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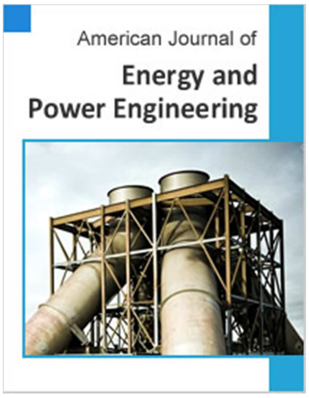

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Energy and Exergy Performance Analysis of Hybrid Solar Photovoltaic/Thermal (PV/T) Collector

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Abstract

A photovoltaic/thermal (PV/T) collector is a combination of photovoltaic cells with a solar thermal collector, through photovoltaic and photothermal interaction, generating solar electricity and solar heat simultaneously. Hybrid PV/T collector has aroused widely range of attention among researchers in the last decade, but so far rare analysis of the fluid mass flux that affect the overall performance has been attempted, and less exergetic balance analysis for a hybrid PV/T has been reported. The effect of fluid mass flux on thermal and electrical performance for a hybrid PV/T collector was tackled in this paper from the point view of the first and second law of thermodynamics. By the given design and operation parameters used for the present study, taking materials consumption, economical and heat transfer performance into consideration, NTU (Number of Transfer Units) for hybrid collector should be optimized to the value of 0.5, and the hybrid PV/T collector operates at optimum mass flux ($0.002 kg/s\cdot m^2$) not only can improve the electrical and thermal efficiency, but also can assure the quality of the output energy.

1. Introduction

It is well-known that more than 80% of the absorbed incident solar radiation by crystalline silicon cells is not converted into electricity but contributed to increase the temperature of module. The cell efficiency is assumed to decrease linearly with temperature [1]. This fact leads many researchers to devote a massive effort on hybrid photovoltaic/thermal (PV/T) collector which is a combined device of a PV module with a solar thermal collector. In a hybrid PV/T collector, the PV module is cooled to improve its electrical performance; simultaneously the excess heat generated in the PV module is removed and converted into useful thermal energy through the thermal collector.

Research efforts on PV/T collector's performance in the past 30 years have been concentrated on i.e. (a) thermal and electrical performance and (b) Exergetic performance. A comprehensive overview of flat-plate PV/T collectors and systems was reported by Zondag [2]. Chow et al. [3] studied a hybrid flat-box photovoltaic-thermosyphon water heating system for residential application under the climate of China. Ji el al. [4] investigated energy performance for wall-mounted water-type PV/T collectors, simulation results indicated that an optimum water flow rate existed in the system through which the desirable integrated energy performance can be reached. The exergy evaluation of PV/T systems has already been conducted in the past among others bysuch as Sahin et al. [5] and Joshi et al. [6], they have evaluated the electrical portion of the exergy by applying two methods: by means of the electrical parameters of the PV system and by using a photonic analysis. A review of exergy performances of solar collectors, PV and PV/T systems has been investigated by Torio et al [7]. Farahat et al. [8] have developed an exergetic optimization method of flat plate solar collectors to determine the optimal performance and design parameters of these solar thermal energy conversion systems. Chow et al. [9] have investigated the performance evaluation of a glazed and unglazed PV/T water system in terms of energy and exergetic efficiency for Hong Kong climates. Tiwari et al. [10] have carried out the energy and exergy analysis of an integrated photovoltaic thermal solar (IPVTS) water heater. They have reported that the overall exergy and thermal efficiency of an IPVTS system reach maximum at the hot water withdrawal flow rate of 0.006 kg/s. Bosanac et al. [11] have carried out the exergy analysis of PV/T water system and reported that maximum exergy efficiency of the system is about 12% against an overall maximum energy efficiency of 60%.

From the above, it can be seen that some studies have compared the energy and exergetic performance of the glazed hybrid PV/T collector, but so far less analysis of the fluid mass flux that affect the overall performance has been attempted, and less exergetic balance analysis for a hybrid PV/T has been reported. These lead to the purpose of this paper of carrying out a more comprehensive study. In this paper a PV/T system for a house is modeled with TRNSYS using meteorological data for Changsha, China. The models used for energy and exergetic performance simulation and exergetic balance analysis are introduced. Recommended Optimized mass flux for hybrid PV/T collector was discussed to improve overall performance. Performance into consideration

2. System Description

The PV/T system considered here is a system for a typical domestic hot water heating and has a structure similar to a conventional hot water heating system. The system construction details are shown in Figure 1 (a). The present system is applied to a house of three persons, comprising a collector aperture area 2 m^2, a 120 L hot water storage tank, a water circulation pump, a differential thermostat and the connecting pipes. A single glass covered flat plate hybrid PV/T collector was used that is composed of Polycrystalline silicon PV cells pasted to a tube-sheet absorber which is the most practical and easier to manufacture as Zondag et al. [2] mentioned in their paper as shown in Figure 1(b). The working fluid flows paralleled under the surface of the absorber transforming excess heat generated on the PV cells to water tank. The system is modeled with the TRNSYS program and meteorological year condition for Changsha, China is used. The temperature and the solar radiation data shown as Figure 2 chosen randomly (August 4th) were used.

