27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0373
ENERGY AND EXERGY LOSSES IN PHOTOVOLTAIC-THERMAL MODULE WITH POLYMERIC HEAT EXCHANGER

Bruna de Oliveira Busson
Uallas Henrique de Oliveira de Brito
Victor César Pigozzo Filho
Alexander Leyton Mopan
Júlio César Passos
Federal University of Santa Catarina, Mechanical Engineering Department, Florianópolis, Brazil
bruna.busson@yahoo.com.br, uallashenrique@gmail.com, victorpigozzo@gmail.com, alexander.leyton@lepten.ufsc.br, julio.passos@lepten.ufsc.br

Abstract. *Photovoltaic-thermal (PVT) modules combine photovoltaic (PV) and solar thermal (ST) concepts. PVT modules improve global energy performance and spatial efficiency for producing electrical energy and hot water in the same area. A new model of the polymeric heat exchanger was installed below the PV module's rear surface, converting it into the PVT module (2.21 m²). Water flows through the heat exchanger parallel channels and removes the heat of the PV module, reducing its operating temperature and improving electrical energy output, because the operating temperature is inversely proportional to conversion efficiency. The main objective of this study is the determination of energy and exergy losses of the PVT module. Energy losses are mainly convection and radiation heat losses occurring in front and rear PVT surfaces. Exergy losses are related to optical losses, heat transfer, and exergy destruction. The optical losses depend on the transmissivity-absorptivity product which, in turn, varies with solar incidence angle. Exergy destruction occurs due to pressure drop for fluid flow through channels and to maximum useful work solar radiation not converted to electrical or thermal energies. One week of measured data between 11:30 and 12:30 hours, hourly of maximum solar incident radiation, is applied to energy and exergy models. On average, electrical and thermal productions were 2.3 kWh and 2.9 kWh, respectively, when the solar irradiation was 4.4 kWh/m²/day. The convection and radiation loss rates fluctuated between 100 and 450 W and 200 to 300 W, respectively, depending on wind velocity and operating cell temperature. However, losses in PVT rear surface were neglected because of the use of thermal insulation. The exergy destruction due to pressure drop and exergy losses due to convection and radiation heat transfers represent about 18%, on average, of total exergy lost. Optical losses are responsible for more than 6% of solar radiation exergy destruction. Some part of exergy destruction not specific evaluated in this work represents about 9.8% on average of total exergy destruction in a PVT module. Moreover, the PVT module is the main component responsible for exergy destruction in a PVT system and electrical and thermal energy conversions are the main contributors to that.*

Keywords: *PVT module, Energy losses, Exergy losses, Exergy destruction.*

1. INTRODUCTION

It is important to ensure energetic security and economic development of the global society but to face global climatic changes, this must be made with improvement in the energetic efficiency of energy systems (Bukarica and Tomšić, 2017; Lima et al., 2017). However, non-renewable sources are still the main suppliers of energy and transport sectors implicating global warming and other environmental problems due to the increase in CO2 emissions (Fraidenraich et al., 2022; Rocha, 2019).

Although the non-renewable sources such as oil, coal, and natural gas reduced their participation in global energy available by 14%, 4% and 2%, respectively, when compared to 2020 related to 2019. Participation of renewable energy increased by 3% during the same period (IEA, 2021). Solar energy is an example of a renewable source and is capable of providing heat and electricity separated or at the same time (Pinho and Galdino, 2014; Barbón, et al., 2019; Mathew and Venugopal, 2021; Fraidenraich et al., 2022). For example, in 2019, solar energy supplied about 1140 TWh of energy in the world, divided into thermal energy and electricity (Weiss and Spörk-Dür, 2020).

A way to convert solar radiation directly into electrical energy is by utilizing photovoltaic (PV) modules through photons impingement in solar cells (Bejan, 2006; Martí, 2008; Pinho and Galdino, 2014; Preet, 2018). The electrical output depends on PV operation temperature, solar radiation, environmental temperature, wind velocity, cell material and aging (Abdin and Rachid, 2021). In turn, PV operation temperature is inversely proportional to electrical conversion efficiency. This temperature rises due to part of solar radiation, which is not converted into electricity or lost to surroundings, accumulated as heat (Guarracino et al., 2016; Dimri et al., 2017; Joshi and Dhoble, 2018; Busson et al., 2021).

