Performance evaluation of PVT-TEC air collector through the characteristic curve

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ABSTRACT

This paper deals with developing an analytical equation for the TEC combined with a PVT air collector. The PVT-TEC air collector produces thermal and electrical energy. The integration of TEC on the bottom side of the PV panel reduces the temperature of the PV cell, and then the system's overall efficiency is increased. For the analysis of the air collector, the input variables, namely solar irradiance and atmospheric temperature, have been taken for April month at Shiv Nadar Institution of Eminence (SNIOE), Gautam Buddha Nagar, India. The air collector has been modelled using MATLAB 2022a to find the temperature of PV cell, TEC, and collector outlet temperatures. After finding all temperatures, we can calculate the PVT-TEC air collector's overall electrical, thermal, and exergy efficiency. The results show how a characteristic curve varies with the thermal, electrical, and exergy efficiency. The η_{el} and $\eta_{eq,th}$ was found to be 11.77 – 14.17 % and 42.21 – 48.18 %, respectively. Further, the overall exergy varied from 12.24 – 14.62 %.

Keywords: *Thermoelectric cooler (TEC), Photovoltaic thermal (PVT), Air collector*

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1. Introduction

Energy is the most essential key in daily life. The excessive use of fossil fuels for generating energy increases greenhouse gas emissions and affects the climate. Renewable energy is a promoting source of generating energy. Sun energy, wind energy, and geothermal energy are the alternative sources for producing electrical and thermal energy. Solar energy is particularly sustainable and eco-friendly energy (Tiwari et al., 2018).

Photovoltaic (PV) cells are commonly adopted for alternative energy, which can be used for different purposes. Generally, PV cells are insignificant due to almost 80% of heat being reflected back to the atmosphere (Nazri et al., 2019). Thus, PVT systems exist, which can generate energy in thermal and electrical forms. Electrical power can be used in remote areas where electricity is scarce, and thermal energy can be used for space applications. PVT collector combines a PV panel, absorber sheet, air duct and some heat extracting unit (Nazri et al., 2018).

(Tiwari et al., 2016) did mathematical modelling for PVT air collector. The finding was that the PVT collector generates both high and low-grade energy. Furthermore, the PVT air collector produces a reasonable amount of thermal energy. (Dimri et al., 2017) proposed a model for the TEC-integrated PVT air collector and compared his results with the PV-TEC air collector. The result showed that when compared to the PV-TEC air collector, the PVT-TEC air collector's overall electrical efficiency was 4.72 percent higher. (Singh et al., 2022) developed a mathematical model for the PVT-TEC air collector and analysed the solar cell transmissivity effect on the air collector's performance. The average thermal energy and η_{el} were 32.4 W and 14.3%, respectively.

(Naderi et al., 2021) developed PCM and TEG-integrated photovoltaic systems. The outcome was that the electrical efficiency was increased by 1.38% compared to the standard PV with the integration of PCM and TEG on the PV module. (Agrawal et al., 2023) fabricated an experimental setup for a PVT air collector with rectangular fins. In this experimental setup, a rectangular fin is inserted on the back side of the PV module to increase the heat exchange from the PV panel. The electrical and useful heat per year was found to be 1186 kW and 121 kW, respectively.

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(Singh et al., 2023) developed an experimental setup for a PVT-TEG air collector integrated dryer. The setup generated the thermal and electrical energy for drying the grapes. The PV panel and η_{th} of the air collector were found to be 14.07% and 48.5%, respectively. (Gupta et al., 2022) proposed a PVT air collector integrated dryer for drying star fruit. The air collector systems' energy and exergy efficiency in FCD and NCD mode were 69.27%, 43.58% and 31.12%, 17.89%, respectively. (Çiftçi et al., 2021) did a computational and experimental study of vertical PVT air collector integrated solar dryer. Fins were placed over the absorber plate in this experimental setup to improve heat transfer. The average η_{th} of PVT collector with fin and without fin was found to be 54.2% and 51.2%, respectively.

In this paper, we have analysed the characteristic curve for PVT-TEC air collector's thermal and electrical efficiency performance.

2. Explanation of PVT-TEC air collector

The PVT-TEC air collector combines a PV panel, TEC, and air duct. Solar energy strikes the PV module, which photonic energy converts into electrical energy. TEC is located just on the bottom side of the PV panel; in TEC, only indirect energy will come from the bottom side of PV panel. Then, using the Seebeck effect, the temperature difference between the TEC ends generates electrical energy. The air duct is located just on the bottom side of the TEC to extract energy in thermal form for use in space heating. The fan is provided to drive the airflow, which has a capacity of (12 V, 0.2 A). The schematic figure of PVT-TEC air collector is given in Fig. 1.

