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Research Article

Investigation of the Effect of Physical Factors on Exergy Efficiency of a Photovoltaic Thermal (PV/T) with Air Cooling

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Thermal photovoltaic systems are used to harness solar energy to generate electricity and thermal at the same time. In this technology, electrical efficiency is very low compared to thermal efficiency; as the cell surface temperature rises, the electrical efficiency decreases, so one of the ways to achieve high efficiency is exergy analysis. Exergy analysis of a process or system shows how much of the ability to perform the work or input exergy has been consumed by that process or system. In this research, an ordinary thermal photovoltaic panel with air cooling has been examined for exergy. To do this, it has identified the effective performance variables from a mechanical point of view, which are inlet air temperature, inlet air flow, and length (number of modules that are connected in series). The effect of changing each of the variables based on Saveh weather conditions has been simulated using MATLAB software. The results show that the exergy efficiency of the panel decreases with the inlet air temperature increasing. It was also observed that the optimal airflow is 0012 (kg/s) and will have the highest efficiency per 8.8 m length.

1. Introduction

Energy is a basic need for continued economic development, human welfare, and comfort. World energy consumption has increased from 10 Gtoelyr crude oil to 14 Gtoelyr by 2020 and is projected to multiply in the near future. Will fossil energy sources meet the world's energy needs for survival, growth, and development in the next century [1–3]? Rising air pollution, including carbon dioxide, has left the world with irreversible and threatening changes, with consequences such as global warming, climate change, rising sea levels, and escalating international conflicts [4–6]. On the other hand, due to the destruction of fossil resources and the prediction of rising prices, policymakers and researchers should think about controlling the environment and renewable sources because these resources are compatible with nature and there is no end to them. Other features of these resources, their dispersion, expansion around the world, the need for less technology, and renewable energy have become more attractive, especially for developing countries [7–10].

Therefore, renewable energy sources have been given a special role in international programs and policies, including UN programs, for sustainable global development. But adopting renewables, with the current system of world energy consumption, it is still associated with problems that have been addressed by a significant amount of world scientific research in recent decades [11, 12]. Wolf introduced the basic concepts of PVT collectors in 1970 [13]. Zhang et al. used a computer simulation of the amount of solar radiation absorbed and the amount of infrared emission in thermal photovoltaic transducers working with weather-working fluid to be less than the type working with water-carrying fluid [14]. Researches examined the exergy performance of a greenhouse-connected photovoltaic module and provided an exergy efficiency of 4% for the system [15, 16]. The exergy and energetic analysis of a thermal photovoltaic cell without a glass cover was conducted. The use of a glass cover is suitable for the photothermic process. If the use of cover is not suitable for the photovoltaic process and due to various applications, it is not possible to determine exactly which one is more economical to use [17, 18]. The electrical and thermal efficiency of a PVT collector with air-operated fluid was determined. They supplied the required power to the fan directly from the photovoltaic panel and showed that there is the highest efficiency for the two collectors in the case of using two fans [19, 20]. Researches evaluated and optimized the performance of a photovoltaic array from the perspective of exergy. They show that the best state occurs when the temperature of the photovoltaic modulus is close to the ambient temperature [21–23]. Finally, different exergies of each component of PVT/water are calculated and a relationship is obtained based on loss of exergy [24–26].

The purpose of this study is to investigate the photovoltaic-thermal system with air cooling, in which exergy analysis has been performed to achieve high efficiency. In this regard, factors such as inlet air temperature-inlet flow and system length are problem variables. The impact of each of these factors has been evaluated for a sample area.

2. Materials and Methods

2.1. Fundamentals of Exergy Analysis. Exergy is the maximum useful work that results from a certain amount of available energy or flow of materials. In exergy analysis, the main purpose is to determine the location and amount of production of irreversibility during different processes of the thermodynamic cycle and the factors affecting the production of this irreversibility. In this way, in addition to evaluating the efficiency of different components of the thermodynamic cycle, ways to increase the efficiency of the cycle are also identified. Exergy analysis tries to obtain the most work produced in the cycle by simultaneously applying the first and second laws of thermodynamics and using the environment as a reference state.

2.2. Principles of Exergy Analysis of Thermal Photovoltaic Panels with Air Cooling. This study is aimed at analyzing the exergy of a photovoltaic-thermal collector with air cooling. Exergy analysis is a new and alternative method to older methods. This method is based on the concept of exergy. Exergy is defined with a bit of negligence as the ability to do work or the quality of different types of energy in a given environment. Exergy analysis of a process shows how much input or exergy functionality has been consumed by that process or system or, in other words, wasted. Contrary to current performance criteria, the concept of irreversibility is based on both laws of thermodynamics. The relation used for exergy analysis is obtained by combining the steady-state energy equation (first law) with the entropy production rate (second law).