A way to improve PV electrical performance, it removes the heat accumulated and converts it into useful thermal energy (Ahmed and Mohammed, 2018). The Photovoltaic-thermal (PVT) technology is an option for cooling the PV module, then it withdraws the excess heat by a fluid while increasing electrical efficiency. Thereby, taking the maximum available energy from solar irradiation for combining electricity generation and thermal energy (Allan et al., 2015).

At the end of 2018, PVT modules water-based without extra glass cover represented almost 60% of installed PVT power (IEA, 2020); this type of PVT module is the study object of the present paper. The PVT module analyzed in the experimental stage is obtained after applying a heat exchanger in a PV module's rear surface, as can be seen in Figure 1. This heat exchanger made of polypropylene (PP) has multiple rectangular channels with a hydraulic diameter of 4.24 mm, as can be seen in Figure 2.

Figure 1. PVT module with PP heat exchanger fixed.

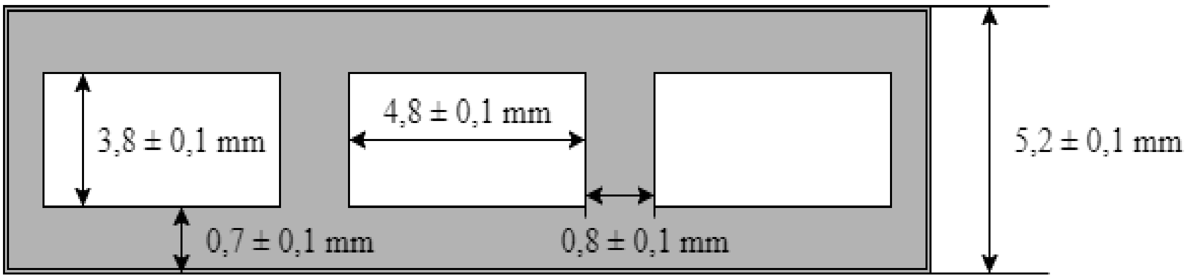

Figure 2. PP heat exchanger cross section (out of scale).

The main objective of the present paper is the modeling and determination of energy and exergy losses that occur during the PVT module operation. Finding the losses enable the project designer of a PVT module to understand what processes compromise the PVT performance and where is possible to make modifications that improve the global efficiency. The losses are evaluated an energy and exergy point of view. Energy losses are mainly due to convection and radiation heat losses in front and rear PVT surfaces. Already exergy losses evolve optical losses, heat transfer as convection and radiation heat losses and exergy destruction between equipment input and output.

2. ENERGY AND EXERGY LOSSES

The energy balance of a PVT module with a PP heat exchanger adopts the first law of thermodynamics. The energy input comes from solar radiation and the energy output is related to electrical and thermal energies. For treating measures done instantaneously, the data are correlated to powers or fluxes. The energy balance combines the solar radiation flux, electrical and thermal powers with rates of heat loss occurring both in front and rear PVT surfaces, as in Eq. (1). However, the rear surface heat losses can be considered negligible, then there is a thermal insulation under the PP heat exchanger.

$$(\tau\alpha)_c G A_c = \dot{W}_{el} + \dot{W}_{th} + \dot{Q}_{(l,top)} + \dot{Q}_{(l,r)} \quad (1)$$

Where $(\tau\alpha)_c$ is the transmissivity-absorptivity product of PV module, G is the incident solar irradiance, A_c is the area of PVT module, $\dot{W}_{el}$ is the electrical power generated by PVT module, $\dot{W}_{th}$ is the thermal power obtained by PVT module, $\dot{Q}_{(l,top)}$ is the rate of heat loss in the front PVT surface and $\dot{Q}_{(l,r)}$ is the rate of heat loss in the rear PVT surface that is negligible.

