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Chapter

Exergy in Photovoltaic/Thermal Nanofluid-Based Collector Systems

Amin Farzanehnia and Mohammad Sardarabadi

Abstract

This chapter focuses on the exergy analysis of photovoltaic/thermal (PVT) systems using nanofluid. The PVT hybrid systems are designed to harness solar energy more efficiently. The thermodynamic theory of exergy in PVT systems is explained in details. The existing researches used various models to perform the exergy analysis for performance evaluation of the PVT systems. These models and formulations are compared with each other to achieve a widely used theory for a better comparison of the results. The exergy analysis is an effective tool to evaluate the performance of PVT systems. The exergy efficiency enhancement in PVT systems and the effect of nanofluid from the literature are presented. The literature survey suggests that the increase in the flow rate increases the exergy efficiencies in collector-based PVT. Using nanofluid as optical filters of solar radiation results in higher exergy efficiencies compared to collector-based PVT systems. According to the recent publications, the long-term thermophysical stability of nanofluid and cost-based exergy analysis still require further investigations.

Keywords: PVT, photovoltaic/thermal, solar energy, nanofluids, exergy, nanoparticles

1. Introduction

Solar energy is a proven alternative for fossil fuels due to its sustainability and availability. The ever-reducing investment costs of solar system installation made this technology highly popular. The use of solar energy is a great method for mitigating the environmental and health problems presented by nonrenewable energy sources in the long term. Photovoltaic (PV) systems and hybrid photovoltaic/thermal (PVT) systems are the major tools for solar radiation to electrical and thermal energy conversion. The PVT systems are a combination of PV and solar collector to produce electricity and heat simultaneously. These hybrid systems have the benefits of increasing the electrical efficiency of the PV, obtaining thermal energy, and avoiding thermal degradation of PV solar panels [1]. **Figure 1** shows the schematic of a PVT system. The diagram of the PVT system with a water-based sheet and tube thermal collector is presented in **Figure 2**. It is shown that by reducing 1°C in PV cell temperature, the electrical efficiency increases by 0.4–0.5% [2]. For amorphous silicon (a-Si), this increase is smaller about 0.25%/°C [3]. Additionally, the combination of solar collector and PV technologies has the

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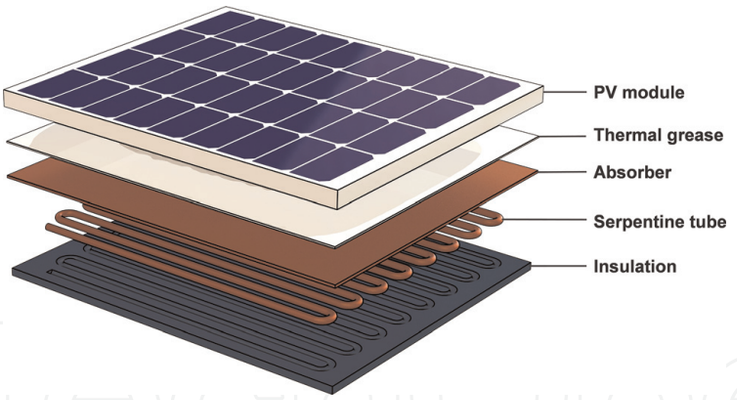


Figure 1.
The schematics of a PVT system.

