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MODELING A PV/T SYSTEM USING THE THERMAL RESISTANCE METHOD

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Abstract. *The generation of electricity by photovoltaic systems stands out for being derived from a renewable, clean, and silent source. However, there is a negative linear dependence between efficiency and operating temperature due to losses from reflection and heat. In this regard, hybrid photovoltaic/thermal (PV/T) systems are capable of generating electricity like traditional systems while cooling the cells through thermal exchange with a fluid contained in a heat exchanger. By doing so, the efficiency is enhanced both by the increase of the photovoltaic cell's performance and by the thermal energy use. This work presents a modeling of a PV/T system using the method of thermal resistances, where heat is transferred through diffusion in a steady-state condition, with constant thermal properties and negligible heat losses from the sides. The heat exchanger is made of corrugated polypropylene material with 153 channels of rectangular profile and is installed in a conventional photovoltaic system. The proposed numerical model allows the performance evaluation of a PV/T system in different operational conditions, according to thermal and electrical parameters shown in the literature. The results demonstrated the proportionality between thermal utilization and the temperature of the circulating fluid in the heat exchanger, achieving around 17% and 55% of electrical and thermal efficiencies, respectively, for an irradiance of 1000 W/m², showing consistency between the modeling and theory.*

Keywords: *Hybrid solar systems, Solar power generation, Solar radiation, Photovoltaic cells, Numerical models.*

1. INTRODUCTION

Motivated by the exacerbated urban and industrial growth nowadays, the advent of sustainability has become a top priority discussion among major nations for the preservation of natural resources. However, the burning of fossil fuels such as coal, petroleum derivatives, and natural gas still persists in the Brazilian Electric Matrix, generating negative impacts on the environment (EPE, 2022). Within this context, the use of renewable sources for electricity production is a significant mechanism of action in line with sustainable progress, ensuring environmental protection and economic development.

There is a notable predominance of hydroelectric sources in electricity generation, which represents an abundant and renewable resource in the country. However, as highlighted by Pereira and Neto (2020), the centralization of hydroelectric power plants leads to supply insecurity due to the vulnerability these sources face in response to climate fluctuations. This element of uncertainty, combined with additional negative factors such as high implementation costs, long construction processes, increased expenses in transmission systems due to their distant location from urban centers, as well as the environmental and social impacts they generate, contribute to the desire to diversify the Brazilian Electric Matrix.

Unlike other sources, solar energy is distributed relatively evenly throughout the national territory, and its availability is virtually infinite. Looking ahead, the share of photovoltaic and concentrated solar power (CSP) solar energy will increase from 2013 to 2050, with an evolution from 0% to 16% and from 1.1% to 7.9%, respectively. This scenario implies a reduced dependence on hydroelectric power plants for electricity generation (Silva and Rampinelli, 2017). However, the efficiency of commercially available solar panels does not solely depend on solar radiation; only about 14% to 22% of the radiation is converted into electrical energy, with the rest being reflected and converted into heat (Brakesley *et al.*, 2020).

In this regard, alternatives for utilizing the discarded energy from conventional photovoltaic systems have been considered. An improved version of photovoltaic systems has emerged, known as hybrid photovoltaic/thermal (PV/T) systems. These systems are capable of simultaneously providing electricity and heat, with the main advantages being the utiliza-

tion of the solar energy dissipated as heat by the photovoltaic module and increased system efficiency through cooling the conventional panels with a working fluid circulating through a heat exchanger. This heat can be utilized for various low-temperature applications, such as water heating for bathing (Kalogirou, 2016).

In the market, one notable product is the DualSun Spring, a next-generation hybrid solar panel that provides electricity and heat for residential use. Protected by multiple patents, the Spring panel produces 2.5 times more energy than a photovoltaic panel of the same surface area, saving space and offering complete integration into the roof at a competitive price compared to energy costs (DualSunSpring, 2023). Another option for residential and commercial areas is the SolarMaster panel, which offers significant advantages in simultaneous electricity and heat production, with an additional 3.6% energy output compared to a conventional photovoltaic module. It allows 70% of the energy to be utilized for thermal production and 25% for electricity generation (SolarMaster, 2023).