Heat capacity of Fluid is assumed to keep constant; the pressure difference of the fluid at entrance is ignored. Taking no account of the influence of non-vertical incident angle, the transmittance of the top glass and absorptance of PV-absorber module surface are simplified. The given design and operation parameters used for the present study have been shown in Table 1. TRNSYS simulation information flow for solar Hybrid PV/T system is shown as Figure 3.

Table 1. *Design and operation parameters of hybrid PV/T collector.*

Parameters	Values	Parameters	Values
Collector area, m^2	2	total heat loss coefficient, W/(m^2 K)	6.5
Outer diameter of the tubes, m	0.01	Transmittance of glazing, -	0.93
Inner diameter of the tubes, m	0.008	Absorptance of absorber plate, -	0.9
tube pitch, m	0.0625	Solar cell temperature coefficient, K^{-1}	-0.0045
special heat capacity of the fluid, KJ/(kg K)	4.19	Storage tank volume, m^3	0.12
internal fluid heat transfer coefficient, W/m^2	300	PV cells efficiency at 25°C reference condition, -	0.12
product of equivalent thermal conductivity and thickness for the PV, W/K	0.143		

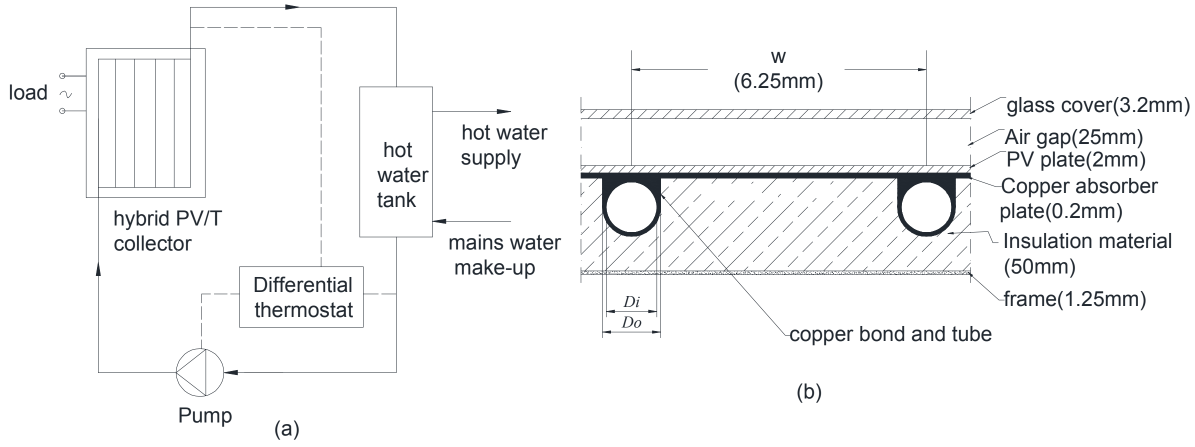

Figure 1. *Hybrid PV/T system construction details.*

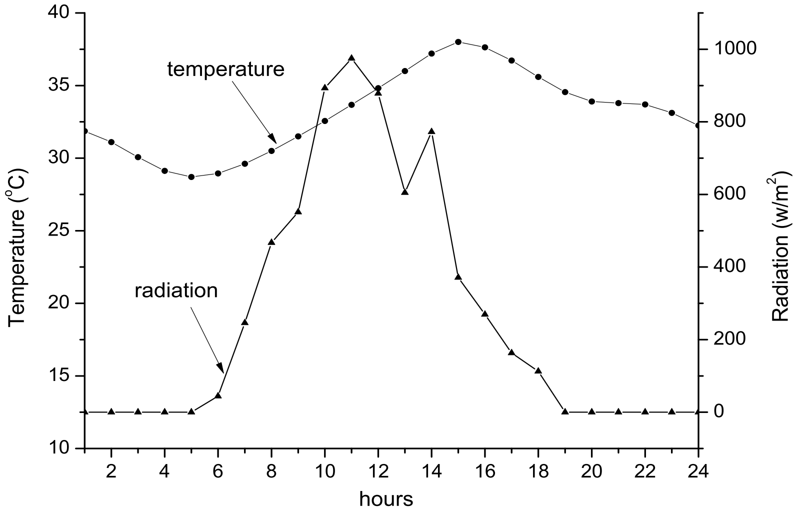

Figure 2. *Solar radiation and ambient temperature in Changsha (Aug. 4th).*

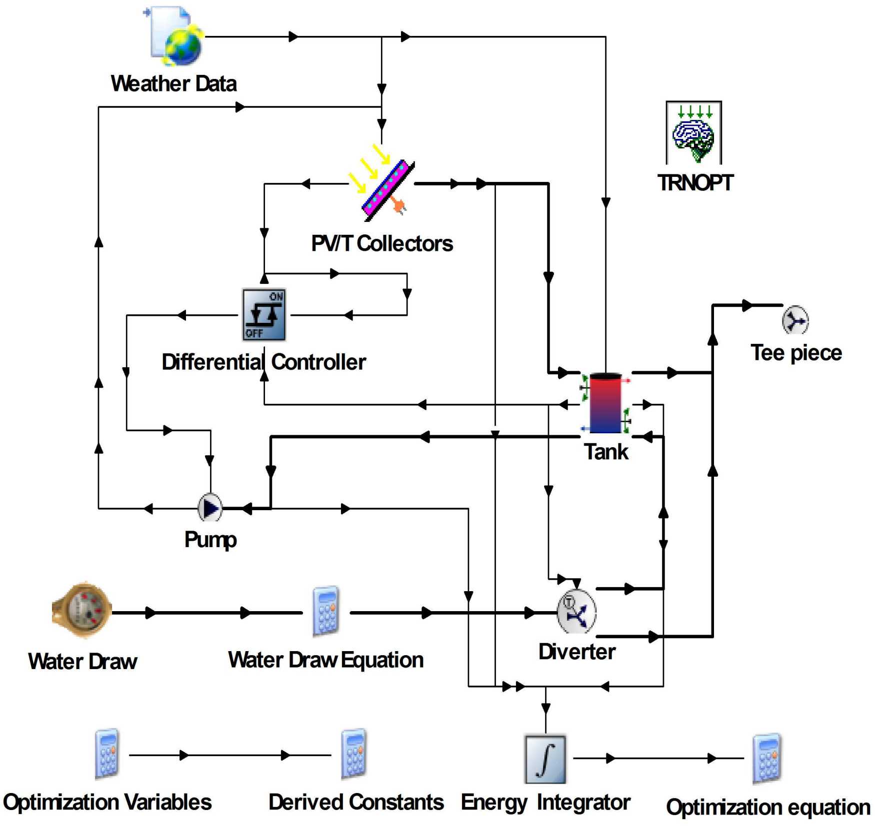

Figure 3. *TRNSYS information flow for solar Hybrid PV/T system.*

3. Performance Analysis of Hybrid PV/TCollector