The energy loss happens mainly in front PVT surface where the rates of heat loss occur owing to convection and radiation heat transfers. The heat transfer coefficient is mostly influenced by forced convection, whilst the radiation heat transfer depends on sky and module operating temperatures. The sky temperature combines formulations of Duffie and Beckman (2006) and Lawrence (2005).

The evaluation of energy quality is named exergy. The exergy is the maximum work obtained from a system and is helpful for comparing processes in a system or between systems (Tiwari and Dubey, 2010; Rocha, 2019; Cavalcanti and Azevedo, 2021). The exergy analysis of a PVT module comprises heat transfers and power generation. The exergy balance encompasses inlet and outlet exergy rates, exergy destruction and exergy loss (Bejan et al., 1996; Rocha, 2019), as in Eq. (2).

$$\dot{E}_{in} - \dot{E}_{out} - \dot{E}_{l,out} = \dot{E}_d \quad (2)$$

Where $\dot{E}_{in}$ is the inlet exergy rate that is the solar radiation exergy, $\dot{E}_{out}$ is the outlet exergy rate that is Eq. (3), $\dot{E}_{l,out}$ is the exergy loss in the PVT system and $\dot{E}_d$ is the exergy destruction. Figure 3 shows a schematic sketch of the PVT module containing the inlet and outlet water representation.

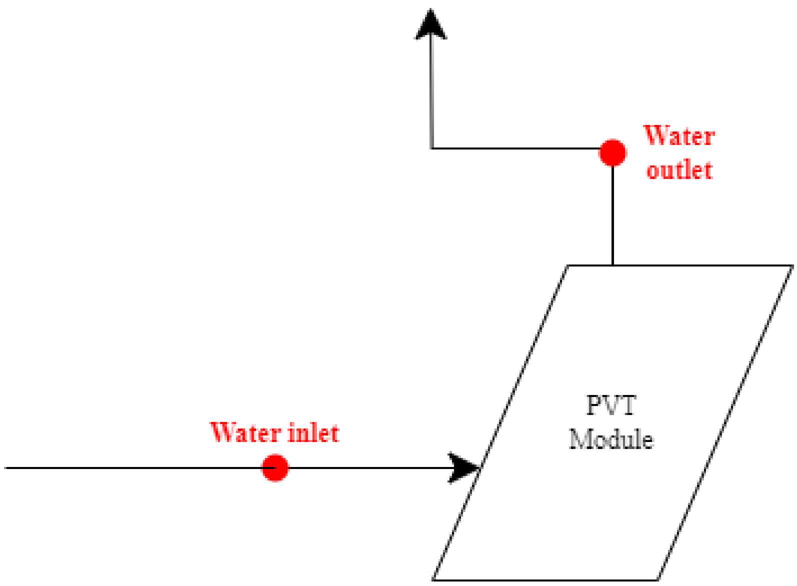

Figure 3. PVT module sketch.

$\dot{E}_{l,out}$ is related to optical and heat losses as in Eq. (4).

$$\dot{E}_{out} = \dot{W}_{el} + \dot{W}_{th}\left(1 - \frac{T_{amb} + 273,15}{T_{out} + 273,15}\right) \quad (3)$$

$$\dot{E}_{l,out} = \dot{E}_{l,opt} + \dot{E}_{l,q} \quad (4)$$

Where T_{amb} is the local ambient temperature, T_{out} is the outlet water temperature, $\dot{E}_{l,opt}$ is the exergy loss rate due to optical losses in PVT module and $\dot{E}_{l,q}$ is the exergy loss rate induced by heat loss. The rate of optical loss depends on transmissivity-absorptivity product and $\dot{E}_{l,q}$ is related to useful work extracted from $\dot{Q}_{(l,top)}$.

3. METHODOLOGY

The main equipment of a PVT system is the PVT module, so special attention must be given to the selection of the heat exchanger which is the component responsible for converting a conventional PV module into a PVT. As mentioned above, the heat exchanger utilized in the present work is made of multiple PP channels. Among the advantages of the PP heat exchanger are low cost, simplicity, flexibility and quick installation.