Filho *et al.* (2021) discusses a new concept of a heat exchanger used in PV/T systems, the focus of this article, made of corrugated polypropylene with 153 channels of rectangular profile for fluid flow. Its installation on the back of the photovoltaic module is characterized as simple and quick, and it is considered an innovative and low-cost technology compared to commercially available PV/T systems, suitable for long-term operations.

In this perspective, this work presents a modeling of a hybrid photovoltaic/thermal (PV/T) system with a corrugated polypropylene heat exchanger using the thermal resistance method. The premise is that heat is transferred by diffusion under one-dimensional and steady-state conditions. To achieve this, a system was developed with the assistance of programming and numerical data analysis software to analyze the available solar energy from the electrical and thermal performances.

2. LITERATURE REVIEW

Many researchers have investigated photovoltaic-thermal (PVT) systems from various perspectives. Gagliano *et al.* (2019) address the performance comparison of a hybrid photovoltaic/thermal (PV/T) power plant with a system consisting of a photovoltaic (PV) power plant and a solar thermal (ST) power plant. The results show higher efficiency for the PV/T module compared to conventional modules; however, the PV power plants had economic advantages.

Fluid circulation methods and challenges related to PV/T systems are studied in Shi *et al.* (2017). Due to the energy consumption of the pump being greater than the electricity generation from fluid cooling, a natural circulation tube plate PV/T system was developed. It was concluded that this model exhibits hysteresis and requires more time to achieve high and stable performance at low radiation intensities.

Kazem *et al.* (2020) evaluate the efficiency of PV/T systems with different cooling systems: web type, direct type, and spiral type, compared to the electrical performance of conventional PV systems in Sohar, Oman. The PV/T systems showed an average cell temperature reduction of at least 3 °C, resulting in significant improvements in voltage, power, and electrical efficiency, especially in the spiral flow system, with an overall efficiency of 35.0%, while conventional systems achieved around 7.8%.

Abdullah *et al.* (2020) discuss experimental data of PV/T systems using MATLAB and compare it with a new design of a dual oscillating copper tube absorber. The performance of the water-based PV/T system was evaluated at different mass flow rates and solar radiation intensities. Increasing the mass flow rate and solar radiation led to an increase in thermal and overall efficiencies; however, after a certain point, there was a decrease. Furthermore, increasing the mass flow rate reduced the cell temperature and increased the electrical efficiency.

Sirqueira *et al.* (2020) develop a mathematical model of a plate-and-tube PV/T system based on energy balance considering the main influences of radiation, convection, and conduction between layers, the environment, and water. The modeling was compared with results obtained using Comsol Multiphysics, revealing coherence between the analytical and simulated parameters.

Considering the importance of studying methods to enhance PV/T systems in order to achieve greater potential for simultaneous electrical and thermal energy production, this article can contribute with the efficiency results of a mathematical model of a simpler system, utilizing an innovative, recyclable, sustainable, and cost-effective heat exchanger coupled with a conventional PV module.

3. METHODOLOGY

To develop the mathematical modeling, the project was carried out using the student version of MATLAB software, with input parameters based on the research by Filho *et al.* (2021), the author of the new model of corrugated polypropylene heat exchanger. With the knowledge of these data, this study aims to analyze the temperature response of the PV/T layers in relation to incident solar radiation, as well as the electrical, thermal, and overall efficiencies.

3.1 Hybrid photovoltaic-thermal system (PV/T)

According to do Nascimento *et al.* (2022), PV/T systems typically consist of specific and essential materials for module construction, such as glass to protect the system from physical and chemical agents in the external environment; EVA for cell encapsulation; Tedlar to prevent contact between the heat exchanger and the cell, protecting it from moisture; and, finally, the photovoltaic cell, responsible for converting solar radiation into electrical energy.

The PV/T system studied in this work consists of a glass cover and a thermal insulator on the lower surface of the heat exchanger. The heat exchanger was introduced and developed by Filho *et al.* (2021), with 153 channels of rectangular profile through which the fluid flows, made of corrugated polypropylene material and installed on the lower side of the conventional photovoltaic module, which acts as a hybrid solar collector. Fig. 1 illustrates the layers of the PV/T system studied in this article, adapted from Filho *et al.* (2021).

