Assessment of Electrical and Thermal Performance of Photovoltaic Thermal Air Collector in the Climate of Pantnagar, Uttarakhand

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Abstract. The photovoltaic thermal collector (PVT) produces electricity and extracts heat from a common area exposed to solar radiation. The present work provides a methodology to assess the potential of PVT at any location. The climate of Pantnagar (a town situated in the Terai belt of Uttarakhand) is selected for the study. An unglazed PVT air heating collector is modelled, taking account of both electrical and thermal aspects of design. The performance of the collector is then simulated on four days, representing average weather of four seasons observed in North Indian Plains, in correspondence with the typical meteorological year (TMY) data of 2006-2015 for the location. The diode parameters and characteristic curves of PV module selected for PVT are obtained for reference and operating conditions. The operating temperature of solar cell and heated air are plotted after convergence of numerical solution at available data points. Finally, electrical and thermal power output of the PVT with associated optical and thermal losses are obtained. The highest electrical power output of 223 W (136 W/m²) is observed at 12:20 hours (IST) on equinox of September while highest thermal power output of 411 W (251 W/m²) is obtained at 12:20 hours (IST) on summer solstice.

1. Introduction

The photovoltaic thermal (PVT) collector is a promising hybrid technology with the benefit of simultaneous electrical and thermal production from a common land or roof area. It is beneficial when the area available for installation is limited. It has been proved that the PVT collector gives increased total yield compared to that provided by photovoltaic module and thermal collector, installed side-by-side on the same area [1]. The increased yield from the same area thus reduces the payback time of the investment. Despite major developments in PVT systems around the world, India is lagging far behind in developing a PVT market with only 7 m² of flat-plate PVT water collectors (total installed capacity of 4 kWth thermal and 1 kWp electrical) and 255 m² of PVT concentrators (total installed capacity of 132 kWth thermal and 27 kWp electrical) installed till 2019 when compared with the total of 1,166,888 m² of installed PVT collector area (total installed capacity of 605,910 kWth thermal and 207,655 kWp electrical) worldwide [2]. A major reason behind low acceptance of this technology in India is a lack of supporting studies which demonstrate the PVT potential in Indian climate.

The earliest studies on PVT collectors appeared in the second half of the 1970s [3–5]. Many researchers contributed in the development of the performance prediction models for PVT collectors and systems in the intermediate period [6–10]. Major developments in the PVT field have been...
witnessed in the past decades [11–12]. Recently, task 60 of Solar Heating and Cooling Programme addressed the issue of low awareness about PVT in heating, ventilation and air conditioning (HVAC) industry with progress in the development of international standards for PVT collectors [13].

The purpose of the study is to simulate the performance of an unglazed PVT air collector with the climatic parameters typically observed in Pantnagar (29.02°N 79.48°E), a town located at an elevation of 229 m above sea level in Terai region of Uttarakhand. The air heated by PVT may be used for space heating during cold months or drying of agricultural produce in any season and helps in achieving renewable targets for a sustainable future. The climate of Pantnagar is hot and humid in summer and monsoon while cold and dry/foggy during winter. The average temperature peaks up to a maximum of 40.6°C in May and drops down to a minimum of 1.2°C in January [14]. Four days (solstices and equinoxes) from the 2006–2015 typical meteorological year (TMY) data of the location are chosen as representative of the average climate of four seasons typically observed in northern India. The data of these days also include weather uncertainties as observed in real time satellite images to simulate dynamic behavior of PVT in actual conditions. For example, there is a fair probability of fog in morning during winter season in Pantnagar which reduces the irradiance as reflected in data.