The test bench is located at the LEPTEN laboratories at the Federal University of Santa Catarina (UFSC) in Florianópolis, Santa Catarina, Brazil. The complete bench is a compound of two modules (PV and PVT modules), but only the data obtained from the PVT module are interesting for the present work. The PVT module has 405 Wp of nominal power and 2,21 m2. The test bench is exhibited in Figure 4.

Figure 4. Outdoor test bench at LEPTEN/UFSC.

Both energy and exergy balance equations presented in Section 2 are applied in a spreadsheet in Excel that receives measurements from the Data Acquisition System (DAS). Connected to DAS where there are sensors that enable measurements throughout the day. But only data gathered between 11:30 and 12:30 are used for the determination of energy and exergy losses.

The days selected to be applied in balance equations are chosen according to sky conditions. Seven days of clear sky conditions are suitable for energy and exergy loss models. Despite DAS acquires measurements along the day, for a better evaluation only data obtained in hourly of maximum solar incident radiation are considered. It is expected that the selected week presents days with almost the same solar irradiation level.

The temperatures are measured by PT100 sensors, the water flux by a flowmeter, the electrical power by the inverter register, the global solar radiation by a class B pyranometer and the wind velocity by an anemometer. These sensors record the measurements every 10 seconds in DAS, which in turn, exports the data acquisition. These data are applied in energy and exergy balance equations in Excel. The Excel spreadsheets contain cells that apply Coolprop commands to determine the specific exergies from temperatures and water flux measured by the sensors.

If the integration of electrical and thermal powers along the measurement period is done, it is possible to obtain the electrical and thermal energy production of the PVT module during the maximum solar incident radiation period. The performance information is interesting to show the PP heat exchanger capacity to improve the global energy production of a PVT system.

4. RESULTS AND DISCUSSION

The seven days are chosen and presented a solar irradiation of 4.4 kWh/m²/day, on average. This irradiation level is an indication that the week had clear sky conditions during the seven days. At the same time, on average, the electrical and thermal energy productions generated by the PVT module were 2.3 kWh and 2.9 kWh, respectively. Figure 5 shows each day with its solar irradiation level and energy production.

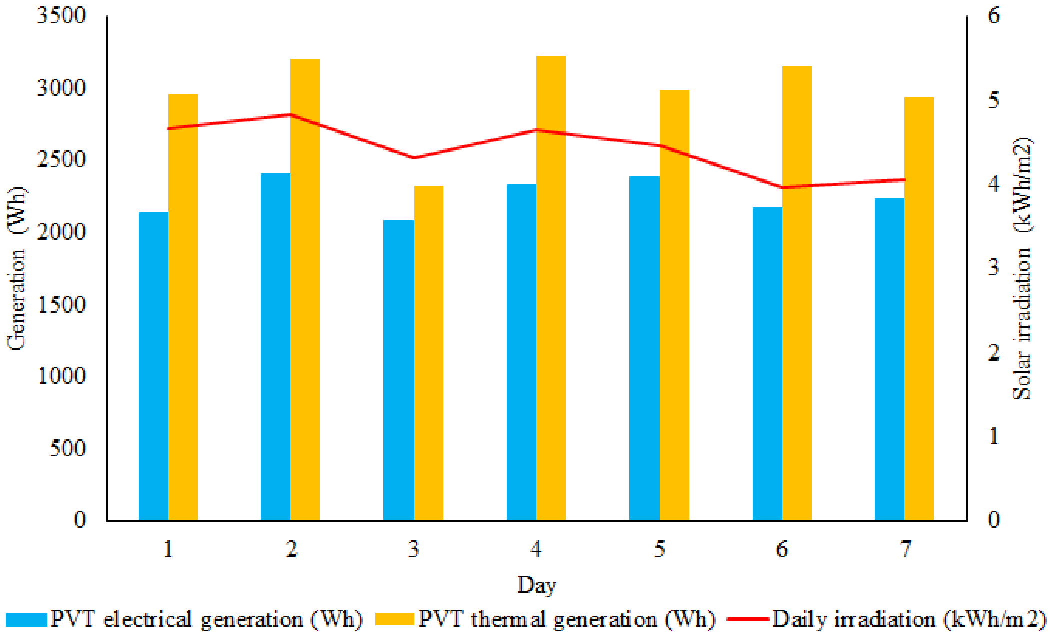

Figure 5. PVT energy production of one week.