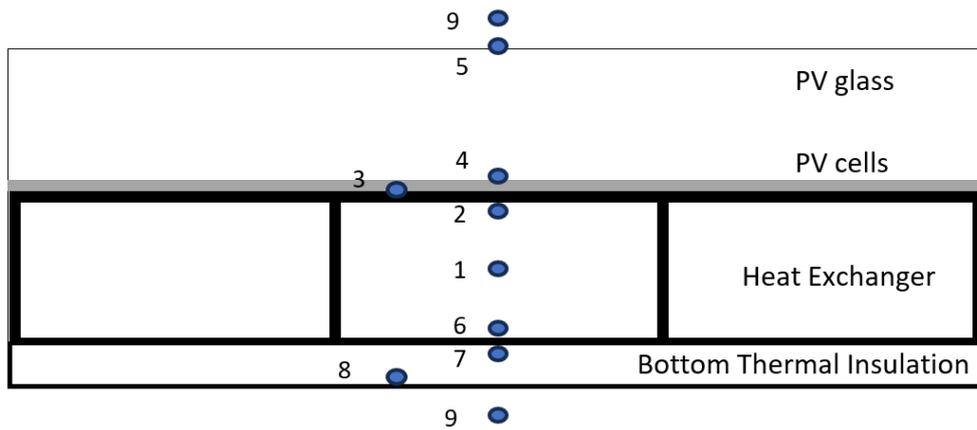


Figure 1. Layers considered for the PV/T system.

Figure 2 contains the representation of the thermal circuit of the system. The schematic allows identifying some considerations of this study, such as the thermal fractions of solar radiation lost through convection and radiation, the portion of heat utilized by the fluid passing through the channels of the heat exchanger, and the fraction converted into electrical energy. It is also considered that the thermal resistances between nodes 2 and 1, 1 and 6 are in series, and their equivalent resistance is in parallel with the resistance between nodes 2 and 6. It is important to note that the heat exchanger has 153 rectangular channels, indicating that the represented circuit has multiple parallel thermal resistances between points 2 and 6.

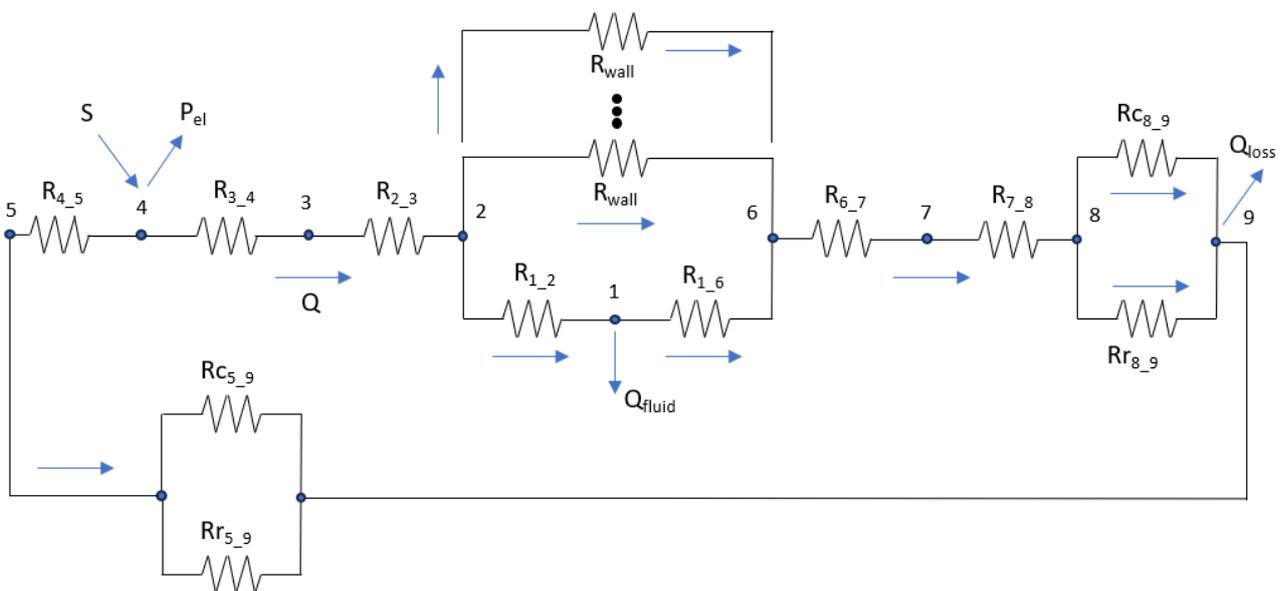


Figure 2. Identification of nodes through thermal resistance modeling.