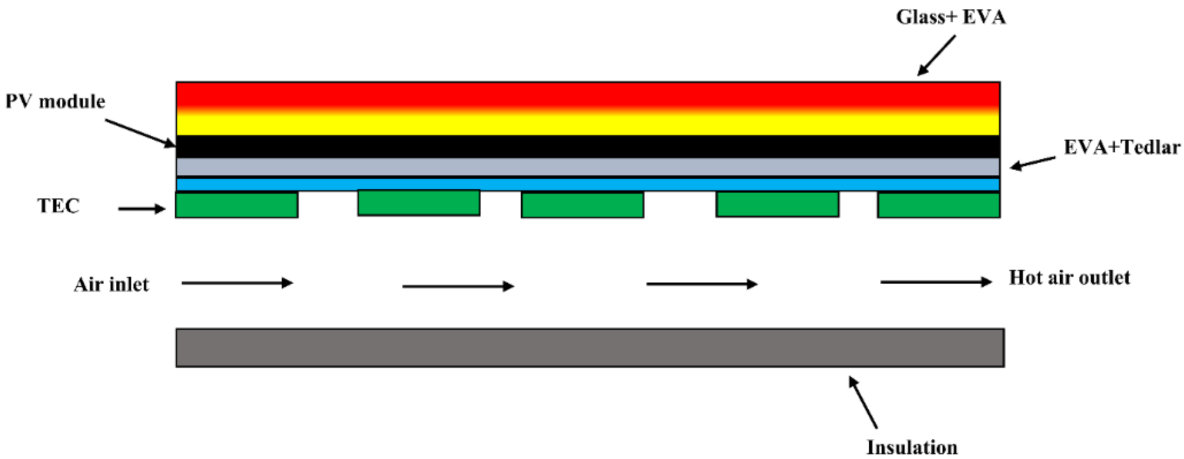


Fig.1. Schematic diagram of PVT-TEC air collector

3. Methodology

The methodology is given below.

- The I_t and T_a are input parameters have been taken from Shiv Nadar Institution of Eminence India for April 2023.
- For finding the solar cell, TEC, and collector temperature, MATLAB 2022a, have been used.
- After finding all temperatures, we can obtain overall electrical efficiency, overall thermal and exergy efficiency.

3.1 Thermal modelling of air collector

The assumptions are as follows.

- PV panel is an opaque type.
- TEC and bottom side of the PV panel consider the same temperature.
- The PVT-TEC air collector is in steady state.

The energy equation for PVT-TEC system is given below.

PV module,

$$I_t\alpha_c\tau_g bdx = h_t(T_C - T_{tec,t})\,bdx + U_{t,c-a}(T_C - T_a)bdx + \eta_c\tau_g I_t bdx \quad \text{(eq.1)}$$

Tedlar,

$$h_t(T_c - T_{tec,t})bdx = U_{b,c-f}(T_{tec,t} - T_f)(1 - \beta_{tec})bdx + U_{tec}(T_{tec,t} - T_{tec,b})\beta_{tec}\,bdx \quad \text{(eq. 2)}$$

TEC,

$$U_{tec}(T_{tec,t} - T_{tec,b})\beta_{tec}\,bdx = h_{tf}(T_{tec,b} - T_f)\,\beta_{tec}\,bdx + \eta_{tec}\,U_{tec}(T_{tec,t} - T_{tec,b})\beta_{tec}bdx \quad \text{(eq. 3)}$$

Air duct,

$$h_{tf}(T_{tec,b} - T_f)\beta_{tec}bdx + U_{b,c-f}(T_{tec,t} - T_f)(1-\beta_{tec})\,bdx = U_{b-a}(T_f - T_a)bdx + \dot{m}_f\,C_f\,\frac{dT_f}{dx}\,dx \quad \text{(eq.4)}$$

Module efficiency (Skoplaki and Palyvos, 2009)

$$\eta_m = \eta_o\,[1 - \beta_o(T_c - T_o)] \quad \text{(eq.5)}$$

Overall electrical energy (Dimri et al., 2018)

$$E_{el} = \eta_m I_t\,A_m + \eta_{tec}U_{tec}(T_{tec,t} - T_{tec,b})\beta_{tec}A_m \quad \text{(eq.6)}$$