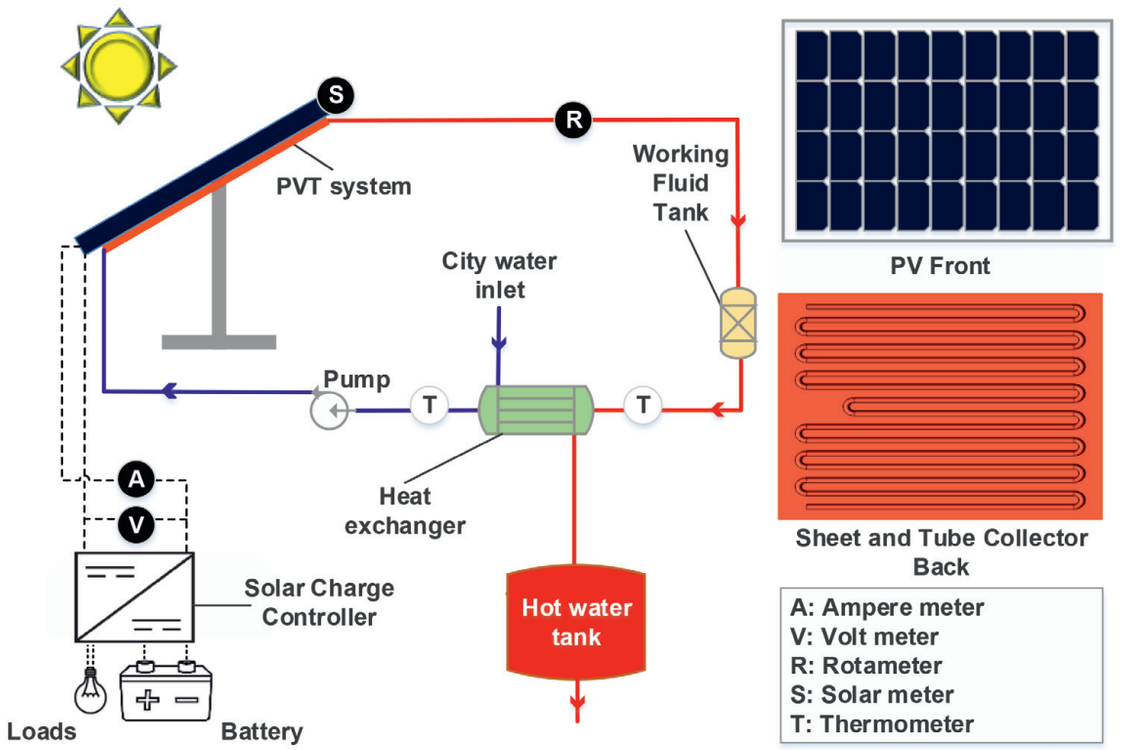


Figure 2.
The diagram of a PVT system with a water-based sheet and tube thermal collector.

advantages of reducing material usage, time of installation, and space required [4]. It is therefore necessary to evaluate the efficiency of PV and PVT systems to improve the design and usage of the systems, moreover, to help researches to make decisions on the usage and improvement of efficient systems.

Regarding the working fluid, PVT systems are classified under three groups of air-based PVT collector [5, 6], water-based PVT collector [7, 8], and a combination of air/water PVT collector [9, 10]. The PVT systems are mainly employed for low-temperature applications including space heating and air/water preheating in domestic buildings [11]. The type of working fluid is of primary significance to achieve energy-efficient systems compared to conventional fluids. The use of nanofluids due to their advanced thermal properties is gaining more and more attention [12]. Nanofluids are able to increase the efficiency of solar systems due to their augmented heat transfer properties such as thermal conductivity [13].

Exergy is an important means to evaluate the efficient use of the PV and PVT systems. The term exergy is defined as the maximum theoretical work potential of a system that interacts with an environment with constant conditions. In other words, exergy is defined as the energy that is available to be used. Therefore, one can evaluate the performance of a system by using the exergetic (second law) of thermodynamics.

2. Theory

The performance of PVT systems could be analyzed by the second law of thermodynamics (exergy analysis). In contrast to energy analysis, the exergy analysis takes the quality of energies into consideration. As mentioned before, the output energy of a PVT system is distributed over two forms of thermal and electrical energies. However, the quality of electrical energy is different from that of thermal energy. The electrical energy is equivalent to the available work, while only a part of thermal energy could be exploited as available work.

2.1 Energy analysis

Prior to performing the exergy analysis, the absorbed solar irradiation and output thermal and electrical power of PVT are required to be found. The PVT system is considered as control volume and is assumed to be in semi-steady state condition. The solar irradiation absorbed by PVT is calculated by [14]:

$$\dot{E}_{sun} = \dot{G_T}\, A_{PV}\, \tau_g\, \alpha_{cell} \tag{1}$$

where $\dot{G_T}$ is the total solar irradiation, A_{PV} is the PV area, τ_g is transmissivity of the glass layer over the PV module, and α_{cell} absorptivity of PV cells. The output energy from the thermal collector is given by:

$$\dot{E}_{th} = \dot{m}\, C_p(T_{out} - T_{in}) \tag{2}$$

In Eq. (2) the term $\dot{m}$ refers to the mass flow rate of the coolant fluid in the thermal collector of PVT system, C_p is the specific heat capacity, and the T_{in} and T_{out} are the inlet temperature and the outlet temperature of the coolant fluid, respectively.

