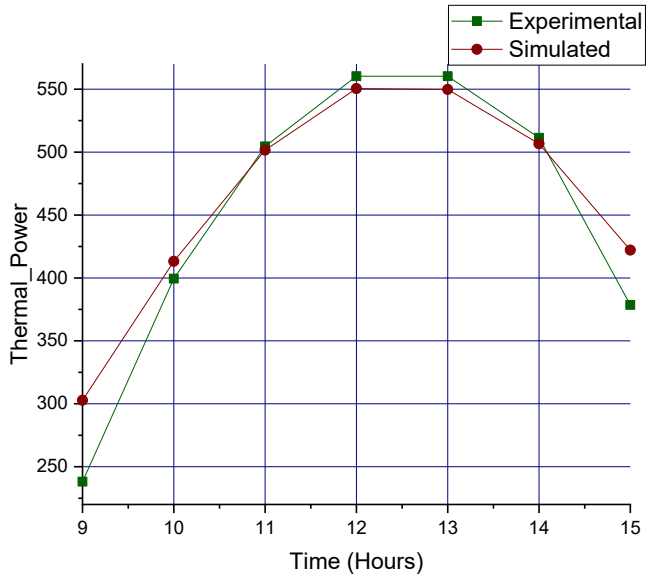


Fig. 3. Comparison of numerical and experimental thermal power results.

3.2. Electrical power

Table 3 also shows the electrical power values obtained experimentally by the authors [9] and those calculated using our numerical model, as well as the values of the relative error between these two sets of data. The associated Figure 4 highlights the electrical output of the CPVT panel throughout the day. We can observe good agreement between the experimental and numerical results, with an average deviation of 4.10% and a minimum deviation of 1.19%.

Table 3. Experimental and numerical results for electrical power during the day.

Time (h)	Electrical power (W)		Error (%)
	Experimental	Simulated	
9:00	28.7	30.95	7.83
10:00	42	39.92	4.95
11:00	48.7	46.57	4.37
12:00	51.7	50.14	3.01
13:00	52.1	50.16	3.72
14:00	46.2	46.75	1.19
15:00	38.8	40.21	3.63

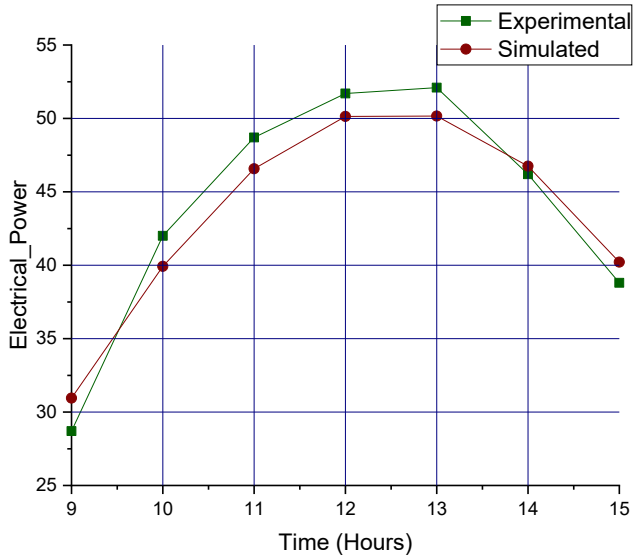


Fig. 4. Comparison of numerical and experimental electrical power results.

These observations confirm that the thermal and electrical powers obtained by the model agree well with the results of the experimental study. This demonstrates that the model developed generates realistic results and can be used for further analysis or optimization.

Table 4 also shows the output temperature, obtained experimentally and simulated, and the corresponding relative error. Figure 5 shows that the HTF output temperature is almost superimposed on the experimental results, with a maximum deviation of just 0.45%.

Table 4. Experimental and numerical results for heat transfer fluid outlet temperature during the day.

Time (h)	Outlet temperature (°C)		Error (%)
	Experimental	Simulated	
9:00	50.4	50.63	0.45
10:00	53.5	53.49	0.018
11:00	55.2	55.16	0.072
12:00	56.4	56.33	0.12
13:00	56.4	56.28	0.21
14:00	56.7	56.63	0.12
15:00	55.7	55.79	0.16

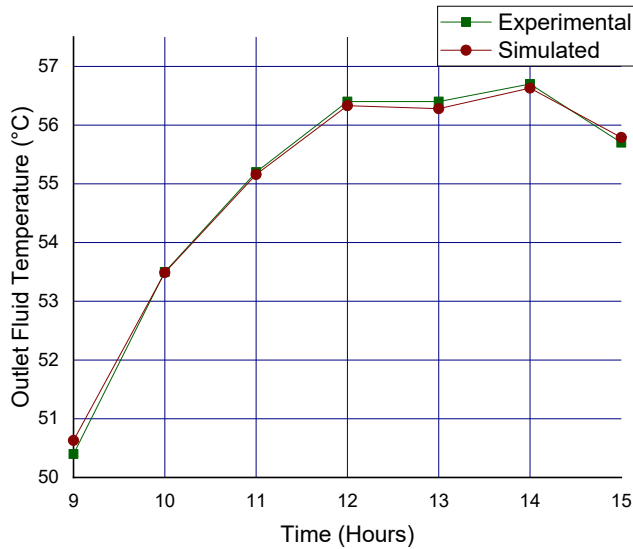


Fig. 5. Comparison of numerical and experimental outlet fluid temperature results.

4. Conclusion

In conclusion, this study simulated a concentrating photovoltaic thermal collector (CPVT) in TRNSYS using a mathematical model validated experimentally under various operating conditions. The validation was carried out using experimental data, demonstrating that the numerical model is capable of accurately predicting the system's daily thermal and electrical performance. The results show satisfactory agreement between model predictions and experimental data, with average deviations of 4.10% for electrical power and 6.74% for thermal power. Although there were some isolated divergences, mainly due to experimental uncertainties, the model developed proved to be a reliable tool for analyzing and optimizing the performance of CPVT systems.

5. References

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