However, the second law is not explicitly used in the analysis of exergy. But as stated, using the above method to evaluate the system implicitly requires applying the results of the second rule. The study of different forms of irreversibility gives a better understanding of it compared to the mere study of relevance and formulas related to the second law. Figure 1 shows the energy balance of the focal area of a thermal photovoltaic system.

The high efficiency of a system is not always a sufficient condition for its feasibility and cost-effectiveness. Factors such as initial costs, maintenance costs, and fuel consumption can affect whether or not a project is viable. In general, PVT collectors can be evaluated in two main ways: (a) exergy analysis and (b) energy analysis. Figure 2 shows the outline of a PVT.

Exergy balance for the collector of the following form is suggested:

$$\sum E_{X\text{out}} = \sum E_{X\text{thermal}} + \sum E_{X\text{electrical}}. \quad (1)$$

Table 1 shows the functional characteristics of the modeling photovoltaic cell.

2.3. Exergy Balance in General for PVT. As can be seen from the above relation, the input exergy caused by solar radiation minus the thermal exergy and electrical exergy will be equal to the exergy loss. Also, the exergy balance for the above collector is in the following form:

$$\begin{bmatrix} \text{rate of solar} \\ \text{energy availabel} \\ \text{on solar cell} \end{bmatrix} = \begin{bmatrix} \text{rate of heat loss from} \\ \text{top surface of solar cell} \\ \text{to ambient} \end{bmatrix}$$

$$+ \begin{bmatrix} \text{rate of heat transfer} \\ \text{from solar cell to} \\ \text{flowing fluid, i.e.,air} \end{bmatrix} + \begin{bmatrix} \text{rate of} \\ \text{electrical energy} \\ \text{produced} \end{bmatrix}$$

The above relationship is the basis for future relationships that will be expanded below. In general, we have presented two basic equations above. These two equations are the basis of energy analysis and exergy analysis of PVT collectors. Finally, with their help, more practical equations can be achieved. In this research, we have tried to perform the analysis based on design and performance parameters and the goal is to find the optimal points in the performance and design parameters so that the exergy efficiency is maximized. From the balance of exergy presented above, the cell

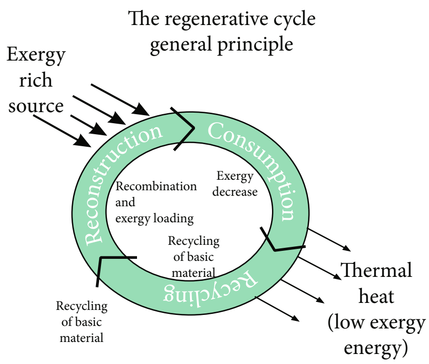

Figure 1: Exergy analysis.

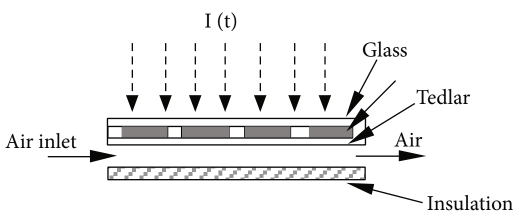

Figure 2: Overview of a PVT air cooler.

Table 1: Photovoltaic module specifications.

Parameter	Quantity
Maximum power	150 V
Maximum voltage	34.5 V
Maximum flow	4.35 A
Short circuit current	4.75 A
Open circuit voltage	43.5 V
Flow temperature coefficient	(0.065 ± 0.015) %/°C
Voltage temperature coefficient	-(16 0 ± 20) mV/°C
The effect of temperature on power	-(0.5 ± 0.05) %/°C
Nominal temperature of cell function	47 ± 2°C

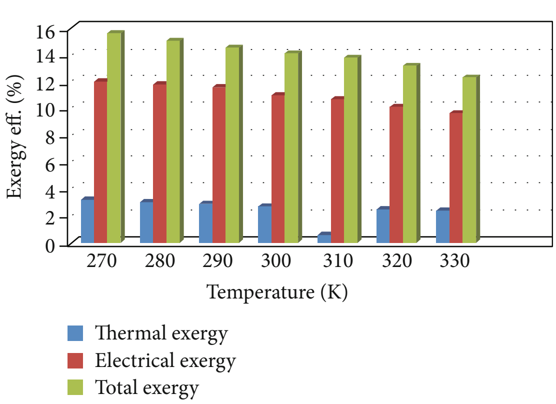

Figure 3: Effect of inlet air temperature change on exergy efficiency.