In the condition where the coolant fluid is a nanofluid, the specific heat capacity of nanofluid is expressed as either Eq. (3) or (4) [15]:

$$C_{p.nf} = \varphi C_{p,np} + (1-\varphi)C_{p,np} \tag{3}$$

$$C_{p.nf} = \frac{\varphi(\rho C_p)_{np} + (1-\varphi)(\rho C_p)_{bf}}{\rho_{nf}} \tag{4}$$

where the subscripts nf, np, and bf denote nanofluid, nanoparticles, and base fluid, respectively. In the above equations, ρ is the density of the corresponding materials. The term φ is the volume fraction of nanoparticles which is given by:

$$\varphi = \left(\frac{m_{np}}{\rho_{np}}\right) \Big/ \left(\frac{m_{np}}{\rho_{np}} + \frac{m_{bf}}{\rho_{bf}}\right) \tag{5}$$

where m_{np} and m_{bf} refer to the mass of nanoparticles and base fluid, respectively. The density of nanofluid ρ_{nf} in Eq. (4) is simply given by the two-phase mixture principle:

$$\rho_{nf} = \varphi\rho_{np} + (1-\varphi)\rho_{bf} \tag{6}$$

Equation (4) is proposed more in the literature than Eq. (3) due to the better agreement with the experimental results [15–17].

The main output of a PV module is the electrical energy output which is given by [18]:

$$\dot{E}_{el} = V_{oc} \times I_{sc} \times FF \tag{7}$$

where V_{oc}, I_{sc}, and FF are the open circuit voltage, short circuit current, and fill factor, respectively.

2.2 Exergy analysis

For better understanding, the diagram of exergy flows belonging to a PVT system is shown in **Figure 3**. The first step to investigate the performance of PVT system from exergy viewpoint is to consider the PVT system as a control volume. It is assumed that the system is in semi-steady condition.

The exergy balance of a PVT system is expressed as:

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{dest} \tag{8}$$

where $\sum \dot{E}x_{in}$ is inlet exergy, $\sum \dot{E}x_{out}$ is the outlet exergy, and $\sum \dot{E}x_{dest}$ is the exergy loss or destruction due to the irreversibility.

The term $\sum \dot{E}x_{in}$ is the net input exergy rate. In solar systems such as PVT, the input energy is the solar radiation that reaches the system; therefore, the input exergy is equal to the exergy of incident solar irradiation to the system ($\dot{E}x_{sun}$):

$$\sum \dot{E}x_{in} = \dot{E}x_{sun} \tag{9}$$

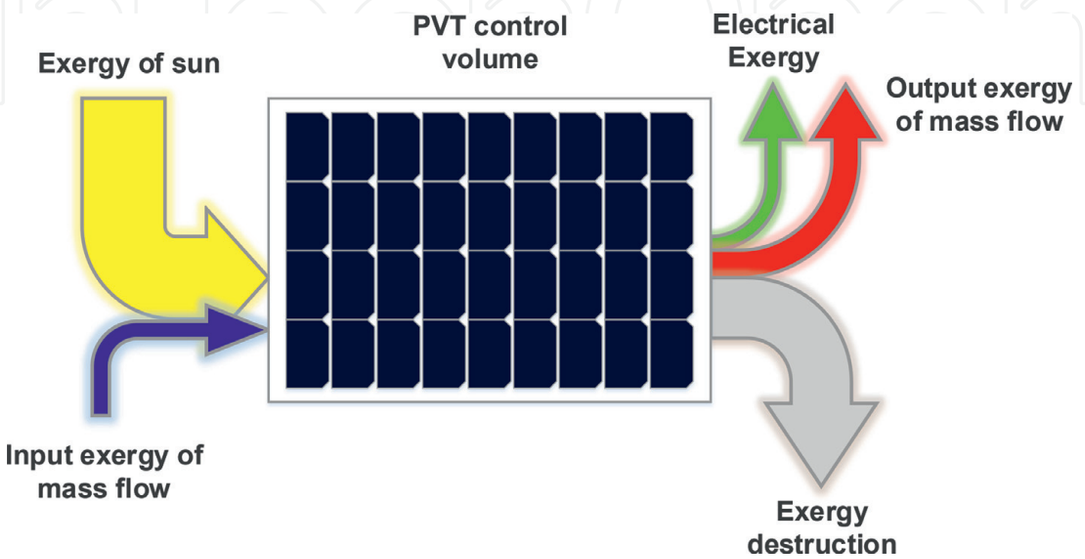


Figure 3.
The exergy flow diagram of a PVT system.

