Effect of thermoelectric materials in electrical and thermal performance of photovoltaic thermal (PVT) collector

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Abstract. A photovoltaic integrated thermal (PVT) collector with thermoelectric material has been proposed in this communication, where a channel or duct has been used below the photovoltaic module in which air has been circulated to extract the heat taken by the photovoltaic module. Hence in PVT system, electrical energy from photovoltaic and thermal energy from duct are taken at the output. In this collector, thermoelectric (TE) is used to change the thermal energy by removing the waste heat of photovoltaic module into electric energy. In proposed PVT with thermoelectric system, TEs are generally appended at the back of the photovoltaic to improve the efficiency of PVT collectors. Thermal modelling has been presented for PVT collector with thermoelectric. The effect of thermoelectric material has been analysed for PVT collector. The electrical energy gain for photovoltaic collector and overall electrical energy gain with thermoelectric has been theoretically calculated. From the computed results, the overall electrical output is observed of PVT system with thermoelectric material; it is higher than only PVT system due to thermoelectric. As PVT system without thermoelectric generates only electrical energy due to PV and thermal energy but PVT system with thermoelectric generates electrical energy due to PV and thermal energy as well as thermal energy so overall exergy of PVT system with thermoelectric is higher than only PVT system. Hence PVT system with thermoelectric shows better results than only PVT system in respect of electrical, thermal and overall exergy gain.

Keywords: PVT collector, PVT collector with thermoelectric, thermal modelling, electrical gain, exergy gain

1. Introduction
Nowadays the renewable energy resources are very popular in terms of the energy generation process. As per the survey, the production of energy through the renewable sources was 9% in the year 2009 will be expected to grow 23% in 2035. Solar power plant is an important source of clean energy and generates a large amount of power in the present scenario. In solar photovoltaic, maximum of the incident sunlight is transformed into heat and only 15%-20% is changed into useful output electrical energy. The generated heat decreases its electrical efficiency as well as reduces the life time of PV module [1]. An integration of photovoltaic with thermal technology has been presented as photovoltaic thermal (PVT) system to use this waste heat. A channel or duct is applied below the PV panel in which air/water is applied to take the heat energy from the photovoltaic by conductive or convective process so as to improve the electrical performance of this hybrid system [2]. Hence both electrical and
thermal energies are obtained at output of PVT system. A considerable number of researches have been conducted in the designs of photovoltaic air/water collector because its performance is affected by several parameters [3].

Mojumdera et al. [4] analyse single-pass PV/T air collector with thin rectangular fins throughout the length of air channel to dissipate heat. Kumar & Rosen et al. [5] presented the comparative study of double-pass PV/T air based collector with and without fins. Fins are used in this system at the base to improve the efficiency of given system by enhancing heat transfer rate. Vats et al. [6] discussed the effect of increasing packing factor on the overall annual energy of photovoltaic and found that increase in packing factor not always increase the overall output energy because with increase in packing factor, the temperature at the output of channel increases by absorbing the higher amount of thermal energy. Dubey and Tiwari [7] outlined and exhibited integrated PV/T solar based water collector. Some logical articulations were inferred as climatic conditions and design parameters, on the basis of absorber area observed that if coverage area of PV is reduced to one third than instantaneous efficiency rises from 33% to 64%.

Chow et al. [8] considered changes when coating on PV/T-thermosyphon system is used from exergy and thermodynamics perspective. From exergy perspective observed that expansions of packing factor, efficiency of cell, wind speed and proportion of water mass to collector region were ideal for system without glazing while surrounding solar radiation and temperature were positive for system with glazing. Mishra and Tiwari [9] examined water based PV/T-system based on constant collector temperature. It was found that fully covered PV was appropriate for generation of electricity as well as partially covered PV was reasonable for generation of heated water. Fudholi et al. [10] presented of spiral/web/direct flow absorber and observed that system’s total efficiency was 68.4% for spiral absorber PV/T collector; it is found better than web and direct absorber. Dupeyrat et al. [11] created PV/T water system having better lamination of cell to get more heat exchange in between fluid and absorber. Hazi et al. [12] created a numerical model; it measured monetary markers and energy limits of PV/T water system and represented payback time was less for given system.

Thermoelectric (TE) are basically combination of many thermocouples and used to change the thermal energy by removing the waste heat of photovoltaic module into electric energy. The temperature of photovoltaic module can be reduced and control by using thermoelectric. In proposed PVT-TE hybrid module, TEs are generally appended to the back of the photovoltaic to improve the efficiency of PVT air/water based collectors [13].