The overall performance of a hybrid PV/T system can be evaluated based on thermodynamics, economics, marketing and/or environmental implications, as demonstrated by Coventry and Lovegrove [12]. The thermodynamic approach is popularly used in optimizing an engineering system that owe their thermodynamic imperfection to heat transfer, fluid flow and mass transfer irreversibilities. Therefore the analysis in this study has been mainly from the view point of thermodynamics [10].

3.1. First Law Efficiency of Thermodynamic

The steady-state energy balance equation of hybrid PV/T:

$$\frac{d^2T_{\mathrm{p}}}{dx^2}=\frac{1}{\Lambda}\left[U_{\mathrm{T}}(T_{\mathrm{p}}-T_{\mathrm{a}})-S+q_{\mathrm{el}}\right] \tag{1}$$

where U_{T}, T_{p}, G_{T}, $(\tau\alpha)_{\mathrm{eff}}$ are total heat loss coefficient of hybrid PV/T collector, temperature of PV-absorber module, total solar radiation incident upon the collector surface and effective transmittance-absorptance product for the solar hybrid PV/T collector, respectively. Λ is product of equivalent conductance and thickness for the PV-absorber module, S the absorbed incident solar radiation per collector's area, can be written as

$$S=G_{\mathrm{T}}(\tau\alpha)_{\mathrm{eff}} \tag{2}$$

q_{el} is the PV power production per collector's area, can be evaluated as

$$q_{\mathrm{el}}=\eta G_{\mathrm{T}}\tau \tag{3}$$

The PV cells efficiency η is assumed to decrease linearly with temperature. Thus,

$$\eta=\eta_{\mathrm{r}}\left[1-\beta_{\mathrm{r}}(T_{\mathrm{p}}-T_{\mathrm{r}})\right] \tag{4}$$

where β_{r}, η_{r} and T_{r} are the temperature coefficient, reference efficiency and reference temperature of the cells, respectively. The present value of reference efficiency is 12% at temperature of 25°C and solar intensity of 1000 W/m^2.