The net output exergy ($\sum \dot{E}x_{out}$) of PVT systems consists of thermal exergy ($\dot{E}x_{th}$) and electrical exergy ($\dot{E}x_{el}$):

$$\sum \dot{E}x_{out} = \dot{E}x_{th} + \dot{E}x_{el} \tag{10}$$

Considering that the thermal exergy is equal to the difference of flow exergy at the outlet and inlet of the collector ($\dot{E}x_{th} = \dot{E}x_{mass.out} - \dot{E}x_{mass.in}$), the exergy balance becomes (Eqs. 8–10):

$$\dot{E}x_{sun} = \dot{E}x_{th} + \dot{E}x_{el} + \dot{E}x_{dest} \tag{11}$$

Many methods have been proposed to evaluate the exergy of the solar irradiation. The three following equations are the most commonly used equations for the exergy of absorbed solar irradiation by the PVT proposed, respectively, by Jeter [19], Spanner [20], and Petala [21]:

$$\dot{Ex}_{sun} = \dot{E}_{sun}\left(1 - \frac{T_{amb}}{T_{sun}}\right) \tag{12}$$

$$\dot{Ex}_{sun} = \dot{E}_{sun}\left(1 - \frac{4T_{amb}}{3T_{sun}}\right) \tag{13}$$

$$\dot{Ex}_{sun} = \dot{E}_{sun}\left[1 - \frac{4T_{amb}}{3T_{sun}} + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4\right] \tag{14}$$

where T_{amb} is the ambient temperature and T_{sun} is the surface temperature of the sun as a blackbody. Although it is hotter inside, the sun temperature could be estimated at its surface where the emissions occur and is approximated as a blackbody at 5770 K. The results from Eqs. (12)–(14) differ from each other less than 2% [22]. However, the literature review by Kalogirou [23] indicates that Eq. (14) (Petala equation) is proposed and used more often than the other two equations.

The output thermal exergy of the PVT system ($\dot{E}x_{th}$) is given by both Eqs. (15) and (16) [24, 25]:

$$\dot{E}x_{th} = \dot{E}_{th}\left(1 - \frac{T_{amb}}{T_{out}}\right) \tag{15}$$

$$\dot{E}x_{th} = \dot{m}[(h_{out} - h_{in}) - T_{amb}(s_{out} - s_{in})] = \dot{m}\ C_p\left[(T_{out} - T_{in}) - T_{amb}\ln\left(\frac{T_{out}}{T_{in}}\right)\right] \tag{16}$$

where h_{out} and s_{out} are the fluid enthalpy and entropy at the outlet of the collector. Similarly, h_{in} and s_{in} are the fluid enthalpy and entropy at the inlet of the collector.

Equation (15) derives the exergy based on a series of imaginary heat engine that operates between source temperature of T_{out} and the sink temperature of T_{amb}. Thus, the thermal exergy is the available work extracted from a Carnot efficiency heat engine between the outlet fluid temperature and ambient temperature. Equation 16 is often encountered in the literature [24, 26].

The electrical energy output is equivalent to the electrical exergy. The electrical energy could be 100% converted to work. Therefore, the electrical exergy of a passive PVT is expressed as:

$$\dot{Ex}_{el} = \dot{E}_{el} \tag{17}$$

However, the electrical exergy of an active PVT system is defined as the difference between electrical power and the required pumping power Eq. (18) [27]. Nevertheless, some studies do not consider the pumping power and simply use Eq. (17) [11]:

$$\dot{Ex}_{el} = \dot{E}_{el} - \dot{E}_{pump} \tag{18}$$

where $\dot{E}_{pump}$ is the electrical power consumption of the pump, which can be expressed as [28]:

$$\dot{E}_{pump} = \frac{\dot{m}\Delta P}{\rho \eta_p} \tag{19}$$

where η_p is the pump efficiency. Thermal and electrical exergy efficiencies based on second law are given as:

$$\varepsilon_{th} = \frac{\dot{Ex}_{th}}{\dot{Ex}_{sun}} \times 100 \tag{20}$$

$$\varepsilon_{el} = \frac{\dot{Ex}_{el}}{\dot{Ex}_{sun}} \times 100 \tag{21}$$

The overall exergy efficiency could be given as follows:

$$\varepsilon_{total} \cong \frac{\dot{Ex}_{th} + \dot{Ex}_{el}}{\dot{Ex}_{sun}} = \frac{\int_{t_2}^{t_1} \left(A_c \dot{Ex}''_{th} + A_{PV} \dot{Ex}''_{el}\right) dt}{A_c \int_{t_2}^{t_1} \left(\dot{Ex}''_{sun}\right) dt} = \varepsilon_{th} + r\varepsilon_{el} \tag{22}$$

where A_{PV} and A_c are the PV panel and collector areas, respectively. $\dot{Ex}''_{th}$ is the rate of the output thermal exergy per unit area of collector, $\dot{Ex}''_{el}$ is the rate of electrical exergy per unit area of PV module, and $\dot{Ex}''_{sun}$ is the rate of solar irradiation exergy per unit area of collector. The term r is the packing factor and defined as the area of PV panel to the collector ($r = A_{PV}/A_c$). Therefore, when the packing factor is equal to 1, the overall exergy is simply the sum of thermal and electrical exergy efficiencies.