2. Methodology

2.1. Meteorological Data
The accurate climate data of any place can be recorded by a weather station. Due to costs and time associated with collection of real data on the site, data from satellites is often used in prediction studies. The meteorological data is obtained from PVGIS database in present study [15]. The solar insolation data is available in hourly, daily, monthly, and TMY formats. The TMY of 2006–2015 obtained from PVGIS for the selected location use data of 2006 for March (Spring equinox) and June (Summer solstice) while data of 2014 for September (Autumn equinox) and data of 2008 for December (Winter solstice). The days corresponding to the occurrence of these events in the respective month of the year are selected for study. The data of the corresponding days are plotted concisely in figure 1.

The dew point temperatures, plotted in figure 1, are obtained from CoolProp thermophysical property library [16] with atmospheric pressure, ambient temperature and relative humidity as input parameters. The sky temperature \( T_s \) is calculated from equation (1) with ambient temperature \( T_a \), dew point temperature \( T_{dp} \) and hour from midnight \( t \) as input parameters (units in parentheses) [17]:

\[
T_s(K) = T_a(K)[0.711 + 0.0056T_{dp}(°C) + 0.000073T_{dp}^2(°C^2) + 0.013 \cos 15t(h)]^{1/4}
\]  

(1)

2.2. PVT Design Data
The PV module selected to design PVT is JJ-M660 (Jain Photovoltaic) with a peak power of 245 W at standard test conditions (STC). The electrical characteristics of PV module, design and thermal characteristics of materials selected to construct the integrated photovoltaic thermal collector (PVT) and operating conditions are specified in table 1. A conceptual line diagram to visualize the layers of unglazed PVT air collector investigated in present study is shown in figure 2.

2.3. Electrical Model
The five parameter single diode model is used to simulate the \( I–V \) curve from the Manufacturer’s specification data. The initial points are obtained by analytical approach while the solution is obtained by numerical approach [18]. The well-known five parameter, single diode equation of current \( I \) and voltage \( V \) is given as [9]:

\[
I = I_L - I_a[\exp((V + IR_a)/a) - 1] - (V + IR_a)/R_{sh}
\]  

(2)
where \( \alpha \) is ideality factor, \( I_L \) is light current, \( I_o \) is reverse saturation current, \( R_s \) is series resistance and \( R_{sh} \) is shunt resistance. These are the five unknown parameters which need to be solved simultaneously from the equations which are obtained by applying open circuit, short circuit and maximum power conditions to equation (2). A set of translation equations are then used to obtain these parameters at operating conditions [10]. The electrical efficiency is then calculated at the maximum power point of the operating \( I-V \) curve, obtained by solving equation (2) with operating parameters.

![Figure 1. Meteorological data of Pantnagar, corresponding to TMY 2006-2015 [15].](image-url)
Table 1. Design and operating parameters of PVT air collector simulated in the study.