Modifying the Eq. (1) to the form of pure solar thermal collector as presented by Duffie and Beckman [13] as long as U_{T} and S are replaced by $\widetilde{U}_{\mathrm{T}}$ and $\widetilde{S}$, the rearrangement form for a hybrid PV/T collector can be written as

$$\frac{d^2T_{\mathrm{P}}}{dx^2}=\frac{\widetilde{U}_{\mathrm{T}}}{\Lambda}\left[T_{\mathrm{p}}-T_{\mathrm{a}}-\frac{\widetilde{S}}{\widetilde{U}_{\mathrm{T}}}\right] \tag{5}$$

where

$$\widetilde{U}_{\mathrm{T}}=U_{\mathrm{T}}-G_{\mathrm{T}}\cdot\tau_{\mathrm{n}}\cdot I_{\mathrm{AM}}\cdot\eta_{\mathrm{r}}\cdot\beta_{\mathrm{r}} \tag{6}$$

$$\widetilde{S}=S\left(1-\frac{\eta_{\mathrm{a}}}{\alpha_{\mathrm{n}}}\right) \tag{7}$$

where η_{a} is the efficiency of PV cells evaluated from Eq. (4) at the ambient temperature, T_{a}. τ and α are transmittance of glass and absorptance of PV-absorber module surface.

Defining equivalent heat loss coefficient $\widetilde{U}_{\mathrm{T}}$, equivalent absorbed solar radiation $\widetilde{S}$ and equivalent heat removal factor $\widetilde{F}_{\mathrm{R}}$ for a hybrid PV/T collector, consequently, solutions and results based on pure solar thermal collector [13] also apply for a hybrid PV/T collector when, U_{T} and S are similarly replaced by $\widetilde{U}_{\mathrm{T}}$ and $\widetilde{S}$ [14]. The useful thermal gain of the hybrid PV/T collector is

$$\widetilde{Q}_{\mathrm{u}}=A_{\mathrm{c}}\widetilde{F}_{\mathrm{R}}\left[\widetilde{S}-\widetilde{U}_{\mathrm{T}}\left(T_{\mathrm{f,i}}-T_{\mathrm{a}}\right)\right] \tag{8}$$

where

$$\tilde{F}_{\mathrm{R}}=\frac{Mc_p}{\tilde{U}_{\mathrm{T}}}\left[1-\exp\left(-\tilde{U}_{\mathrm{T}}\tilde{F}'/(Mc_p)\right)\right] \tag{9}$$

$$\tilde{F}'=\frac{\dfrac{1}{\tilde{U}_{\mathrm{T}}}}{W\left\{\dfrac{1}{\tilde{U}_{\mathrm{T}}\left[D_{\mathrm{o}}+(W-D_{\mathrm{o}})F\right]}+\dfrac{1}{c_{\mathrm{b}}}+\dfrac{1}{\pi D_{\mathrm{i}}h_{\mathrm{f}}}\right\}} \tag{10}$$

where, $F=\dfrac{th\left[m\left(W-D_{\mathrm{o}}\right)/2\right]}{\left[m\left(W-D_{\mathrm{o}}\right)/2\right]}$, $m^2=\dfrac{\tilde{U}_{\mathrm{T}}}{\Lambda}$

where $\tilde{F}'$ is hybrid PV/T collector efficiency factor, A_{c} the hybrid PV/T collector, W the tube pitch, c_{b} the conductance between the absorb plate and the bonded tube. h_{f} and c_p are internal fluid heat transfer coefficient and heat capacity of the fluid. D_{i}, D_{o} are inner and outer diameter of the tubes.

M is mass flux for inlet flow fluid, defined as

$$M=\frac{\dot{m}}{A_{\mathrm{c}}} \tag{11}$$

where $\dot{m}$ is mass flow rate of fluid through the hybrid PV/T collector.