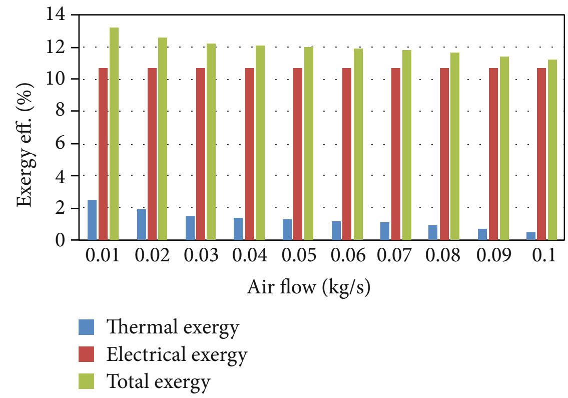

Figure 4: The effect of air flow change on exergy efficiency.

temperature will be obtained as follows [27, 28]:

$$T_c = \frac{((\alpha_{\text{eff}}.I(t)) + (Utca.Ta) + (Tbs.UT))}{Utca + UT}. \quad (2)$$

In the above relation α_{eff} is equal to

$$\alpha_{\text{eff}} = \tau_g(\alpha c.\beta + \alpha T.(1-\beta) - \eta.\beta). \quad (3)$$

The relationship between temperature and electrical efficiency is expressed as follows:

$$\eta = \eta_0[1 - \beta_0(T_C - T_a)]. \quad (4)$$

For the surface behind Tedlar,

$$U_T(T_C - T_{bs})bdx = h_T(T_{bs} - T_f)bdx, \quad (5)$$

$$\begin{bmatrix}\text{the rate of heat}\\ \text{transfer from cell to}\\ \text{back surface of Tedlar}\end{bmatrix} = \begin{bmatrix}\text{the rate of heat transfer}\\ \text{from back suface of Tedlar}\\ \text{to flowing fluid}\end{bmatrix}$$

The following will be done to balance the energy balance [27, 28]:

$$m_f C_f \frac{dT_f}{dX} + U_b(T_f - T_a)bdx = h_T(T_{bs} - T_f)bdx, \quad (6)$$

$$\begin{bmatrix}\text{rate of heat transfer}\\ \text{from solar cell to}\\ \text{flowing fluid, i.e.,air}\end{bmatrix} = \begin{bmatrix}\text{rate of heat transfer}\\ \text{flowing fluid}\end{bmatrix} + \begin{bmatrix}\text{an overal heat transfer}\\ \text{from flowing fluid}\\ \text{to ambient}\end{bmatrix}.$$

The outlet air temperature of the N module, which is connected in series, is calculated from the following equation:

$$T_{foN} = \left[\frac{\alpha_{\text{eff}} h_p}{u_l} + T_a\right]\left[1 - e^{(-blu_l/m c_f)}\right] + T_{fi} e^{(-(blu_l/m c_f))}. \quad (7)$$

If the size of the modules is the same, the useful heat obtained from the N modules that are connected in series

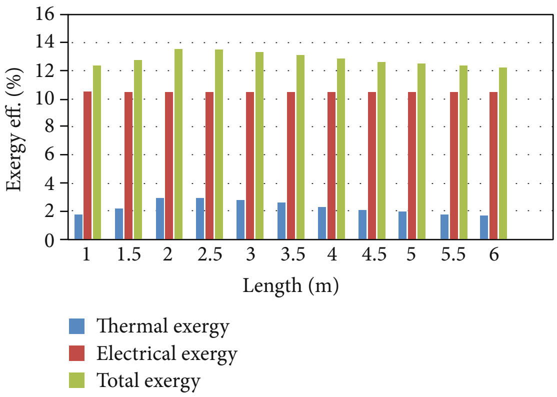

Figure 5: The effect of length change on exergy efficiency.

is calculated from the following equation [27, 28]:

$$Q_U.N = n_{pv} \times m_f c_f \left[1 - e^{\left(Nblu_l/m c_f\right)}\right]\left[\frac{h_p.\alpha_{\text{eff}}}{u_l} I(t) + T_{fi}\right],$$
$$K_k = \frac{b.l.u_l.F_R}{m_f c_f} \quad (8)$$