| Symbol | Parameter                                                      | Value                           |
|--------|----------------------------------------------------------------|---------------------------------|
| $L$    | Length of collector (= Length of PV module)                    | 1643 mm                         |
| $W$    | Width of collector (= Width of PV module)                      | 996 mm                          |
| $H$    | Thickness of collector (= Thickness of PV module frame)        | 40 mm                           |
| $\delta$ | Depth of air duct                                           | 20 mm                           |
| $V_{oc}$ | Open circuit voltage of PV module                           | 36.75 V                         |
| $I_{sc}$ | Short circuit current of PV module                         | 8.87 A                          |
| $V_{mp}$ | Maximum power point voltage of PV module                    | 29.31 V                         |
| $I_{mp}$ | Maximum power point current of PV module                    | 8.36 A                          |
| $\alpha$ | Temperature coefficient of PV module current                  | $4.08 \times 10^{-3}$ A/K        |
| $\beta$ | Temperature coefficient of PV module voltage                  | $-0.121$ V/K                    |
| NOCT   | Nominal operating cell temperature of PV module              | $45 \pm 2$ °C                   |
| $\alpha_c$ | Absorptance of solar cell                                  | 0.9                             |
| $\alpha_T$ | Absorptance of TPE backsheet                               | 0.5                             |
| $\beta_c$ | Cell packing factor in PV module                           | 0.89                            |
| $\tau_g$ | Transmittance of glass (Low iron, tempered)                 | 0.917                           |
| $\varepsilon_g$ | Emittance of glass                               | 0.88                            |
| $\varepsilon_d$ | Emittance of duct inner surfaces                  | 0.95                            |
| $L_g$    | Thickness of glass                                          | 3.2 mm                          |
| $k_g$    | Thermal conductivity of glass                                | 1.7 W/m K                       |
| $L_E$   | Thickness of EVA                                             | $350 \pm 50 \mu$m               |
| $k_E$   | Thermal conductivity of EVA                                  | 0.235 W/m K                     |
| $L_c$   | Thickness of solar cell (Polycrystalline silicon)             | $200 \pm 30 \mu$m               |
| $k_c$   | Thermal conductivity of solar cell (Silicon)                  | 148 W/m K                       |
| $L_T$   | Thickness of TPE backsheet                                    | $300 \pm 5 \mu$m                |
| $k_T$   | Thermal conductivity of PVF (Tedlar)                         | 0.16 W/m K                      |
| $k_p$   | Thermal conductivity of PET                                  | 0.15 W/m K                      |
| $L_i$   | Thickness of insulation                                      | 20 mm                           |
| $k_i$   | Thermal conductivity of insulation (Polyurethane foam)       | 0.035 W/m K                     |
| $v_a$   | Velocity of air at inlet (Vary in 0.25 m/s steps; Peak at noon) | $1 - 2.5$ m/s                   |

2.4. Thermal Model

The thermal behavior of PVT is simulated by energy balance equations with following simplifying assumptions:

1. At a particular data point, the collector is in steady-state with the environment.
2. The thermal inertia of collector material is considered negligible.
3. The heat conduction is one-dimensional and perpendicular to the layers of PVT.
4. The temperature variation along width of a particular layer of PVT collector is neglected.
5. The heat losses from the edges of the PVT collector frame are neglected.
6. The ohmic losses in cell due to bad contacts, current leakage and hotspots are not present.
7. The optical properties of PV module are independent of temperature.
8. The ambient temperature along the collector front and back is same.
9. The flow of air inside duct is uniform and fluid properties are evaluated at bulk temperature.
10. The wind flows at a constant speed on top and bottom surface with no directional effects.

The thermal model of present study is developed taking Amori et al. [10] as reference with several improvements like good convergence of parameters in the electrical model with analytical guess values for numerical solution [18], improved material property definitions and fluid property evaluations from reference tables [16]. An interactive program for coupled solution of electrical and thermal model is developed in MATLAB. The flow of information and conditional statements in the program are coded according to the flowchart scheme of the computer program developed by Amori et al. [10] and validated by replication of design parameters in test run which shows excellent similarity between results of both programs. The collector characteristics are calculated at each step of iteration from the Hottel-Whillier-Bliss model which is omitted here for brevity [17]. The mean fluid temperature can be obtained from approximate solution of these parameters which is then used to calculate the fluid properties at next iteration using CoolProp library [16].

![Cross-section of unglazed PVT air collector with corresponding thermal network](image)

**Figure 2.** Cross-section of unglazed PVT air collector with corresponding thermal network: Labels denote thermal resistance between nodes of temperature while arrows show the direction of heat flow.

### 3. Results and Discussion

#### 3.1. PV Characteristic Curves at Reference and Operating Conditions

The solution of the five parameter single diode model for the selected module (245 Wp) at STC conditions (1000 W/m², 25°C and 1.5 AM) results in an ideality factor \( (a) \) of 1.6048, light current \( (I_L) \) of 8.87 A, reverse saturation current \( (I_S) \) of \( 1.005 \times 10^{-9} \) A, series resistance \( (R_s) \) of 0.34 Ω and shunt
resistance ($R_{sh}$) of 9098 Ω. The $I$–$V$ curve with maximum power point (MPP) located with the help of $P$–$V$ curve at reference and operating conditions are plotted in figure 3. The drop in the PV power output at operating conditions is due to higher cell temperature as PV module voltage has a negative temperature coefficient (see table 1).

