A parabolic trough photovoltaic thermal concentrating collector using triangular reciver

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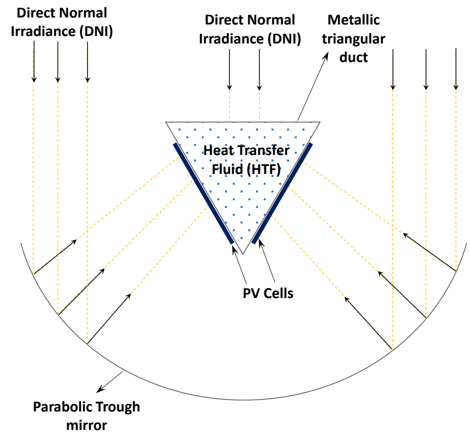
Global warming and air pollutions caused mainly by the overuse of the fossil fuels have been increasing the need for transition to renewable resources of energy. Over the last decade, the energy consumption has risen drastically, while the fossil fuels were still the main source of the energy [1-4]. Solar energy is the most abundant available resource of renewable energy that has potential to cover the whole world needs for energy. However, current technologies on collection and energy conversion of solar radiation are still not efficient and cost effective to support this energy transition practically [5-7]. Concentrating solar photovoltaic/thermal (CPV/T) systems are among those research topics focusing on increasing the efficiency of solar collectors and the capital cost reduction [8-11]. Using less expensive solar concentrators, CPV/T systems can provide a high flux of solar radiation on smaller areas of highly expensive photovoltaic cells to generate electricity [4].

In this research, an innovative concentrating photovoltaic/thermal (CPV/T) hybrid solar system employing monocrystalline PV cells with a new design of cooling channel was designed, manufactured, and investigated. The main objective of this study is to demonstrate the new design of a cooling channel for PV cells under high flux of solar radiation and to evaluate the overall performance of the system through experiments and computational simulation. The cooling channel through which the cooling fluid circulates has a triangular cross-section made of a thin stainless-steel metal, and PV cells are placed on its outer sides as shown in Figure 1. A parabolic trough concentrator with a single axis sun tracking mechanism was used in the system. The performance of the system was tested in two different tracking orientations of E-W polar axis and N-S horizontal axis. The daily performances of the system with different rates of cooling fluid was recorded and compared with theoretical outputs.

(a)



(b)

Figure 1. Schematics of (a) the concentrating Photovoltaic Thermal collector with E-W polar axis tracking mechanism, and (b) the receiver cross-section at the focal spot of the concentrator.

The E-W polar tracking mechanism is designed to rotate the collector around the center of gravity of the concentrator and receiver which significantly minimizes the required power and allows using small size electromotors. A DC electromotor was used to rotate the collector and the rotation monitored by an angular encoder (model HE50B-8-1000-3-T-24) connected to a microprocessor. The process was set to repeat every 4 minutes based on the acceptance angle of the concentrator.

The receiver consists of a metallic duct with triangular cross-section made of a thin galvanized steel sheet, and monocrystalline silicon solar cells which are located on both sides of the duct facing towards the concentrator. In order to not allow the concentrated solar radiation exceeds beyond the PV cells area during the operation time, the dimensions of the duct were designed to be within the concentrator acceptance angle range. The triangular receiver of the collector is designed to create a band of concentrated solar radiation on its sides to cover the whole area of the solar cells instead of a narrow focal line at the centre. Figure 2 shows the photo of the receiver illustrating the incident solar radiation bands on the PV cells. The active size of the receiver in each side is 1100 mm in length and 55 mm in width. The design of electrical contacts was considered to provide a high finger density inside the solar concentration band area. The assembled PV module consisting of 8 half cut PV cells interconnected in series and placed on each sides of the receiver duct (16 half cells overall connected in series).

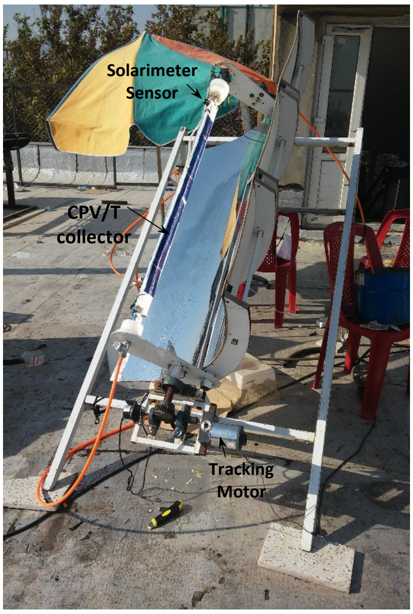


Figure 2. The receiver of the CPV/T system illustrating the location of the incident solar irradiation bands on the PV cells.

The parabolic trough concentrator has the overall the active aperture area of the concentrator is 0.94 m^2 and a focal length of 1.5 m. The height and width of parabola are equal to 0.175 m and 0.92 m, respectively, while the rim angle is 75°. While the collector is working, PV cells generate power under the concentrated solar irradiance and get heated at the same time. So, to cool down the cells, heat transfer fluid (HTF) is pumped through the duct and carry away the heat. The top surface of the receiver duct is exposed to the direct solar radiation to increase the thermal heat gain of the collector and improve the thermal performance of the system. Figure 2 shows the experiment setups of the designed system tested under different conditions.