Table 1 presents the nomenclature identification corresponding to Fig.2, for further clarification.

Table 1. Description of the parameters used in the thermal circuit.

Parameters	Description
R_{4_5}	Thermal resistance of conduction os the glass
R_{3_4}	Thermal resistance of conduction of the cell
R_{2_3}	Conduction resistance in the upper wall of the heat exchanger
R_{1_2}	Convective resistance in the upper part of the water channel
R_{1_6}	Convective resistance in the lower part of the water channel
R_{wall}	Conduction resistance through the walls of the heat exchanger
R_{6_7}	Conduction resistance in the lower wall of the heat exchanger
R_{7_8}	Thermal resistance of conduction of the insulation
R_{c8_9}	Convective resistance between the insulation and the environment
R_{r8_9}	Radiation resistance between the insulation and the environment
R_{c5_9}	Convective resistance between the glass and the environment
R_{r5_9}	Radiation resistance between the glass and the environment
Q	Heat in the photovoltaic cells
Q_{fluid}	Heat utilized for the fluid
Q_{loss}	Heat lost to the environment through a combination of convection and radiation
S	Corrected radiation
P_{el}	Electrical power generated by the photovoltaic cells

3.2 Mathematical modeling

Considering a steady-state system and constant thermal conductivity, a detailed analysis was proposed using the heat diffusion equation in the PV/T system as represented in Cengel and Ghajar (2012), where temperature is a function of a single coordinate and heat is transferred exclusively in that direction. For one-dimensional conditions without distributed energy sources inside, the heat equation was adopted, represented by Eq. (1).

$$\frac{d}{dx} \left(k \frac{dT}{dx} \right) = 0, \quad (1)$$

Where k is the thermal conductivity of the system and $\frac{dT}{dx}$ is the temperature distributed as a function of a single coordinate.

Cengel and Ghajar (2012) formulate the means of obtaining the thermal resistances for heat transfer, whether it be through conduction, convection, or radiation, following the models of Fourier's Law, Newton's Cooling Law, and Heat Transfer by Radiation, respectively, expressed in Eq. (2), Eq. (3), and Eq. (4). A thermal resistance modeling of the problem was carried out, representing the layers of the photovoltaic-thermal project.

$$R_{cond} = \frac{E_g}{K_g A_g}, \quad (2)$$

$$R_{conv} = \frac{1}{h_g A_g}, \quad (3)$$

$$R_{rad} = \frac{1}{h_r A_g}, \quad (4)$$

Where E_g is the thickness of a generic material, K_g is the thermal conductivity of a generic material, A_g is the area of a generic material, and h_g and h_r are the convective and radiative heat transfer coefficients, respectively. The generic material adopted is the photovoltaic module.

With the thermal resistances of each material in the PV/T known, it is possible to determine the transferred heat, as it depends on the temperature difference between the involved layers, as well as their thermal properties and the conditions of conduction, convection, and radiation. Eq. (5) formulates the determination of the transferred heat in the system, where R is the determined thermal resistance.

$$Q = \frac{\delta T}{R}, \quad (5)$$

According to Kalogirou (2016), the incident solar radiation is corrected by the relationship expressed in Eq (6). Under steady-state conditions, an energy balance is performed in the system, where a fraction of the heat in the cell is converted

into electrical energy, while a portion is lost to the glass layer, and the remaining is transferred to the process, as stated in Eq. (7).

$$S = G \tau_{\alpha} A_{cell} \quad (6)$$

$$Q = S - P_{el} - Q_{loss}, \quad (7)$$

Where G is the total incident solar radiation on the glass, τ_{alpha} is the transmissivity-absorptivity of the glass, A_{cell} is the cell area, Q is the heat transferred to the fluid in the heat exchanger, P_{el} is the electrical power of the module, and Q_{loss} is the heat reflected back to the environment.