The useful electrical gain of the hybrid PV/T collector can be determined from the energy balance equation

$$Q_{\mathrm{el}}=A_{\mathrm{c}}\frac{S}{\alpha}\eta_{\mathrm{a}}\left\{1-\frac{\eta_{\mathrm{r}}\beta_{\mathrm{r}}}{\eta}\left[\tilde{F}_{\mathrm{R}}\left(T_{\mathrm{f,i}}-T_{\mathrm{a}}\right)+\frac{\tilde{S}}{\tilde{U}_{\mathrm{T}}}\left(1-\tilde{F}_{\mathrm{R}}\right)\right]\right\} \tag{12}$$

From the first law of thermodynamics, the overall hybrid PV/T performance can be evaluated by η_{PVT}, which can be described by a combination of thermal efficiency η_{th} and electrical efficiency η_{el}. Thus,

$$\eta_{\mathrm{PVT}}=\eta_{\mathrm{th}}+\eta_{\mathrm{el}} \tag{13}$$

where, η_{th} and η_{el} are thermal efficiency and photovoltaic efficiency of PVT collector, defined as the ratio of the useful thermal gain and electrical gain of the hybrid PV/T collector to the incident solar irradiation on the collector's aperture within a given period, respectively. From Eq. (8) and Eq. (12), η_{th} and η_{el} can be determined as

$$\eta_{\mathrm{th}}=\tilde{F}_{\mathrm{R}}\cdot(\tau\alpha)_{\mathrm{n}}\cdot I_{\mathrm{AM}}\cdot\left(1-\frac{\eta_{\mathrm{a}}}{\alpha_{\mathrm{n}}}\right)\cdot\left[1-\frac{\tilde{U}_{\mathrm{T}}}{\tilde{S}}\left(T_{\mathrm{f,i}}-T_{\mathrm{a}}\right)\right] \tag{14}$$

$$\eta_{\mathrm{el}} = \eta_{\mathrm{a}}\left\{1-\frac{\eta_{\mathrm{r}}\beta_{\mathrm{r}}}{\eta_{\mathrm{a}}}\left[\tilde{F}_{\mathrm{R}}\left(T_{\mathrm{f,i}}-T_{\mathrm{a}}\right)+\frac{\tilde{S}}{\tilde{U}_{\mathrm{T}}}\left(1-\tilde{F}_{\mathrm{R}}\right)\right]\right\} \quad (15)$$

3.2. Second Law Efficiency of Thermodynamic

3.2.1. Exergetic Efficiency Versus Fluid Mass Flux

The outputs of a hybrid PV/T collector, thermal energy and electrical energy, have essentially not the same quality, even if they have the same quantity. Thermal energy can't produce work until a temperature difference exist between heat source and heat sink, while electrical energy can completely transform into work irrespective of the environment temperature. The energy performance analysis based on the first law efficiency of thermodynamic does not show internal irreversibility [15]; it cannot be a sufficient criterion in order to evaluate the performance of a hybrid PV/T collector.

Exergy is defined as the maximum amount of work that can be produced by a system or a flow of mass or energy as it comes to equilibrium with a reference environment [16, 17]. From the second law of thermodynamics, the overall hybrid PV/T performance can be evaluated by the exergetic efficiency, which provides a more realistic view of process than energy efficiency and offers a qualitative evaluation of the hybrid performance. The hybrid PV/T collector exergetic efficiency is defined as the increase of fluid flow exergy upon the primary radiation exergy by the radiation source.

The exergetic efficiency can be calculated in terms of the net output exergy rate of the system or exergy loss rate in the system. In terms of the net output exergy rate, the exergetic efficiency of ahybrid PV/T collector in the previous studies [9, 18, and 19] has been defined as:

$$\varepsilon_{\mathrm{PVT}} = \frac{\int_{t_1}^{t_2}(Ex_{\mathrm{el}}+Ex_{\mathrm{th}})dt}{\int_{t_1}^{t_2}Ex_{\mathrm{sun}}dt} = \varepsilon_{\mathrm{el}}+\varepsilon_{\mathrm{th}} = \eta_{\mathrm{el}}+(1-\frac{T_{\mathrm{a}}}{T_{\mathrm{f,o}}})\eta_{\mathrm{th}} \quad (16)$$

where $\varepsilon_{\mathrm{el}}$ and $\varepsilon_{\mathrm{th}}$ are electrical exergetic efficiency and thermal exergetic efficiency of a hybrid PV/T collector. Ex_{el}, Ex_{th} and Ex_{sun} are electrical exergy output, thermal exergy output of a hybrid PV/T collector and exergy input of solar radiation, respectively.