It worth mentioning that the exergy destruction term $\dot{Ex}_{dest}$ in Eqs. (8) and (11) is due to heat transfer losses and frictional losses in the collector tube. In the active PVT systems, in addition to heat transfer exergy loss, there is another exergy loss due to head or frictional loss in the collector tube, which can be derived by:

$$\dot{E}_{loss,fr} = \frac{\dot{m}\Delta P}{\rho} \frac{T_{amb} \cdot \ln\left(T_{out}/T_{in}\right)}{\left(T_{out} - T_{in}\right)} \tag{23}$$

where ΔP is the pressure drop along the collector and ρ is the fluid density. The rate of entropy generation by irreversibility in the control volume could be calculated as:

$$\dot{S}_{gen} = \frac{\dot{Ex}_{dest}}{T_{amb}} \tag{24}$$

where the $\dot{Ex}_{dest}$ is the total rate of exergy destruction which is the sum of exergy destruction due to the heat transfer loss and due to pressure drop in the collector tube and is given by Eq. (11).

3. Development of nanofluid-based PVT

The PVT system is employed to produce electrical and thermal energies simultaneously. The study of PVT water-based collectors has been limited in the literature due to the small market size. Also, most literature is focused on custom-made PVT systems [4]. However, now there are various configurations of commercialized PVT available, and these systems became popular [29, 30]. As the market size increases, it is necessary to evaluate and enhance the performance of PVT systems. Recently, the nanofluids are used in the PVT systems as working fluid or as optical filters resulting in increased efficiency of the systems. There are several reviews published on the topic of nanofluid PVT in the last couple of years such as by Said et al. [31], by Yazdanifard et al. [27], by Al-Shamani et al. [12], and by Ali et al. [32].

Sardarabadi et al. [14] performed an experimental investigation on silica/water nanofluid PVT systems based on first and second laws of thermodynamics. The mass flow rates 20, 30, and 40 L/h were studied, and the optimum mass flow rate for the working fluid was determined. The thermal exergy efficiency of the system was much smaller than the electrical efficiency. This was attributed to the small temperature difference between outlet and ambient temperatures. The results indicated that using thermal collector with the PV module increases the overall efficiency. Also using nanofluid enhances the energy efficiency of the system. However, comparing the results from the second law to the first law of thermodynamics, it was shown that although the thermal and overall efficiency from the first law viewpoint is high, the thermal exergetic and therefore overall efficiency were low (**Table 1**). This was due to the low-quality (low temperature) thermal energy in PVT systems.

Moradgholi et al. [35] studied two-phase closed thermosyphon (TPCT) PVT system using Al_2O_3/methanol nanofluid as the working fluid. They studied the effects of various mass fractions of nanoparticles 1, 1.5, and 2 wt%, and also the effect of filling ratio (the working fluid volume to the evaporating section volume) was studied. The optimum values of thermal and electrical performance of the system were obtained at the mass concentration of 1.5 wt% and the filling ratio of 50%. The average overall exergy efficiency was 11.7, 12.5, and 12.7% for PV module, PVT module with base fluid, and PVT module with nanofluid, respectively.

Sardarabadi et al. [34] studied the effects of both ZnO/water nanofluid and phase-change material (PCM) as a coolant in photovoltaic thermal systems. They used a PV module as a reference point and performed energy and exergy analysis on PV, PVT, and PVT with PCM systems with water and ZnO/water nanofluid as working fluids. An increase of nearly twice in the thermal exergy output was observed using PCM in PVT modules. This was also shown in other studies [26] and is because the heat generated in PV cells is absorbed in PCM and could be used as thermal energy. Also, the overall exergy efficiency of 10% was found for the PV module, whereas the PVT module and PVT module with PCM using nanofluid had an efficiency of 12.29 and 13.42%, respectively.