According to Kalogirou (2016), the sky temperature is established as an empirical relationship associated with measured meteorological variables, represented by Eq. (8). Thus, the radiation coefficient is estimated as shown in Eq. (9), and the convection coefficient is formulated based on wind speed and the length of the photovoltaic module in the direction of the wind, as given in Eq. (10), assuming that the system's convection coefficient is greater than 5 W/m²K.

$$T_{sky} = 0.0552(T_9)^{1.5}, \quad (8)$$

$$h_r = e_{cell} \alpha (T_5 + T_9) (T_5^2 + T_9^2) \frac{T_5 - T_{sky}}{T_5 - T_9}, \quad (9)$$

$$h_w = \frac{8.6V^{0.6}}{1.8^{0.4}}, \quad (10)$$

Where T_9 represents the ambient temperature, T_5 is the temperature of the PV/T glass, e_{cell} is the emissivity of the cell, α is the Stefan-Boltzmann constant, and V is the wind speed.

According to do Nascimento *et al.* (2022), starting from the electrical power of the module, the heat rate of the transported working fluid, the total solar radiation reaching the glass, and the collector area, the overall utilization of the system is obtained by summing the electrical and thermal efficiencies, as represented by Eq (11) and Eq. (12).

$$\eta_{el} = \frac{P_{el}}{G_t A_c}, \quad (11)$$

$$\eta_{th} = \frac{Q_u}{G_t A_c}, \quad (12)$$

3.2.1 Numerical solution

According to Clausius' statement, the Second Law of Thermodynamics states that "it is impossible for any system to operate in such a way that the sole result is the transfer of energy as heat from a colder body to a hotter body" (Moran *et al.*, 2013). In other words, for spontaneous heat transfer to occur, the flow always goes from the hotter body to the colder body.

In this sense, the Second Law of Thermodynamics was used to solve a challenge faced in this work: obtaining parameters that were interdependent on each other. In this case, the parameters were varied using constraints of maximum and minimum values until an appropriate result with the lowest possible error was obtained. For example, knowledge of the glass temperature (T_5) was crucial for determining the heat transferred based on the temperature difference between the glass and the cell, which allowed for the development of the rest of the modeling. However, the heat between the cell and the glass was unknown, revealing that the glass temperature and the heat transferred from the glass to the cell are interrelated parameters. Therefore, the glass temperature was varied in a way that it could not be higher than the cell temperature, while also not being lower than the ambient temperature according to the Second Law of Thermodynamics. Assuming that the heat between the environment and the glass is equal to the heat transferred from the glass to the cell, the ideal glass temperature for the system conditions can be determined.

Similarly, the same approach was taken with the temperature of the lower wall of the heat exchanger (T_6). This temperature value, located below the rectangular channels of the heat exchanger, should not be lower than the ambient temperature and should not exceed the temperature of the upper wall of the heat exchanger, considering the spontaneous flow of heat between the layers. With the knowledge of T_6 , the heat that was not utilized by the fluid, directed towards the lower wall of the heat exchanger and the existing thermal insulation layer, was determined.

3.2.2 Input data

Based on the methods presented, fixed parameters were applied, as shown in Tab. 2 and Tab. 3, collected from Filho *et al.* (2021) and essential for the detailed mathematical modeling. It is worth noting the value of the collector area (A_c), which is 0.54 m².

Table 2. Thickness between the layers of the PV/T.

Thickness, mm	Value
Glass	3.20
Solar cell	0.30
Heat exchanger	0.80
Insulating	30.0

Table 3. Input parameters for obtaining results.

Quantity	Value
Wind speed, m/s	2.0
Contact resistance, K/W	0.008
Ambient temperature, K	293.0
Power temperature coefficient, K^{-1}	0.0037
Nominal cell temperature, K	315.0
Nominal PV efficiency	0.1811
Solar cell emissivity	0.95
Glass transmittance-absorptance product	0.90

The cell temperature (T_4) was estimated based on the graphical results from Filho *et al.* (2021), which is dependent on the incident radiation, as shown in Eq. 13, obtained through linear regression of a graph presented in the referenced article.

$$T_4 = (0.0096 G) + 24.626, \quad (13)$$

With the adopted methodology, it is expected that the efficiency data will be consistent with those presented in the literature, that the modeling will yield good results in terms of thermal utilization by taking into account the heat between the layers of the system, and that consequently, the PV/T system will exhibit a high heat transfer rate due to the configuration of the new heat exchanger design.