While, there appeared two over simplifications in the definition of ε_{th} according to Eq. (16), in which $\varepsilon_{\mathrm{th}}$ was related to η_{th} by Carnot efficiency. Firstly, actual thermal exergetic efficiency of a hybrid PV/T collector almost occurs within heat resource of limited volume, which temperature decreases following the process of heat release. Secondly, the inlet fluid exergy should be taken into account for the calculation of the thermal exergy.

The inlet exergy includes the inlet thermal exergy with fluid flow and the absorbed solar radiation exergy. Considered varying temperature of heat source and ignored the pressure difference of the fluid at entrance, the inlet thermal exergy with fluid flow for the whole heat release process which temperature decline from $T_{f,i}$ to T_a without phase change, can be expressed as [20]:

$$\sum Ex_{\mathrm{f,i}} = \int_{T_{\mathrm{f,i}}}^{T_{\mathrm{a}}}(1-\frac{T_a}{T})\delta Q = \int_{T_{\mathrm{f,i}}}^{T_{\mathrm{a}}}(1-\frac{T_{\mathrm{a}}}{T})\dot{m}c_p dT = \dot{m}c_p(T_{\mathrm{f,i}}-T_{\mathrm{a}})-\dot{m}c_pT_{\mathrm{a}}\ln\frac{T_{\mathrm{f,i}}}{T_{\mathrm{a}}} = \dot{m}c_p(T_{\mathrm{f,i}}-T_{\mathrm{a}})\left(1-\frac{T_{\mathrm{a}}}{T_{\mathrm{f,i}}-T_{\mathrm{a}}}\ln\frac{T_{\mathrm{f,i}}}{T_{\mathrm{a}}}\right) \quad (17)$$

where $T_{\mathrm{f,i}}$, $T_{\mathrm{f,o}}$, C_p and $\dot{m}$ are the fluid inlet and outlet temperature, heat capacity and mass flow rate of the agent fluid, respectively.

The outlet exergy includes the thermal exergy of outlet fluid flow and output electrical exergy. The outlet thermal exergy with fluid flow is similar to the inlet fluid thermal exergy given by [20]

$$\sum Ex_{\mathrm{f,o}} = \dot{m}c_p(T_{\mathrm{f,o}}-T_{\mathrm{a}})\left(1-\frac{T_{\mathrm{a}}}{T_{\mathrm{f,o}}-T_{\mathrm{a}}}\ln\frac{T_{\mathrm{f,o}}}{T_{\mathrm{a}}}\right) \quad (18)$$

where $T_{\mathrm{f,i}}$ and $T_{\mathrm{f,o}}$ are inlet and outlet fluid temperature.

To determing the exergy of solar radiation, the calculation method suggested by Jeter [21] was used in the following analysis as:

The exergy input for PV/T collector was obtained using Eq. (11) [9]

$$\sum Ex_{\mathrm{sun,i}} = \left(1-\frac{T_{\mathrm{a}}}{T_{\mathrm{sun}}}\right)G\cdot A_{\mathrm{c}} \quad (19)$$

where T_{a} is the environment temperature and T_{sun} the solar radiation temperature 6000 K.

The outlet electrical exergy is numerical equal to the electrical energy [22], thus

$$\varepsilon_{\mathrm{pvt}} = \varepsilon_{\mathrm{el}} + \varepsilon_{\mathrm{th}} \quad (20)$$

$$\varepsilon_{\mathrm{pvt}} = \eta_{\mathrm{el}} + \frac{\sum Ex_{\mathrm{f,o}} - \sum Ex_{\mathrm{f,i}}}{\sum Ex_{\mathrm{sun,i}}} \quad (21)$$

Substituting Eq. (18)-(21) into Eq. (16), the exergetic efficiency equation of the hybrid PV/T collector is derived:

$$\varepsilon_{\mathrm{PVT}} = \varepsilon_{\mathrm{el}} + \varepsilon_{\mathrm{th}} = \eta_{\mathrm{el}} + \eta_{\mathrm{th}} \frac{1 - \dfrac{T_{\mathrm{a}}}{T_{\mathrm{f,o}} - T_{\mathrm{f,i}}} \ln \dfrac{T_{\mathrm{f,o}}}{T_{\mathrm{f,i}}}}{1 - \dfrac{T_{\mathrm{a}}}{T_{\mathrm{sun}}}} \tag{22}$$

3.2.2. Outlet Fluid Temperature Versus Fluid Mass Flux

The effectiveness of heat exchanger equation ($E-NTU$) for a hybrid PV/T collector can be written as

$$E = 1 - e^{-NTU} \tag{23}$$

where E is the effectiveness of heat exchanger, NTU Number of Transfer Units. The latter is calculated as

$$NTU = K \cdot (\pi \cdot A_{\mathrm{c}} \cdot \frac{D_{\mathrm{i}}}{W}) \cdot \frac{1}{\dot{m} c_p} \tag{24}$$

where K is thermal transfer coefficient of heat exchanger.