3.2. Temperature of Solar Cell and Heated Air

The solar irradiance, ambient temperature, wind speed and velocity of air in duct has a direct impact on the operating temperature of the solar cell in the PVT collector. The meteorological parameters are uncontrollable and vary with season, the operating parameters can be optimized for high yield through the day and throughout the year. The PVT is fixed at the optimum slope and azimuth for the year in consideration as suggested by PVGIS for providing in-plane irradiance. The velocity of air in the duct is varied each hour in steps of 0.25 m/s with peak (2.5 m/s) occurring at noon so that high yield is obtained at high level of irradiance. The hourly simulated temperature of solar cell and heated air are plotted in figure 4. The highest cell temperature of 57°C is obtained at 13:20 hours for the day of summer solstice and the highest outlet air temperature of 45°C is attained an hour later. The inlet air velocity is 2.25 m/s at the time of highest cell temperature and 2 m/s for highest outlet air temperature.

3.3. Power Output and Losses

The accounting of electrical and thermal power output with associated losses in the collector is presented in figure 5. It provides a clear view of PVT potential at the selected location. The fraction of in-plane solar irradiance that reaches the solar cell is determined by optical efficiency of the transparent cover material. The electrical power output is determined from electrical conversion efficiency of the solar cell at the operating conditions. The amount of thermal power that can be extracted from the PVT depends on the maximization of heat transfer from solar cell to working fluid and minimization of heat losses to the environment. The maximum power that can be obtained from PVT primarily depends on the level of irradiance that is available on the plane of the collector. As the tilt of the collector is optimized for whole year operation by fixing it facing the median of the paths of the sun in the sky during year, the angle of incidence on the plane of PVT at noon in equinoxes is lower than that in solstices. The operating temperature of solar cell is also higher in summer solstice due to higher ambient temperature in summer. The irradiance on the plane of PVT and temperature of solar cell are lowest in winter solstice hence lowering the thermal yield but the electrical yield is still higher than in summer due to better cell efficiency at low temperature. The highest electrical power of 223 W is observed at 12:20 hours (IST) on autumn equinox while the highest thermal power of 411 W is obtained at 12:20 hours (IST) on summer solstice. These results are normalized with the area of collector to determine the highest PVT electrical and thermal power potential of 136 and 251 W/m²,
respectively, that is available in the typical climate of the location during the median and extremes of the sun in the sky. The highest thermal and overall (electrical + thermal) efficiencies are 27.56% and 40.46%, respectively, both observed at 12:20 hours (IST) on summer solstice while the highest electrical efficiency of 15.08% is observed at 9:20 hours (IST) on winter solstice.

Figure 4. Simulated air and average cell temperature in PVT for different seasonal days in Pantnagar.

4. Conclusions
The power produced by the PVT during the days selected in the present study are instantaneous values at corresponding points of time, obtained from irradiance data from the satellite images and climate data from weather monitoring services. These data do not represent the true ultimate potential of PVT at the location but only provide a snapshot of the possible yields that can be obtained from PVT. If these values are assumed as a constant for the hour, the energy yield from the PVT at the midpoint of different seasons can be estimated. The calculations with this assumption gives a total daily yield of 1.76, 2.57, 2.22 and 1.20 kWh/m² with energy conversion efficiency of 32.9%, 37.5%, 33.4% and 31.3% on spring equinox, summer solstice, autumn equinox and winter solstice, respectively. The ratio of thermal and electrical yield during these days are 1.39, 1.83, 1.45 and 1.18, respectively. The simulation results show the potential and utility of PVT for heating air with electricity generation in Pantnagar.
Figure 5. Distribution of irradiance available on PVT plane for different seasonal days in Pantnagar.

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