A lot of research has been conducted in the field of PVT in last 30 years but there is very limited study in the literature of PVT with thermoelectric system. Lertsatithanakorn et al. [14] designed an air based TE solar collector with double-pass in Thailand. It is reported that the overall efficiency of this hybrid TE system is increased. Yang and Yin [15] based on theoretical approach observed for a hybrid system comprising of photovoltaic, thermoelectric and hot water gives 30% more output electrical power contrasted with photovoltaic hot water thermal system and only PV system. Deng et al. [16] presented a hybrid design containing photovoltaic, thermoelectric generators with a heat collector. Also, it is exhibited that the overall efficiency of thermoelectric generators and photovoltaic are improved in this hybrid system. Onget. al. [17] assessed the execution of a PV based, evacuated tube heat pipe system for water heating and additionally, TE modules for generating electrical energy. Experimentally different temperatures are recorded by taking various water coolant flow rates and electrical efficiency is calculated as about 0.16%. Li et al. [18] experimentally considered a hybrid photovoltaic thermoelectric generator system in which TEG module is attached by a micro-channel heat pipe with PV to remove the heat. The electrical performance of this given hybrid PV/TEG is compared with a conventional PV system under different ambient conditions. It is found an improvement in overall electrical efficiency by 0.82% of this hybrid system over conventional PV system.

Dimri et al. [19, 20] presented thermal modelling of PVT-TE collector to observe the efficiency of this hybrid system. The designed PVT-TE collector is compared with only PV and PV-TE collector, and found that PVT-TE collector gives better overall electrical efficiency than PV-TE and PV.
collector by 4.7% and 7.3% respectively. Dimri et al. [21] considered a PVT-TE collector with different kinds of base materials of photovoltaic modules. It is found that for opaque base material, the overall electrical efficiency by 1.9 – 2.8% and thermal efficiency by 20.8 – 21.8% of PVT-TEC water collector is more than PVT-TEC air collector. The performance of all three types of base cover material (opaque, semitransparent and Aluminium) of PVT-TEC water collector is considered and on comparing it is found that the performance for PVT-TEC water collector with Aluminium base is much better than other. In literature, hybrid PV-TE generator system is found in many studies and many of them having heat sink in the TE generators cold side to make a large temperature gradient. However, the expelled heat for this situation is discharged to the environment so the overall efficiency of the system is reduced as this energy is lost. Lekbir et al.[22] proposed a nanofluid based hybrid PVT-TEG design. As nanofluid is having higher cooling potential than heat sink so in this design nanofluid is used in place of heat sink to increase both photovoltaic and TE generators performance, and also using waste heat as valuable energy.

2. System description

In this paper, a PVT collector with thermoelectric has been considered, where the thermoelectric material is used below the PV module to convert waste heat in to electrical energy as shown in Figure 1. In this given model, a channel has been used below the photovoltaic and thermoelectric material in which air is passed to absorb the heat of the panel. The electrical output of photovoltaic improves by placing a thermal system below the PV and thermoelectric. Additional electrical energy is also generated by using thermoelectric material. In this system, an insulation layer below the thermal channel has been used to trap the heat so that heat may not dissipate through the bottom part of the system. In this research work, analyse the electrical and thermal performance of the PVT system with thermoelectric.

![Proposed photovoltaic thermal system with thermoelectric material](image)

3. Thermal modelling

The energy balance equations have been developed for photovoltaic thermal air collector integrated with thermoelectric material [19-24], when taking an elemental area \( bdx \). The following equations can be given for different part of the integrated PVT thermoelectric system:

a) For photovoltaic module-

\[
\tau_g \alpha_{sc} I(t) bdx = U_{t,c-a}(T_{sc} - T_a) bdx + h_t(T_{sc} - T_{tec,top})\beta_{tec} bdx + U_{b,c-a}(T_{sc} - T_f)(1 - \beta_{tec}) bdx + \eta_{sc} \tau_g I(t) bdx \\
\]

b) For tedlar-

\[
h_t(T_{sc} - T_{tec,top})\beta_{tec} bdx = U_{tec}(T_{tec,top} - T_{tec,bottom})\beta_{tec} bdx \\
\]

c) For TE module-

\[
U_{tec}(T_{tec,top} - T_{tec,bottom})\beta_{tec} bdx = h_f(T_{tec,bottom} - T_f)\beta_{tec} bdx + \eta_{tec} U_{tec}(T_{tec,top} - T_{tec,bottom})\beta_{tec} bdx \\
\]

d) For fluid flowing below TE module-
The expressions for $T_{sc}$, $T_{tec,top}$ and $T_{tec,bottom}$ are obtained, after solving Eqs. (1-3) and given as:

$$T_{sc} = \frac{(\alpha r)_{eff}(t) + U_{b,c-a} + h_i T_{tec,top} \beta_{tec} + U_{b,c-a}(1 - \beta_{tec}) T_f}{U_{b,c-a} + h_i \beta_{tec} + U_{b,c-a}(1 - \beta_{tec}) T_f}$$  \hfill (5)