The outlet fluid temperature can be expressed as

$$T_{\mathrm{f,o}} = T_{\mathrm{f,i}} + (T_{\mathrm{p}} - T_{\mathrm{f,i}})(1 - e^{-NTU}) \tag{25}$$

4. Results and Discussions

The effect of mass flux of inlet fluid on the electrical and thermal efficiency is shown in Figure 4. It is evident that both η_{el} and η_{th} increase with the increasing of *M*. The peak value for η_{el} and η_{th} are reaching to 10% and 70% when mass flux *M* is at the range of 0.001~0.008 kg/(s·m^2). It is observed that η_{el} improved slightly as *M* increases to 0.002kg/s·m^2. The simulation results consistent with conclusions from Kalogirou [23] This shows that the increase of mass flux is beneficial for cooling of PV cells, while the advantage brought by the increased mass flux diminishes after reaching the critical mass flux, because more pump power consumptions may outweigh the electrical efficiency improvement.

Figure 5 shows the effect of mass flux on heat removal factor and total energy efficiency of hybrid PV/T collector. $\widetilde{F}_{\mathrm{R}}$ and η_{pvt} follow the same trend as the mass flux increases.

Figure 6 shows the effect of mass flux on electrical and thermal exergetic efficiency. It can be seen that the results of the total exergetic efficiency analysis are different from the energy efficiency analysis. For glazed hybrid PV/T collector, electrical exergetic efficiency overweighs the thermal exergetic efficiency, the peak value for $\varepsilon_{\mathrm{el}}$ and $\varepsilon_{\mathrm{th}}$ is 10% and 3.8%, respectively. A general trend is that the increase of mass flux is favorable for $\varepsilon_{\mathrm{el}}$, while it is the other way round for $\varepsilon_{\mathrm{th}}$. By increasing the fluid mass flux until the value of 0.0016 kg/s·m^2, $\varepsilon_{\mathrm{th}}$ increases and then decreases quickly; $\varepsilon_{\mathrm{pvt}}$ follows a same trend as $\varepsilon_{\mathrm{th}}$, but decreases slowly after peak value. The primary cause is the drop of the stored water temperature as fluid mass flux increases, which leads to the decrease of useful thermal exergy.

Figure 7 shows the effect of NTU on the effectiveness of heat exchanger and total exergetic efficiency. It can be seen that ε increases following the increases of NTU, and the overall exergetic efficiency increases significantly with the NTU up to 0.5 and then decreases rapidly. It is due to the fact that there will be increase of outlet temperature and PV cells temperature and hence lower electrical exergy obtained when the NTU increases. Since the electrical exergetic efficiency overweighs the thermal exergetic efficiency from the above Figure 3, increased NTU results in decline of overall PV/T exergetic efficiency. Taking everything into consideration, such as materials consumption, economical and heat transfer performance, NTU should be optimized to critical value.

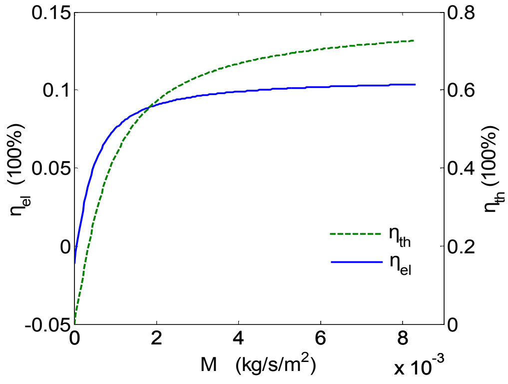

Figure 4. *Electrical and thermal efficiency versus mass flux.*

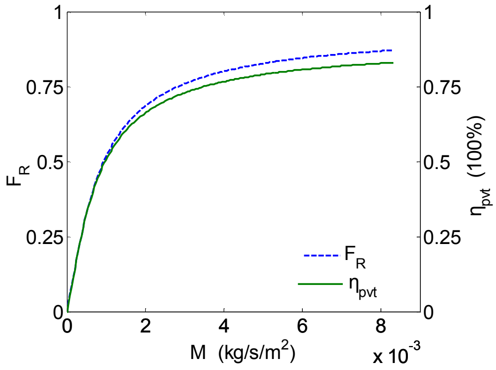

Figure 5. *Heat removal factor and total energy efficiency of hybrid PV/T collector versus mass flux.*