Overall electrical efficiency

$$\eta_{el} = \frac{E_{el}}{I_t A_m} \quad \text{(eq.7)}$$

Thermal efficiency

$$\eta_{th} = \frac{\dot{m}_f\,C_f\,(T_{fo} - T_{fi})}{I_t A_m} \quad \text{(eq.8)}$$

Equivalence thermal efficiency (Tiwari, 2017)

$$\eta_{eq,th} = \eta_{th} + \frac{\eta_{el}}{0.38} \quad \text{(eq.9)}$$

Exergy efficiency (Tiwari and Tiwari, 2016)

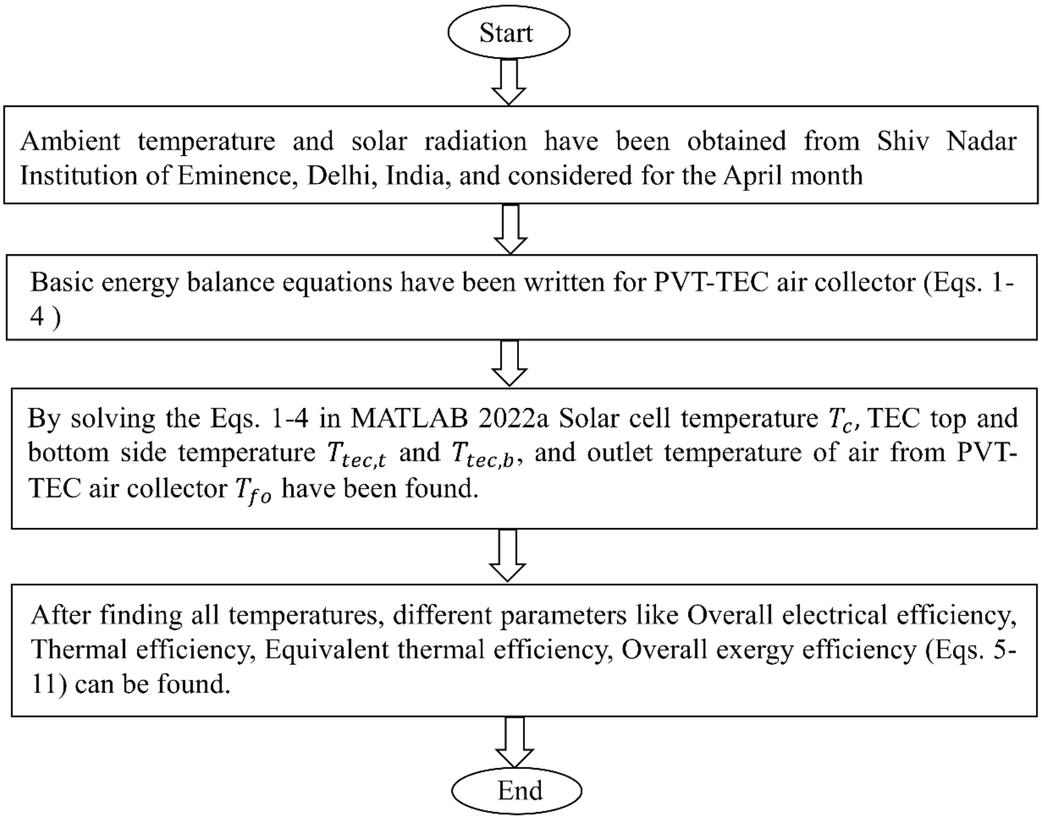
$$\eta_{th,ex} = \frac{\dot{Q}_{th,ex}}{[(I_t A_m)(1 - \left(\frac{4}{3}\right)\frac{(T_a+273)}{6000} + \left(\frac{1}{3}\right)\left(\frac{T_a+273}{6000}\right)^4)]} \quad \text{(eq.10)}$$

Total exergy efficiency (Tiwari and Shyam, n.d.)

$$\eta_{eq,ex} = \eta_{th,ex} + \eta_{el} \quad \text{(eq.11)}$$

The different design and heat transfer coefficient parameters are given in the appendix for finding the air collector's solar cell, TEC and outlet temperature.

The methodology is given in a flow chart to better understand the overall approach used for calculating the different results of the system.



4. Results and discussion

Figure 2. represents the input parameters that have been taken from SNIOE, Gautam Buddha Nagar, India for April month. I_t and T_a are the input parameters.