4. RESULTS

In this chapter, the results obtained using the described methodology will be presented, and they will be discussed and interpreted based on the studied theoretical framework. With the application of the input data provided, graphs were developed to analyze certain variable parameters in the system as the solar radiation, ambient temperature, temperatures of the PV/T layers, and electrical, thermal, and overall efficiency data changed.

The distribution of temperatures in the glass, cells, and working fluid was the first observed result. In the process, it is understood that solar radiation impinges on the glass, corrected by the area and the transmissivity-absorptivity factor, and transferred to the cells, which, in turn, transfer heat to the rest of the system, taking into account the generated electrical energy and the heat lost through convection and radiation. In this regard, Fig.3 illustrates the temperature graph as a function of solar radiation, showing higher temperatures in the cells, reaching values close to 308 K, followed by the thermal distribution of the glass and water.

Figure 4 represents the cell heat as a function of incident solar radiation on the PV/T glass, ranging up to 1000 W/m^2 . It can be observed that, as expected, there is a linear dependence between the parameters, and the heat can reach levels of approximately 300 W/m^2 . The graph also shows that for low solar radiation values, the photovoltaic cells begin to lose heat to the environment, as indicated by negative values. It is interesting to note that the heat curves are very close to each other, indicating that the working fluid achieved significant thermal utilization.

Lastly, Figure 5 confirms what was observed in Fig.3 and Fig. 4, revealing thermal efficiency data for the system close to 60% for solar radiation of 1000 W/m^2 , while showing electrical efficiency data around 17%, indicating a small increase in electrical utilization. Through the analysis of the graphs, it was verified that the utilization results obtained from the simulation confirm that the study aligns with the efficiency margin presented by the theoretical framework, providing greater confidence in the modeling.

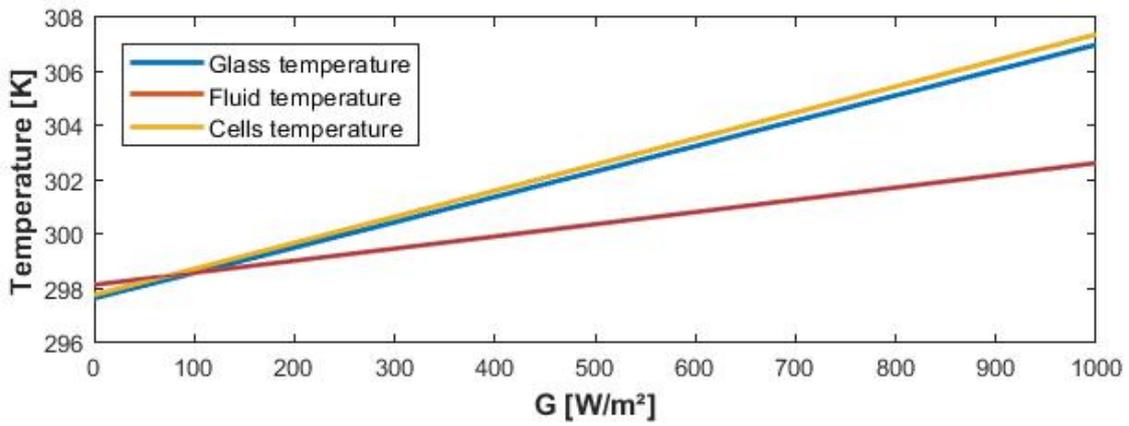


Figure 3. Variation of temperatures as a function of incident solar radiation.