It can be noted that thermal energy production was bigger than electrical energy production. When thermal and electrical productions are added, is obtained global performance. The global energy generated from solar radiation is the main advantage of a PVT module, then more energy is produced from solar radiation.

The calculated convection and radiation loss rates fluctuated between 100 and 450 W and 200 and 300 W, respectively, during hourly of maximum solar incident radiation. The loss rate range is due to the intermittence of wind speed (0 to 5 m/s) and variation of operating cell temperature (in the range of 34.5 °C and 41.8 °C). When the wind speed increased, the convection heat transfer was enhanced, consequently, the convection loss rate increased. Convection heat transfer is useful to cool the PV cells and enhance the electrical conversion efficiency. Nevertheless, thermal energy production is impaired. In turn, the radiation loss rate depends on operating cell temperature, but the major contribution to the heat loss rate resulted from convection top losses.

The main contributor in the operating PVT temperature reduction is the cooling promoted by water circulation inside heat exchanger channels. One PV module, near the PVT module analyzed, during the period of 11:30 and 12:30 hours presented temperatures between 39.1 °C e 48.6 °C. So, the temperature difference reached up to 6.9 °C. As the electrical efficiency is dependent of operating cell temperature, the lower PVT module temperature related to PV module temperature higher is the electrical conversion efficiency.

From the point of view of exergy losses, the convection and radiation heat transfers amongst exergy destruction due to pressure drop cause, on average, 17.5% of total exergy lost. Therefore, the heat losses and the pressure drop inside rectangular channels are responsible for part of potential work lost during the process of converting solar incident radiation into electrical and thermal powers.

When comparing the exergy lost due to optical losses and through heat transfer to the surroundings with the exergy destroyed obtained from Eq. (2), it is noticed that the PVT module also presents exergy destruction in processes not evaluated in the present work. This part of exergy destruction not specific evaluated represents about 9.8% on average of total exergy destruction in a PVT module.

Exergy is destroyed due to pressure drop by water flow inside the PP heat exchanger channels. The solar radiation conversion into electrical current measured by the inverter exhibits some losses capable of destroying exergy too. Water heating presents heat losses that compromise the thermal energy gain. The optical losses are influenced by the transmissivity-absorptivity product and vary with the solar incidence angle. Thus, between 11:30 and 12:30 hours, period of study, or in hourly of maximum solar incident radiation, this kind of loss is smaller because of small solar incidence angles. Notwithstanding, the exergy destruction due to optical losses represents more than 6% of exergy destruction. However, part of the destroyed exergy is not well defined and needs further analysis.

The main contribution to exergy destruction in a PVT module is by electrical and thermal energy conversions. Nonetheless, these energy conversions are not specifically studied in this work.

5. CONCLUSIONS

The PVT module analyzed in the present work is a conventional PV module converted into a PVT just by installing a PP heat exchanger. This heat exchanger presents a profile compound of rectangular channels where water circulates to cool down the operating cell temperature and, consequently, enhances the electrical conversion efficiency. Though the main advantage of a PVT module is the increase in global energy production because of thermal generation obtained with water heating.

The PVT module performance during seven clear sky days was evaluated during the hourly of maximum solar incident radiation. Along these days, the electrical and thermal energy productions were respectively 2.3 kWh and 2.9 kWh, on average. Even with the global performance gain, a portion of the solar irradiation is lost in heat transfer processes.

Energy losses narrow the knowledge about PVT actual global performance. Therefore, it is interesting to know about exergy losses too. Moreover, the PVT module is the main component responsible for exergy destruction in a PVT system.

The exergy losses are related to potential work lost with heat transfer and optical loss processes. Between 11:30 and 12:30 hours, the convection and radiation loss rates fluctuated from 100 to 450 W and 200 to 300 W, respectively. But these heat transfer losses represent about 18% of total exergy destroyed. The exergy destruction by optical losses cause more than 6% of exergy destruction. However, part of the destroyed exergy needs further analysis.