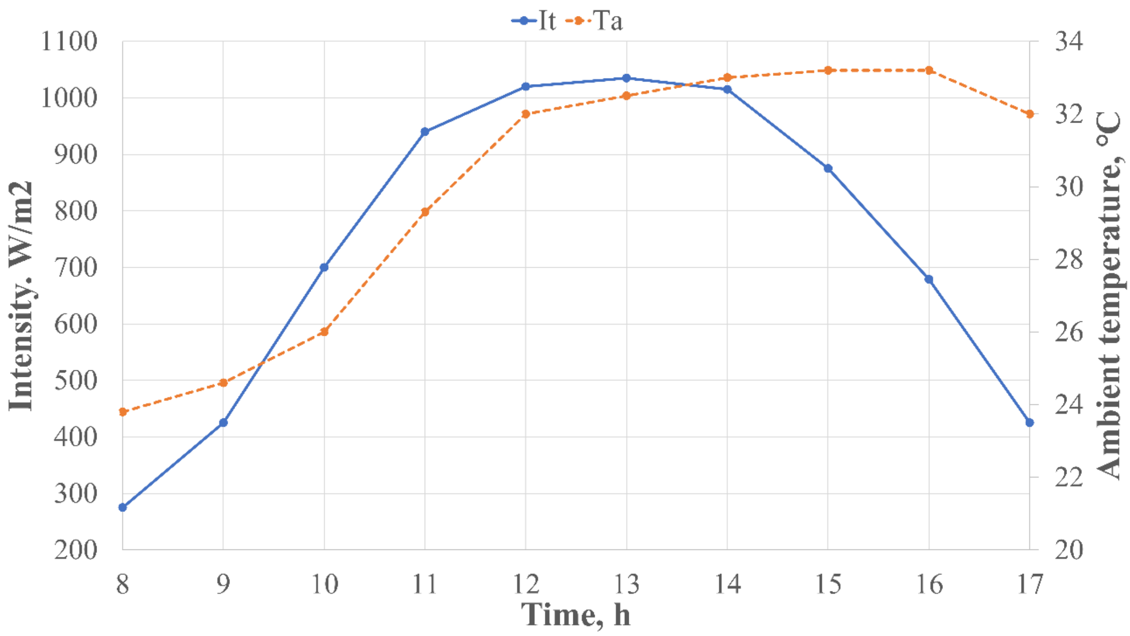


Fig. 2. Hourly variation of I_t and T_a

Figure 3. shows the changes in solar cell, TEC and air collector outlet temperature. The figure shows that the temperature of solar cells is greatest, followed by TEC and air collector outlet temperature. This is because

cells absorb photonic energy from the sun, indirect energy from the bottom side comes to TEC, heat from the bottom side of TEC, and air temperature increases.