Sardarabadi et al. [24] studied the effects of using metal-oxides/water nanofluids on a PVT system from energy and exergy viewpoints. The Al_2O_3, TiO_2, and ZnO nanoparticles with the mass fraction of 0.2 wt% were considered. It was shown that the ZnO/water nanofluid had the highest energy and exergy efficiencies and TiO_2/water had the highest electrical exergy efficiency than other systems. The average overall exergy efficiency for the PV, PVT/water, PVT/TiO_2, PVT/ZnO, and PVT/Al_2O_3 was 10.29, 11.56, 11.93, 12.17, and 11.88%, respectively.

Brekke et al. [36] proposed a performance model of a concentrating hybrid PVT system utilizing selective spectral nanofluid absorption. The proposed system used nanofluid to absorb the portion of the solar spectrum not efficiently exploited by

Ref.	Working fluid type	Concentrations	Flow rate	Amb. temp. (°C)	Exergy efficiencies (%)		
					Thermal	Electrical	Overall
[14]	Without cooling	—	—	33	0	11.53	11.53
	Pure water	0	30 L/h		1.23	12.47	13.54
	SiO_2/water	1 wt%			1.48	12.57	13.85
	SiO_2/water	3 wt%			1.68	12.59	14.02
[33]	Ag/water	2 and 4 wt%	0.0085, 0.016, and 0.029 kg/s corresponding to laminar, transient, and turbulent regimes	25			4 wt%, turbulent regime: 50 and 30% improvements in exergy efficiency compared to water coolant
[34]	Without cooling	—	—	—	0	10.9	10.9
	PVT pure water	0	30 kg/h	—	0.50	11.73	12.23
	PVT ZnO/ water	0.2 wt%			0.51	11.78	12.29
	PVT/PCM Pure water	0			0.87	12.30	13.17
	PVT/PCM ZnO/water	0.2 wt%			1.08	12.35	13.42
[35]	Without cooling	—	—	—	—	—	11.7
	Pure water	—	15 (l/min)		—	—	12.5
	Al_2O_3/ methanol	1, 1.5, and 2 wt %			—	—	12.7 for the optimum conditions
[24]	Without cooling			—	0	10.29	10.29
	Pure water		30 kg/h		0.72	10.84	11.56
	TiO_2/water	0.2 wt%			0.91	11.02	11.93
	ZnO/water	0.2 wt%			1.18	10.99	12.17
	Al_2O_3/ water	0.2 wt%			1.01	10.87	11.88
[36]	Au/ Duratherm S	—	0.05 kg/s	19	—	—	41.3
	ITO/ Duratherm S				—	—	42.3
[37]	Ag/water	0.001–1.5 vol.%	0.08 kg/s	—	—	—	By increasing nanofluid volume fraction for GaAs cells: 24.2–30% For Si cells: 19.8–24.4%

Table 1.
List of studies on the PVT nanofluid collector-based systems.

the PV module. Two common PV cell materials of crystalline silicon (c-Si) and gallium arsenide (GaAs) were used in their numerical study. The heat transfer fluid of Duratherm S and gold nanoparticles were considered for c-Si, and indium tin oxide (ITO) nanoparticles were considered for GaAs PV module. The GaAs exhibited higher exergy efficiency due to higher PV efficiency of this cell; however, this results in the reduction of thermal exergy percentage of these cells because a smaller portion of thermal energy is absorbed by the spectral fluid. The results of exergy efficiency of previous studies are summarized in **Table 1**.

4. Conclusion

This chapter addresses the exergy in photovoltaic/thermal systems that contain nanofluid-based collector. These systems provide both thermal and electrical energies. The comprehensive theory of exergy analysis in these systems is elaborated. It is shown that existing researches used various models to perform the exergy analysis for performance evaluation of the photovoltaic/thermal systems. These models are compared with each other to achieve a widely used theory for a better comparison of the results. The literature survey on nanofluid in PVT indicates that the overall exergy efficiency is generally in the range of 10–14% for PVT collectors. The increasing flow rate and transition to turbulent flow increase exergy efficiency. When using nanofluid as optical filters, higher exergy efficiencies were observed. The performance of PVT systems could be analyzed by exergy analysis. Despite the benefits of nanofluid PVT system, barriers to the development of these systems are agglomeration, required pumping power, and pipe erosions. Additionally, the use of nanofluid collectors and optical filters brings much cost to the system. Therefore future investigation is required on exergy-based cost analysis, nanofluid stability, and optimization of PVT systems.