6. ACKNOWLEDGEMENTS

We thank Human Resources Programm of Oil, Natural gas and Biofuel National Agency (Programa de Recursos Humanos da Agência Nacional do Petróleo, Gás natural e Biocombustíveis – PRH-ANP), suported with resources coming from of oil company investments qualified in R, D&I Clause of ANP Resolution nº 50/2015.

7. REFERENCES

Allan, J., Dehouche, Z., Stankovic, S., Mauricette, L., 2015, Performance testing of thermal and photovoltaic thermal solar collectors, Energy Science & Engineering, Vol. 3, n. 4, pp. 310–326.

Barbón, A., Bayón-Cueli, C., Bayón, L., Rodríguez, L., 2019, Investigating the influence of longitudinal tilt angles on the performance of small scale linear Fresnel reflectors for urban applications, Renewable Energy, Vol. 143, pp. 1581–1593.

Bejan, A., 1996. *Transferência de calor*. Editora Edgard Blücher Ltda., São Paulo.

Bukarica, V., Tomšić, Ž., 2017, Energy efficiency policy evaluation by moving from techno-economic towards whole society perspective on energy efficiency market, Renewable & Sustainable Energy Reviews, Vol. 70, pp. 968–975.

Cavalcanti, E. J. C., Azevedo, J. L. B., 2021, Energy, exergy and exergoenvironmental (3E) analyses of power plant integrated with heliostats solar field, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol. 43, n. 4, pp. 1–13.

Duffie, J. A., Beckman, W. A., 2006. *Solar engineering of thermal processes*. Editora John Wiley & Sons, New Jersey.

Fraidenraich, N., Krenzinger, A., Tiba, C., Pereira, E. D., 2022. *Ciência e tecnologia solar no Brasil: 60 anos*. Editora Mariola Comunicação, Recife.

Guarracino, I., Mellor, A., Ekins-Daukes, N. J., Markides, C. N., 2016, Dynamic coupled thermal-and-electrical modelling of sheet-and-tube hybrid photovoltaic/thermal (PVT) collectors, Applied Thermal Engineering, Vol. 101, pp. 778–795.

IEA, 2021, *Global Energy Review 2021: Assesing the effects of economic recoveries on global energy demand and CO2 emissions in 2021*, International Energy Agency IEA, IEA Publications.

Lawrence, M., 2005, The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications, Bulletin of the American Meteorological Society, Vol. 86, pp. 225-233.

Lenin, N., Sivamurugan, P., Srimanickam, B., Ramanan, P., Kumar, M. S., 2019, Thermal and electrical performance evaluation of PV/T collectors in Southern India, International Journal of Ambient Energy, Vol. 42, n. 7, pp. 751–757.

Lima, L. C., Ferreira, L. A., Morais, F. H. B. L., 2017, Performance analysis of a grid connected photovoltaic system in northeastern Brazil, Energy for Sustainable Development, Vol. 37, pp. 79–85.

Mathew, A. A., Venugopal, T., 2021, Solar power drying system: a comprehensive assessment on types, trends, performance and economic evaluation, International Journal of Ambient Energy, Vol. 42, n. 1, pp. 96–119.

Pinho, J. T., Galdino, M. A., 2014. *Manual de engenharia para sistemas fotovoltaicos*. Editora CEPEL- CRESESB, Rio de Janeiro.

Rocha, D. H. D., 2019. *Análise Exergoambiental de Centrais Termelétricas Supercríticas e Ultrassupercríticas*. Master's thesis, Post-graduate Program in Mechanical Engineering, Mechanical Engineering Institute, Federal University of Itajubá, Itajubá, Brazil.

Tiwari, G. N., Dubey, Swapnil, 2010. *Fundamentals of Photovoltaic Modules and Their Applications*. 1ª ed. The Royal Society of Chemistry (RSC Publishing), Cambridge.

Weiss, W., Spörk-Dür, M., 2020. *Solar Heat Worldwide 2020 - Global market development and trends in 2019, edition 202*. International Energy Agency, Gleisdorf.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.