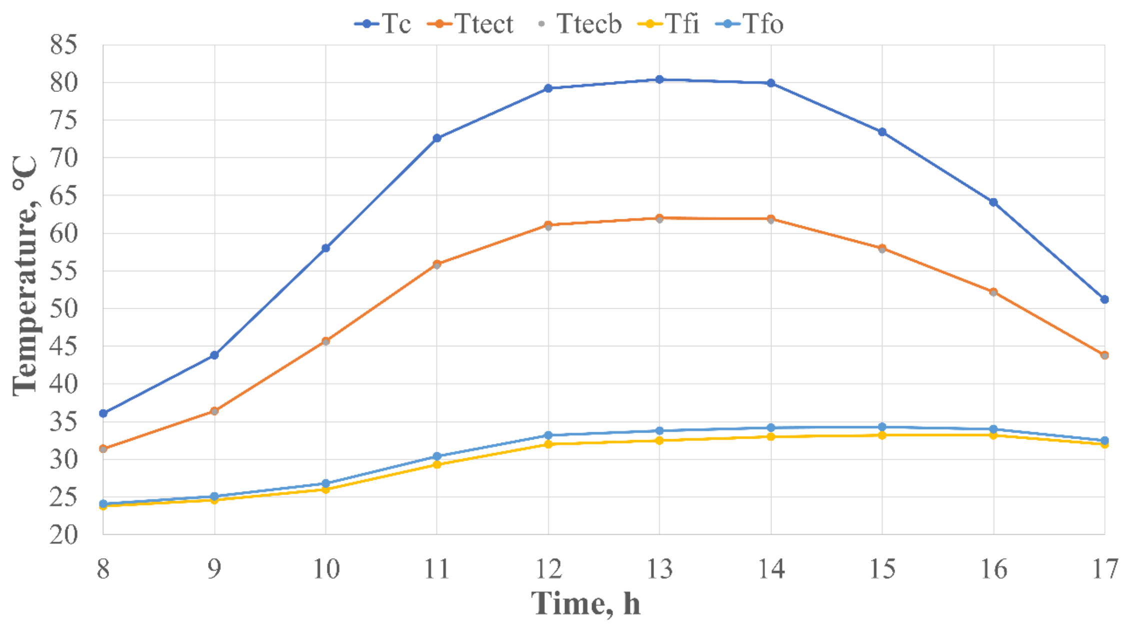


Fig. 3. Hourly changes of T_c, TEC and T_{fo} temperature on air collector

Figure 4 depicts the characteristics curve for η_{el}. The overall efficiency is a summation of the PV module and TEC efficiency. The overall electrical efficiency varies from 11.77 – 14.17 %. The overall electrical efficiency after fan operation varied from 11.35-12.68 % because some electrical power was consumed to operate the fan. The figure shows that with an increment the temperature of solar cell, its efficiency decreases with a negative slope. The higher temperature of solar cells drops the overall efficiency because charged electrons collide in the PV module.

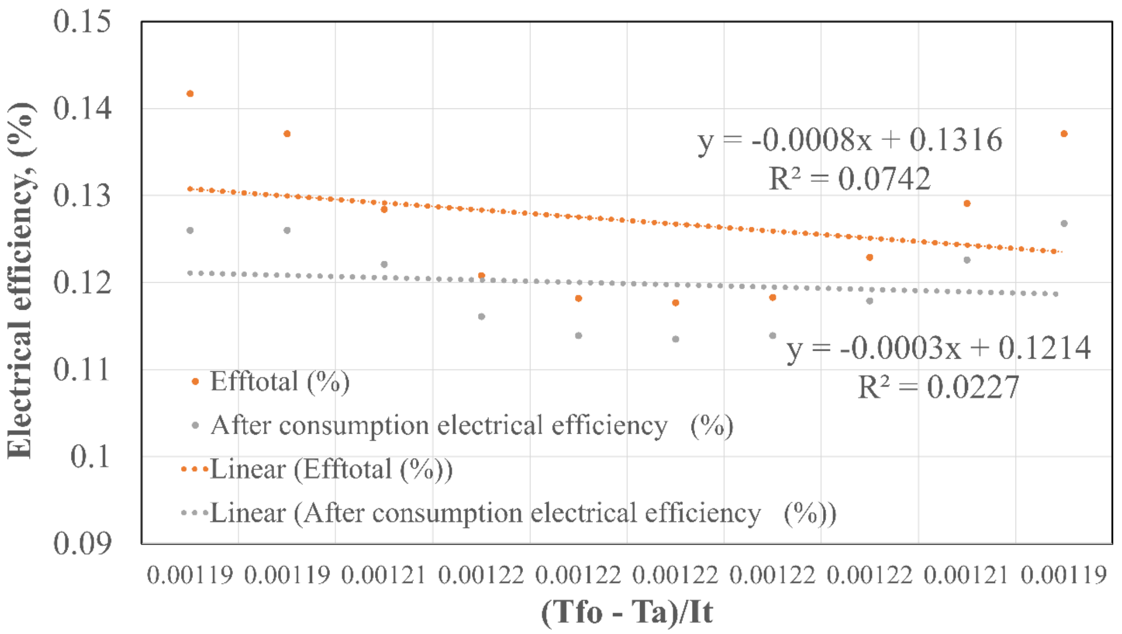


Fig.4. Characteristics curve for η_{el} in air collector

Figure 5 depicts the characteristic curve for η_{th}. The thermal efficiency varies from 10.9 – 11.25%. The figure reveals that the slope of thermal efficiency is positive. The reason behind that heat is being transferred from the back surface of the TEC, which is increasing the air temperature at the collector's outlet.

Figure 6 depicts the characteristic curve for $\eta_{eq,th}$. The overall (equivalence) thermal efficiency varies from 42.21 – 48.18 %. The graph itself reveals that the slope of overall thermal efficiency is negative. The reason behind this is that the overall thermal efficiency is the combination of thermal and electrical efficiency, and this η_{el} has more effect on overall efficiency, and we found a negative slope in overall thermal efficiency.