Nomenclature

A	area (m^2)
C_P	specific heat capacity (J kg^{-1} K^{-1})
E	energy (J)
Ex	exergy (J)
$\dot{E}$	power (W)
FF	fill factor
$\dot{G}$	solar irradiation rate (W m^{-2})
I	electrical current (A)
$\dot{m}$	mass flow rate (kg s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
P	pressure (Pa)
T	temperature (K)
V	velocity (m/s)
r	packing factor

Greeks

α	absorptivity
ε	exergy efficiency (%)

ρ	density (kg m^{-3})
τ	transmissivity
ϕ	nanoparticles volume fraction

Subscripts

amb	ambient
bf	base-fluid
dest	destruction
el	electrical
in	inlet
n	nanoparticle
nf	nanofluid
oc	open circuit
out	outlet
ov	overall
t	total
sc	short circuit
th	thermal

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References

[1] Al-Musawi AIA, Taheri A, Farzanehnia A, Sardarabadi M, Passandideh-Fard M. Numerical study of the effects of nanofluids and phase-change materials in photovoltaic thermal (PVT) systems. Journal of Thermal Analysis and Calorimetry. 2018

[2] Al-Waeli AH, Sopian K, Chaichan MT, Kazem HA, Hasan HA, Al-Shamani AN. An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system. Energy Conversion and Management. 2017;**142**:547-558

[3] Nižetić S, Giama E, Papadopoulos A. Comprehensive analysis and general economic-environmental evaluation of cooling techniques for photovoltaic panels, Part II: Active cooling techniques. Energy Conversion and Management. 2018;**155**:301-323

[4] Good C. Environmental impact assessments of hybrid photovoltaic–thermal (PV/T) systems–A review. Renewable and Sustainable Energy Reviews. 2016;**55**:234-239

[5] Sarhaddi F, Farahat S, Ajam H, Behzadmehr A, Mahdavi Adeli M. An improved thermal and electrical model for a solar photovoltaic thermal (PV/T) air collector. Applied Energy. 2010;**87**: 2328-2339

[6] Su D, Jia Y, Alva G, Liu L, Fang G. Comparative analyses on dynamic performances of photovoltaic–thermal solar collectors integrated with phase change materials. Energy Conversion and Management. 2017;**131**:79-89

[7] Yazdanpanahi J, Sarhaddi F, Mahdavi Adeli M. Experimental investigation of exergy efficiency of a solar photovoltaic thermal (PVT) water collector based on exergy losses. Solar Energy. 2015;**118**: 197-208

[8] Fudholi A, Sopian K, Yazdi MH, Ruslan MH, Ibrahim A, Kazem HA. Performance analysis of photovoltaic thermal (PVT) water collectors. Energy Conversion and Management. 2014;**78**: 641-651

[9] Yu B, Jiang Q, He W, Liu S, Zhou F, Ji J, et al. Performance study on a novel hybrid solar gradient utilization system for combined photocatalytic oxidation technology and photovoltaic/thermal technology. Applied Energy. 2018;**215**: 699-716

[10] Othman MY, Hamid SA, Tabook MAS, Sopian K, Roslan MH, Ibarahim Z. Performance analysis of PV/T Combi with water and air heating system: An experimental study. Renewable Energy. 2016;**86**:716-722

[11] Bayrak F, Abu-Hamdeh N, Alnefaie KA, Öztop HF. A review on exergy analysis of solar electricity production. Renewable and Sustainable Energy Reviews. 2017;**74**:755-770

[12] Al-Shamani AN, Yazdi MH, Alghoul M, Abed AM, Ruslan MH, Mat S, et al. Nanofluids for improved efficiency in cooling solar collectors–A review. Renewable and Sustainable Energy Reviews. 2014;**38**:348-367

[13] Al-Shamani AN, Sopian K, Mat S, Hasan HA, Abed AM, Ruslan M. Experimental studies of rectangular tube absorber photovoltaic thermal collector with various types of nanofluids under the tropical climate conditions. Energy Conversion and Management. 2016;**124**: 528-542

[14] Sardarabadi M, Passandideh-Fard M, Heris SZ. Experimental investigation of the effects of silica/water nanofluid on PV/T (photovoltaic thermal units). Energy. 2014;**66**:264-272

[15] Mahian O, Kianifar A, Kleinstreuer C, Al-Nimr MA, Pop I, Sahin AZ, et al. A review of entropy generation in nanofluid flow. International Journal of Heat and Mass Transfer. 2013;**65**: 514-532