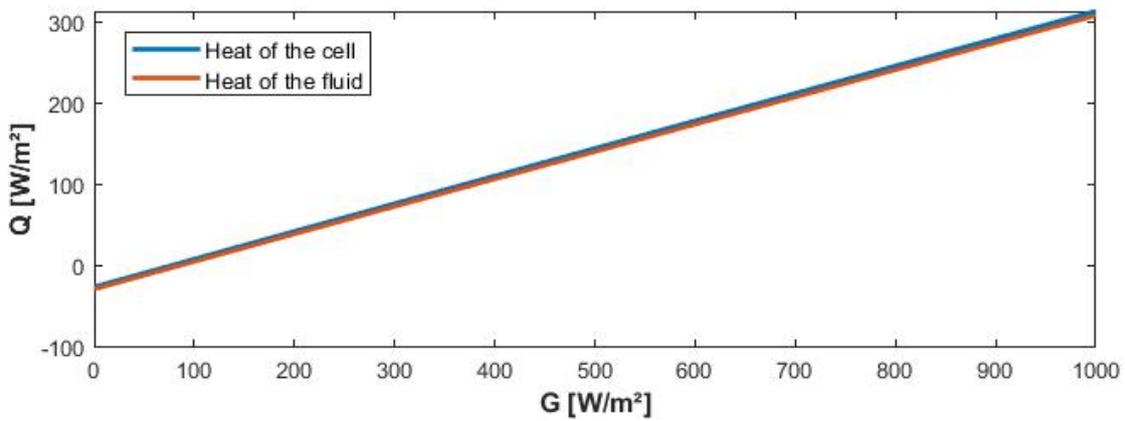


Figure 4. Generation of thermal energy from the PV/T utilized in the system.

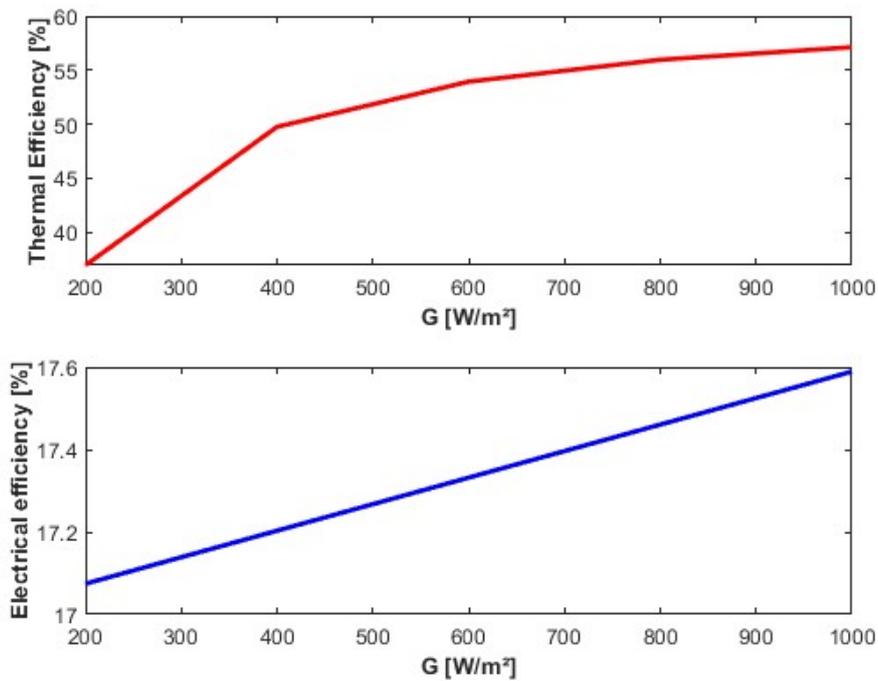


Figure 5. Thermal and electrical efficiencies as a function of solar radiation.

5. CONCLUSIONS

The development of the hybrid photovoltaic-thermal (PV/T) system was crucial to observe, in practice, the parameters of a PV/T and its influence on the system. With the obtained results, it was possible to understand the application of numerical methods in one-dimensional heat conduction along a single axis of the Cartesian plane, applied in a data development software, and to comprehend the behavior of temperature variables between the layers and their direct correlation with thermal and electrical efficiencies. Therefore, it can be concluded that the results are consistent with what has been studied in the literature, especially with the data provided by Filho *et al.* (2021), the creator of the heat exchanger modeled in this article. It is worth noting that for similar efficiency results, this PV/T model promises simplicity, lower cost, and easier installation.

However, hybrid photovoltaic-thermal collectors still need recognition and greater confidence in the benefits of the system, especially regarding the parameters that influence thermal efficiency. It is recommended to continue with research and develop commercially viable and large-scale PV/T systems, being able to predict the overall efficiency for different climatic conditions, seasons, and locations in the long term, in order to achieve control over the return on investment period. This work is an integral part of an ongoing project. In the upcoming stages, the developed model will undergo validation in an experimental system, which is currently in its final phase of construction.

6. ACKNOWLEDGEMENTS

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