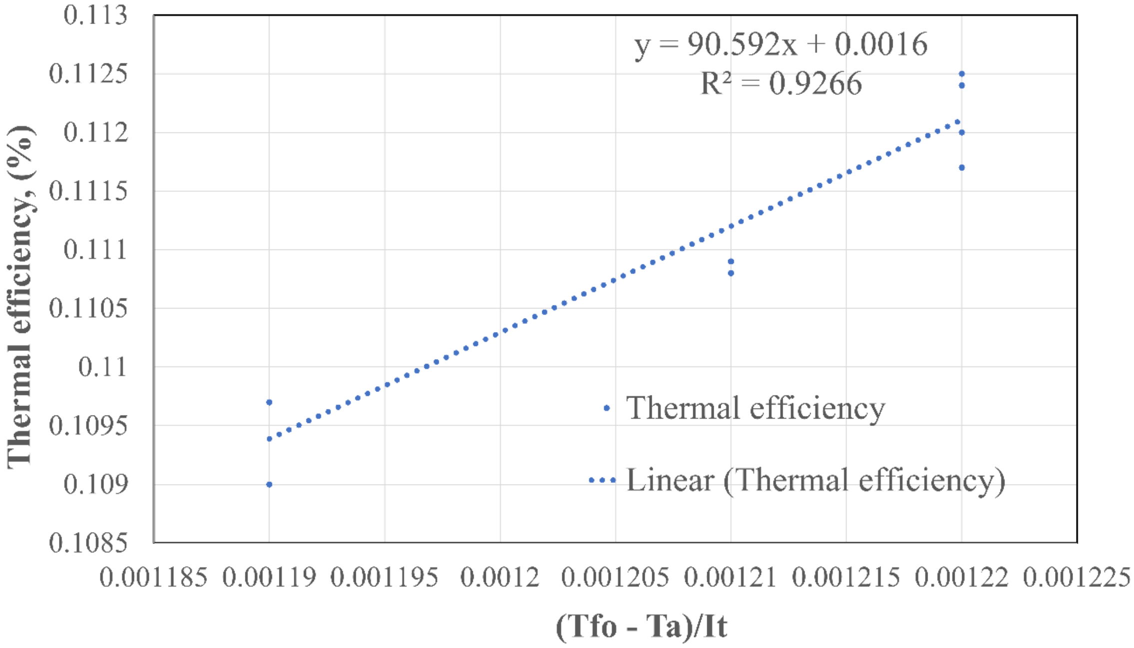


Fig.5. Characteristics curve for η_{th} in air collector

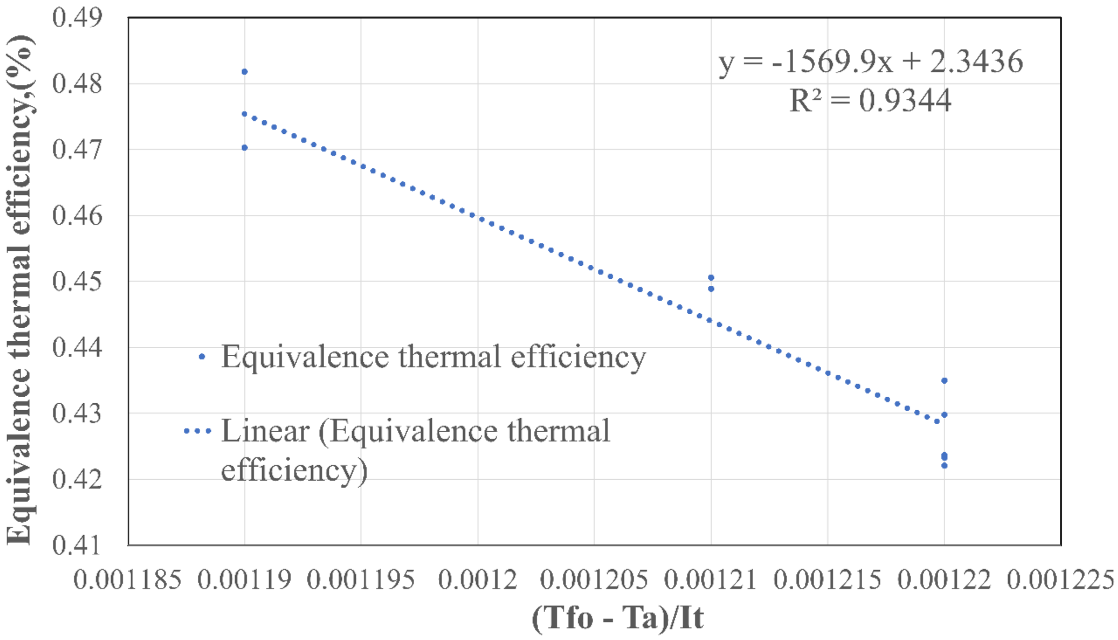


Fig.6. Characteristics curve for $\eta_{eq,th}$ in air collector

Figure 7 depicts the characteristic curve for $\eta_{eq,ex}$. The $\eta_{eq,ex}$ varies from 12.24 – 14.62 %. The overall exergy is a high-grade energy that is the addition of overall electrical energy and exergy. The overall exergy efficiency slope is also negative due to the overall electrical efficiency slope.

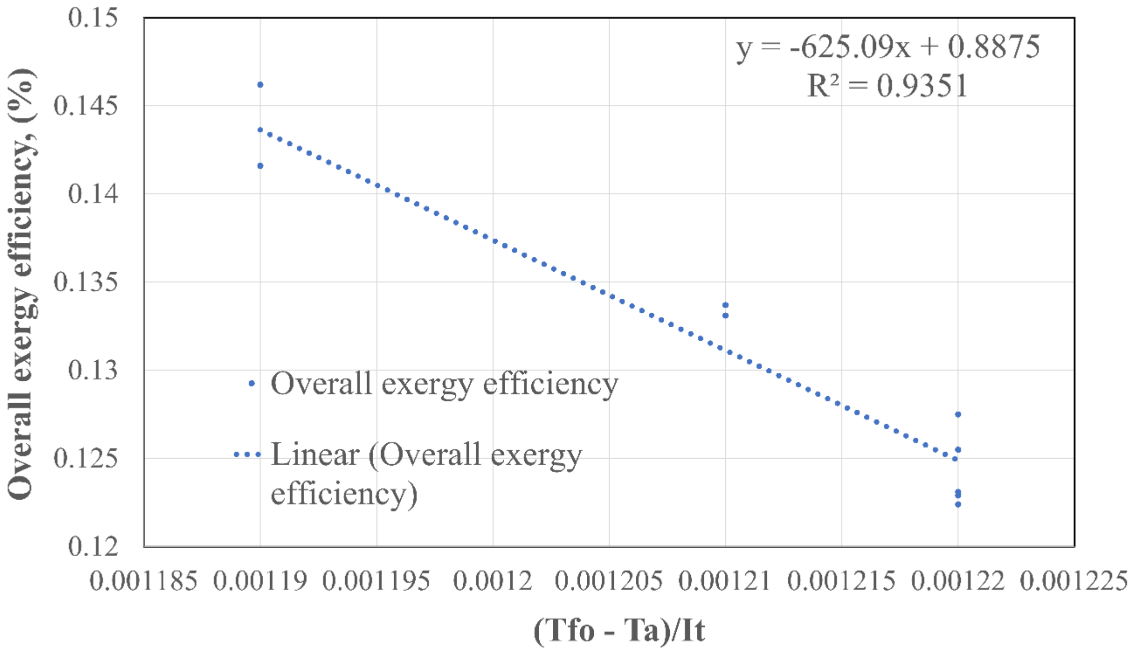


Fig.7. Characteristics curve for Overall exergy efficiency for PVT-TEC air collector

5. Conclusion

The conclusion is as follows.

- The η_{el} and $\eta_{eq,th}$ were 11.77 – 14.17 % and 42.21 – 48.18 %, respectively.
- The $\eta_{eq,ex}$ was found to be 12.24 – 14.62 %.
- TEC generates electrical energy, decreases the solar cell's temperature, and increases the system's overall efficiency.

6. Acknowledgment

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Nomenclature

Quantity	Symbol	Unit
PV module area	A_m	m^{-2}
Collector breadth	b	m
Air specific heat	C_f	Jkg^{-1} K^{-1}
Overall electrical energy	E_{el}	W
PV module electrical energy	E_{PV}	W
TEC electrical energy TEC	E_{tec}	W
Heat transfer coefficient due to wind velocity	h_i	W$m^{-2}K^{-1}$
Outside heat transfer coefficient	h_o	W$m^{-2}K^{-1}$
Tedlar heat transfer coefficient	h_t	W$m^{-2}K^{-1}$
TEC to fluid heat transfer coefficient	h_{tf}	W$m^{-2}K^{-1}$