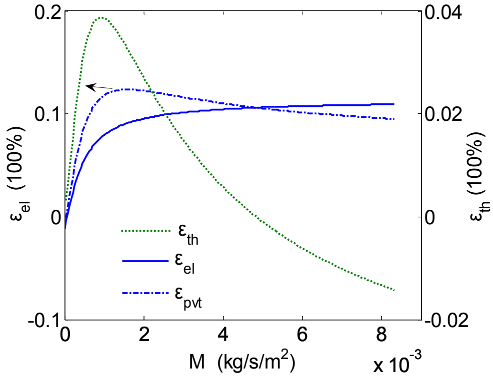

Figure 6. *Electrical and thermal exergetic efficiency versus mass flux.*

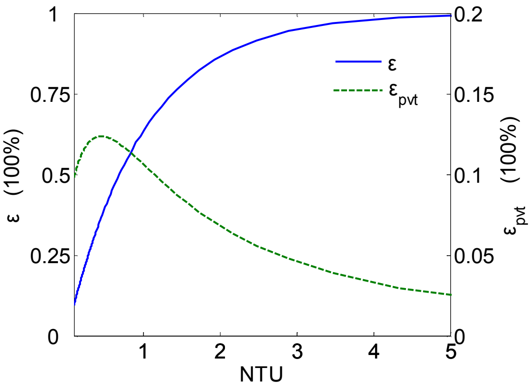

Figure 7. *Effectiveness of heat exchanger and total exergetic efficiency versus NTU.*

5. Conclusions

This paper has built a thermal and electrical performance analytical model for a hybrid PV/T collector from the first and second law of thermaldynamic point of view.

Based on numerical method, the effect of inlet fluid mass flux on a hybrid PV/T collector performance has been evaluated.

The simulation results showed that both electrical and thermal efficiency increased together with the increasing of mass flux, after reaching to critical flux $0.002\mathrm{kg/s \cdot m^2}$, the first law performance improved slowly.

However, the exergetic efficiency results were different from the energy efficiency analysis. Thermal exergetic efficiency decreased rapidly because the increased mass flux resulted in decreased of outlet temperature.

Hybrid PV/T collector operates at critical mass flux not only can improve the electrical and thermal efficiency, but also can assure the quality of the output energy.

The simulation results also showed that the NTU should be adapted to optimized critical value taking many factors into consideration, such as materials consumption, economical and heat transfer performance, the critical value of NTU is 0.5 for the hybrid PV/T collector here.

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Nomenclature

A	area, $\mathrm{m^2}$
c_{b}	thermal conductance, W/(m K)
c_p	special heat capacity of the fluid, KJ/(kg K)
D	diameter of the tubes, m
E	effectiveness of heat exchanger, -
Ex	exergy output or input, $\mathrm{W/m^2}$
$\tilde{F}'$	hybrid PV/T collector efficiency factor, -
$\tilde{F}_{\mathrm{R}}$	equivalent heat remove factor, -
G_{T}	total solar radiation incident, $\mathrm{W/m^2}$
h_{f}	internal fluid heat transfer coefficient, $\mathrm{W/m^2}$
I_{AM}	incidence angle modifier, -
$\dot{m}$	flow rate fluid through the solar collector, kg/s
M	fluid mass flux for inlet flow fluid, $\mathrm{kg/(m^2\ s)}$
q_{el}	PV power production per collector's area, $\mathrm{W/m^2}$
$\tilde{\mathrm{Q}}_{\mathrm{u}}$	equivalent useful thermal gain, W
$\tilde{S}$	equivalent absorbed incident solar radiation, $\mathrm{W/m^2}$
S	absorbed incident solar radiation, $\mathrm{W/m^2}$
T	temperature, K
U_{T}	total heat loss coefficient, $\mathrm{W/(m^2\ K)}$
W	tube pitch, m
Greek letters	
α	Absorptance, -
β	temperature coefficient of PV cells, $\mathrm{K^{-1}}$
ε	exergetic efficiency, -
η	efficiency, -
Λ	product of equivalent thermal conductivity and thickness for the PV, -
τ	transmittance
$(\tau\alpha)_{\mathrm{eff}}$	equivalent transmittance, -
Subscripts	
a	ambient air
c	collector
el	electrical
f	fluid
f,i	inlet fluid
f,o	outlet fluid
i	inflow, inner
n	verticle
o	outer
P	plate of PV-absorber module
PVT	hybrid PV/T collector
r	reference
sun	sun
T	total
th	thermal

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