$$T_{tec,top} = \frac{h_{p1}(\alpha r)_{eff}(t) + U_{tec,top} - a + U_{tec,top} \beta_{tec} + U_{tec,top} - f T_f}{U_{tec,top} + a + U_{tec,top} + U_{tec,top} - f T_f}$$  \hfill (6)

$$T_{tec,bottom} = \frac{(\alpha r)_{eff}(t) + (1 - \eta_{tec}) U_{tec,bottom} - a + h_i T_f \beta_{tec} + (1 - \eta_{tec}) U_{tec,bottom} - f T_f}{(1 - \eta_{tec}) U_{tec,bottom} - a + h_i \beta_{tec} + (1 - \eta_{tec}) U_{tec,bottom} - f T_f}$$  \hfill (7)

By taking the inlet and outlet boundary conditions, following expression for average fluid temperature is computed:

$$\bar{T}_f = \left[\frac{h_{p3}(\alpha r)_{eff} + h'_{p1}(\alpha r)_{eff} + h'_{p2}(\alpha r)_{eff} + h'_{p3}(\alpha r)_{eff}}{(U_{fa} + U_b) \left(1 - \exp\left(-\frac{(U_{fa} + U_b) bl}{m_f C_f}\right)\right)} + T_a\right] + \frac{1 - \exp\left(-\frac{(U_{fa} + U_b) bl}{m_f C_f}\right)}{(U_{fa} + U_b) bl}$$  \hfill (8)

After putting $\bar{T}_f$ from Eq. (8) in Eq. (7), the TE bottom end temperature, $T_{tec,bottom}$ is calculated. Further, putting $T_{tec,bottom}$ in Eq. (6), the expression for TE top end temperature, $T_{tec,top}$ is obtained. Finally, by putting $T_{tec,top}$ in Eq. (5), the expression for average solar cell temperature, $T_{sc}$ can be computed.

4. Comparative results of PVT module with and without thermoelectric

![Figure 2. Variation of solar radiation and ambient temperature with time](image-url)
thermoelectric material below the photovoltaic module. Fig. 2 shows the variation of the solar radiation (in W/m²) and ambient temperature (°C) for New Delhi, India from 8:00 a.m. to 5:00 p.m. on a day of January, 2019. It is observed from the graph as shown in Fig. 2 that solar radiation is maximum at 1:00 p.m. and ambient temperature is in the range of 6–17 °C.

Fig. 3 indicates the variation of theoretically calculated electrical energy gain generated by photovoltaic, thermoelectric material and overall gain for the PVT system with thermoelectric material. The overall electrical energy of this hybrid system is the total electrical energy due to photovoltaic and thermoelectric material; it is higher than the electrical energy only due to the photovoltaic only. Hence the electrical energy of the given photovoltaic thermal collector with thermoelectric is better than only PVT collector.

![Figure 3. Variation of theoretically calculated electrical energy by PVT collector with thermoelectric material](image)

![Figure 4. Variation of overall exergy of PVT collector with and without thermoelectric material](image)
Variation of overall exergy of the PVT collector with and without thermoelectric material is shown in Fig. 4. It is observed that overall exergy of PVT collector with thermoelectric material having component of thermal energy along with electrical energy of photovoltaic and thermoelectric is higher than the overall exergy of PVT collector that is having component of thermal energy and electrical energy of photovoltaic only.

5. Conclusions
In the given work, theoretical modelling for PVT collector with thermoelectric material has been presented and compared with the PVT collector. TAs per the above study, the following points have been concluded:
• The overall electrical energy of PVT collector with thermoelectric is higher than the PVT collector only, as thermoelectric material is capable to generate electrical energy.
• In this proposed PVT module with thermoelectric material, TEs are appended to the back of the photovoltaic to attain the improved performance of PVT air collectors.
• This PVT collector with thermoelectric material shows better overall exergy, when compared with same type PVT collector.

6. Nomenclature

| Symbol | Description |
|--------|-------------|
| $\tau_g$ | Transmittivity of glass |
| $b$ | Width of collector (m) |
| $L$ | Length of collector (m) |
| $dx$ | Small length (m) |
| $A_c$ | Area of solar cell ($m^2$) |
| $I(t)$ | Solar radiation intensity ($W/m^2$) |
| $\eta_{sc}$ | Efficiency of solar cell (%) |
| $C_f$ | Specific heat of fluid or ($J/kg^\circ K$) |
| $m_f$ | Mass flow rate of fluid in channel ($kg/s$) |
| $T_{sec, top}$, $T_{sec, bottom}$ | Temperature of top and bottom surface of thermoelectric ($^\circ C$) |

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