Global solar radiation	I_t	Wm^{-2}
Fluid thermal conductivity	K_f	W$m^{-1}K^{-1}$
Glass thermal conductivity	K_g	W$m^{-1}K^{-1}$
Insulation thermal conductivity	K_i	W$m^{-1}K^{-1}$
Tedlar thermal conductivity	K_t	W$m^{-1}K^{-1}$
TEC thermal conductivity	K_{tec}	W$m^{-1}K^{-1}$
Length of collector	L	m
Fluid thickness in duct	L_f	m
Thickness of glass	L_g	m
Insulating material thickness	L_i	m
Tedlar thickness	L_t	m
TEC module thickness	L_{tec}	m
Air mass flow rate	$\dot{m}_f$	kgs^{-1}
Thermal energy gain	$\dot{Q}_{th}$	W
Equivalent thermal exergy	$\dot{Q}_{eq,ex}$	W
Atmospheric temperature	T_a	℃
Standard Solar cell temperature	T_0	℃
Solar cell temperature	T_c	℃
Temperature of fluid	T_f	℃
Inlet fluid temperature	T_{fi}	℃
Outlet fluid temperature	T_{fo}	℃
Temperature of TEC top end	$T_{tec,t}$	℃
TEC bottom end temperature	$T_{tec,b}$	℃
Heat transfer coefficient from top of solar cell to ambient	$U_{t,c-a}$	W$m^{-2}K^{-1}$
Overall heat transfer coefficient from tedlar to fluid	$U_{b,c-f}$	W$m^{-2}K^{-1}$
TEC heat transfer coefficient	U_{tec}	W$m^{-2}K^{-1}$
Heat transfer coefficient from insulation to ambient	U_{b-a}	W$m^{-2}K^{-1}$
Solar cell absorptivity	α_c	
Standard temperature coefficient	β_0	
Packing factor of TEC	β_{tec}	
Transmissivity of glass	τ_g	
Efficiency of solar cell	η_m	
Standard Solar cell efficiency	η_0	
Efficiency of TEC	η_{tec}	
Overall electrical efficiency	η_{el}	
Thermal efficiency	η_{th}	
Equivalent thermal efficiency	$\eta_{eq,th}$	
Equivalent exergy efficiency	$\eta_{eq,ex}$	

Combine form of absorptivity and transmittivity	$(\alpha\tau)_{eff}$	
Velocity of air in ambient	v	$\mathrm{m}s^{-1}$
Prandtl number	Pr	
Photovoltaic thermal	PVT	
Thermoelectric cooler	TEC	
Phase change material	PCM	
Thermoelectric generator	TEG	
Forced convection dryer	FCD	
Natural convection dryer	NCD	

Appendix I

Some Parameters

$(\alpha\tau)_{eff} = \tau_g\,(\alpha_c - \eta_c)$

$U_{t,c-a} = \left[\frac{L_g}{K_g} + \frac{1}{h_o}\right]^{-1}$

$U_{b,c-f} = \left[\frac{L_t}{K_t} + \frac{1}{h_i}\right]^{-1}$

$h_t = \frac{K_t}{L_t}$

$U_{b-a} = \left[\frac{L_i}{K_i} + \frac{1}{h_i}\right]^{-1}$

$h_i = 2.8 + 3\,v$

$h_o = 5.7 + 3.8\,\mathrm{v}$

$h_{tf} = \frac{K_f}{L}\,Nu$

$Re = \frac{V\,L}{\nu}$

$Nu = 0.332\,Re^{0.5}\,Pr^{0.33}$

Appendix II

Design parameters

A_m=0.5471 m^2	L= 1.077 m
b = 0.508 m	L_f = 0.01 m
C_f = 1005 $Jkg^{-1}\,K^{-1}$	L_g =0.003 m
K_f = 0.02622 $Wm^{-1}K^{-1}$	L_i =0.100 m
K_g =0.816 $Wm^{-1}K^{-1}$	L_t =0.005 m
K_i = 0.166 $Wm^{-1}K^{-1}$	L_{tec} =0.004 m
K_t = 0.033 $Wm^{-1}K^{-1}$	$\dot{m}_f$ =0.05 kgs^{-1}
K_{tec} =1.82 $Wm^{-1}K^{-1}$	T_a= 25 °C
V = 2 ms^{-1}	β_{tec} = 0.4324
η_{tec} = 0.08	η_o = 0.15