[16] Mahian O, Kianifar A, Sahin AZ, Wongwises S. Entropy generation during Al_2O_3/water nanofluid flow in a solar collector: Effects of tube roughness, nanoparticle size, and different thermophysical models. International Journal of Heat and Mass Transfer. 2014;**78**:64-75

[17] Khanafer K, Vafai K. A critical synthesis of thermophysical characteristics of nanofluids. International Journal of Heat and Mass Transfer. 2011;**54**:4410-4428

[18] Hosseinzadeh M, Salari A, Sardarabadi M, Passandideh-Fard M. Optimization and parametric analysis of a nanofluid based photovoltaic thermal system: 3D numerical model with experimental validation. Energy Conversion and Management. 2018;**160**: 93-108

[19] Jeter SM. Maximum conversion efficiency for the utilization of direct solar radiation. Solar Energy. 1981;**26**: 231-236

[20] Spanner DC. Introduction to Thermodynamics. London and New York: Academic Press; 1964

[21] Petela R. Exergy of heat radiation. Journal of Heat Transfer. 1964;**86**: 187-192

[22] Chow TT, Pei G, Fong K, Lin Z, Chan A, Ji J. Energy and exergy analysis of photovoltaic–thermal collector with and without glass cover. Applied Energy. 2009;**86**:310-316

[23] Kalogirou SA, Karellas S, Braimakis K, Stanciu C, Badescu V. Exergy analysis of solar thermal collectors and processes. Progress in Energy and Combustion Science. 2016;**56**:106-137

[24] Sardarabadi M, Hosseinzadeh M, Kazemian A, Passandideh-Fard M. Experimental investigation of the effects of using metal-oxides/water nanofluids on a photovoltaic thermal system (PVT) from energy and exergy viewpoints. Energy. 2017;**138**:682-695

[25] Ghadiri M, Sardarabadi M, Pasandideh-fard M, Moghadam AJ. Experimental investigation of a PVT system performance using nano ferrofluids. Energy Conversion and Management. 2015;**103**:468-476

[26] Hosseinzadeh M, Sardarabadi M, Passandideh-Fard M. Energy and exergy analysis of nanofluid based photovoltaic thermal system integrated with phase change material. Energy. 2018;**147**: 636-647

[27] Yazdanifard F, Ameri M, Ebrahimnia-Bajestan E. Performance of nanofluid-based photovoltaic/thermal systems: A review. Renewable and Sustainable Energy Reviews. 2017;**76**: 323-352

[28] Zainine MA, Mezni T, Dakhlaoui MA, Guizani A. Energetic performance and economic analysis of a solar water heating system for different flow rates values: A case study. Solar Energy. 2017; **147**:164-180

[29] Axaopoulos PJ, Fylladitakis ED. Performance and economic evaluation of a hybrid photovoltaic/thermal solar system for residential applications. Energy and Buildings. 2013;**65**:488-496

[30] Lamnatou C, Chemisana D. Photovoltaic/thermal (PVT) systems: A review with emphasis on environmental issues. Renewable Energy. 2017;**105**: 270-287

[31] Said Z, Arora S, Bellos E. A review on performance and environmental

effects of conventional and nanofluid-based thermal photovoltaics. Renewable and Sustainable Energy Reviews. 2018; **94**:302-316

[32] Ali HM, Shah TR, Babar H, Khan ZA. Microfluidics and Nanofluidics. IntechOpen; 2018

[33] Aberoumand S, Ghamari S, Shabani B. Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: An experimental study. Solar Energy. 2018;**165**:167-177

[34] Sardarabadi M, Passandideh-Fard M, Maghrebi MJ, Ghazikhani M. Experimental study of using both ZnO/water nanofluid and phase change material (PCM) in photovoltaic thermal systems. Solar Energy Materials and Solar Cells. 2017;**161**:62-69

[35] Moradgholi M, Nowee SM, Farzaneh A. Experimental study of using Al_2O_3/methanol nanofluid in a two phase closed thermosyphon (TPCT) array as a novel photovoltaic/thermal system. Solar Energy. 2018;**164**:243-250

[36] Brekke N, Dale J, DeJarnette D, Hari P, Orosz M, Roberts K, et al. Detailed performance model of a hybrid photovoltaic/thermal system utilizing selective spectral nanofluid absorption. Renewable Energy. 2018;**123**:683-693

[37] Hassani S, Taylor RA, Mekhilef S, Saidur R. A cascade nanofluid-based PV/T system with optimized optical and thermal properties. Energy. 2016;**112**: 963-975