Finally, the electrical energy obtained from the panel is calculated from the following equation:

$$Ex_{\text{electrical}} = \eta.N.I(t).A. \quad (9)$$

3. Results

The parameters affecting the exergy analysis are the intensity of solar radiation in the environment, wind speed, ambient temperature, inlet and outlet air temperature, the surface temperature of the photovoltaic module, open-circuit voltage, short circuit current, voltage, and current at the maximum power point, panel length photovoltaics (the number of modules that are connected in series to form a module), input flow, etc. are many other parameters. Among these, we have selected four mechanical performance parameters, namely, modulus length and radiation intensity, inlet temperature, and flow rate, and simulated the effect of changing each of the parameters on total exergy, thermal efficiency, and electrical efficiency. This research is based on Saveh weather conditions. Information about the weather conditions of Saveh has been extracted from valid research on the intensity of radiation in Saveh and data of the Meteorological Organization. One of the disadvantages of the work of the past was the lack of sufficient attention to the influence of climate on the efficiency of exergy and mere parametric research. Except for a few specific cases, the research is based on the performance of the collector on a few specific days. In this research, it has been tried to do this based on meteorological and weather information of Saveh for a long time, and the results of the research are as practical as possible. Figure 3 shows the changes in exergy over temperature. It is observed that the exergy efficiency decreases with increasing the inlet temperature to the collector. This is due to the limited heat capacity of the air. In fact, by increasing the inlet temperature to the inlet air panel, it has less capacity to carry heat. Therefore, less heat is dissipated from the panel, resulting in a hot collector and reduced efficiency.

Figure 3 examines the performance of the panel in the temperature range of 270 to 330 degrees Kelvin. It is observed that for each degree of temperature increase, 0.6% exergy efficiency and 0.5% electrical efficiency decrease and 0.01% exergy efficiency due to exhaust air decreases. Note that if cool air was not used, the exergy efficiency would be reduced by 0.5% for each degree of temperature increase, and this diagram clearly shows the superior performance of PVTs compared to solar cells. In Figure 4, the behavior of the solar cell can be seen about the different flow rates of the cooling fluid.

As can be seen in Figure 4, the effect of air inlet flow rate from 0.01 to 0.1 (kg/s) on cell efficiencies has been evaluated. As an observation at first, we see an increase in efficiency with a steep slope. After reaching a peak, the efficiency decreases with a gentle slope and the reason for this behavior is the heat capacity of the air. As the flow rate increases, so does the heat transfer inlet speed. After reaching the peak, due to the reduced exchange of air molecules with the module, due to the high speed of the fluid entering the panel, the heat capacity decreases. As a result, the temperature of the air leaving the panel decreases and as a result, the efficiency of the exergy decreases. As it is known, the specifications of the maximum point are as follows: the optimal air inlet flow is 0.0035, for which the exergy efficiency is equal to 15.2%. Exergy efficiency due to air heat is 4.49%. Electrical efficiency is not dependent on flow; its value will be constant and equal to 10.7%. Figure 5 shows the effect of cool fluid channel length on electrical and thermal exergy efficiencies. The length of each module is 0.4 (m), and the length increase from 1 to 6 modules has been examined.

According to Figure 5, it can be seen that the length of the system does not affect electrical efficiency and the length of the system affects the thermal efficiency, so that the highest thermal exergy efficiency is related to the length of the system which is 2.5 (m) with a value of 3%. Then, with increasing length, a decrease in efficiency will be seen. The reason for this is the saturation of the air due to the absorption of heat by the collector. In this case, the end modules will always be hotter than the initial modules. At the maximum point, exergy efficiency is 13.81%. Thermal efficiency is equal to 3.1050%. The electrical efficiency will be constant and equal to 10.7.

4. Conclusion

In this research, a thermal photovoltaic system with air cooling has been performed to achieve high efficiency by exergy analysis. Observations showed that the photovoltaic/thermal collector performs better when water is injected and its performance in large areas will be very impressive. But for various reasons, such as simplicity of design, cheap, transfer speed, easy transportation, and no need for ancillary facilities in critical situations such as floods and earthquakes or conditions that only mean electricity generation, a collector with cooling air is recommended. Other results are increased temperature or velocity, reduced contact surface, and reduced air heat capacity.

Nomenclature

C: Specific heat (J/kg·C)
F_R: Flow rate factor (dimensionless)
h_T: Penalty factor due to Tedlar through glass, solar cell
L: Length (m)
$I(t)$: Incident solar intensity (W/m^2)
$\dot{m}$: Mass flow rate (m^3/s)
T: Temperature (C)
U_L: Overall heat transfer coefficient from solar cell to ambient through top and back surface of insulation (W/m^2·C)
T_{cell}: Solar cell temperature
α_c: Solar cell absorption coefficient
η_{el}: Electrical efficiency
τ_G: Glass transfer coefficient
m: Fluid flow rate
U_L: Overall heat loss coefficient.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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