The mathematical modelling of the CPV/T hybrid system was performed using energy balance equations on different components including PV cells, receiver duct, and heat transfer fluid. An equivalent electrical circuit, modelling the operation of PV cells, was proposed. It was coupled to the main model in order to calculate the electrical output of PV cells under different incident solar irradiance and temperatures. Figure 3 illustrates the schematic of the receiver used for the computer modelling. For modelling the electrical behaviour of the PV cells, a model which includes a single-diode, series electrical resistance (R_s), and a parallel electrical resistance (R_{sh}) were used. R_s represents the resistance inside the cell structure, and R_{sh} indicates the resistance of the external electrical contacts. Consequently, the I-V characteristic curve of a PV module, consisting of numbers of PV cells connected in series, as a function of operating parameters is provided below:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V + IR_s)}{n N_s k_B T_{pv}} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

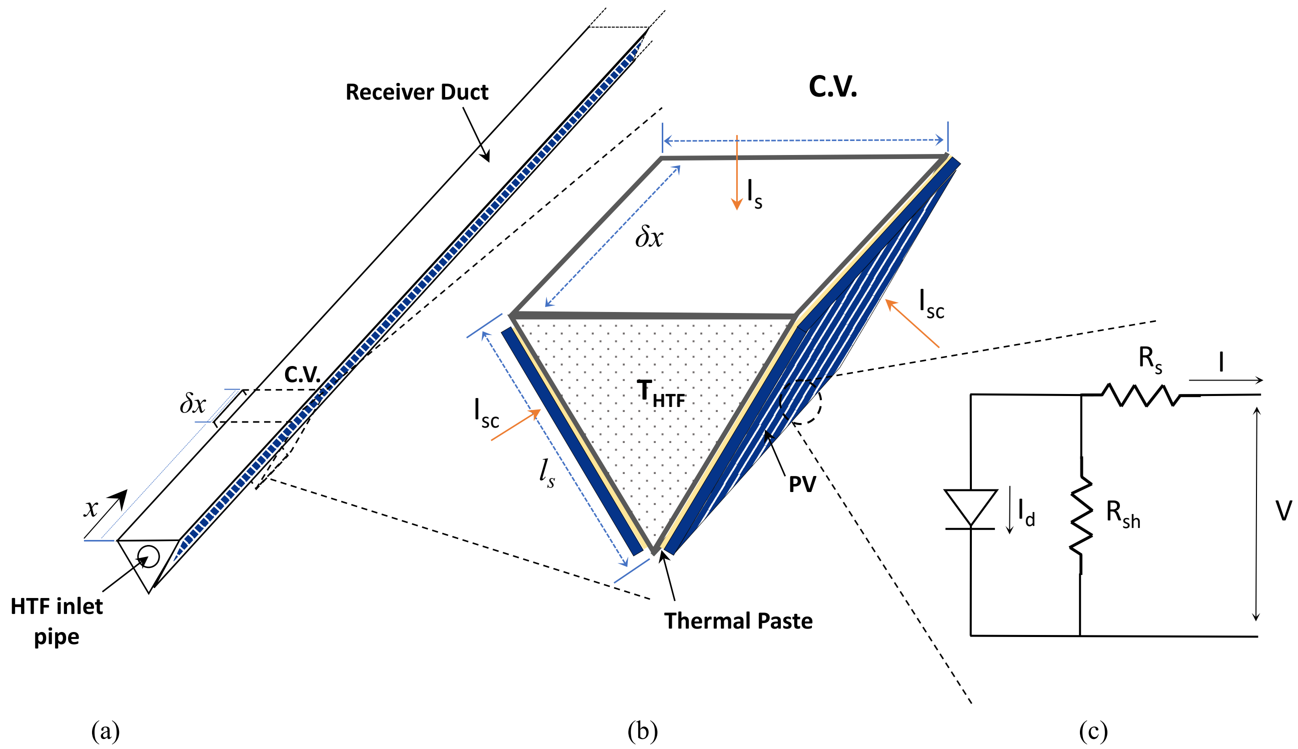


Figure 3. Schematic view of (a) receiver duct, (b) the infinitesimal control volume on the receiver duct, and (c) the equivalent electrical circuit model of PV cell.

Figure 4 shows the characteristic I-V curves of the PV cells on the PV/free module and the CPV/T system in both cases of polar axis and the horizontal axis. It can be discerned that electric current output of the CPV/T system regardless of its tracking mechanism is approximately equal to 4.4A at the maximum power point, while the value for the PV/free stationary module is 1.7A. Likewise, the value of the short-circuit current in the CPV/T system is significantly higher than that in the PV/free module due to the concentrated solar radiation. The short-circuit current in the CPV/T system with polar axis is 5.8A, in the CPV/T system with horizontal axis is 5.6A, and in the PV/free module is 2.1A.

The maximum variation of 6% was obtained between theoretical and experimental results. The simulation was used to characterize the performance of the system under different working parameters. The highest performance was obtained for the system with E-W polar tracking mechanism. The main results of experiments on this system during clear days of the summer at Tehran (35°41’N latitude) indicated that the daily average of electrical and exergy efficiencies are 5.0% and 5.1%, respectively, and it generates 43.7 W electrical power per square meter of the collector aperture area. It is nearly 3.5 times higher than the production of the same quantity of solar cells in a conventional photovoltaic panel. The results of experiments showed that the average thermal efficiency is 40% for the flow rate of 0.05 L s^{-1} which produces 364 W m^{-2} of thermal power. The economic evaluation of the present hybrid solar system shows that the initial cost of electric power generation is 5.58 $/watt in respect to conventional photovoltaic panels, which is about 2.24 $/watt. This predicts 5 years for capital cost return for this CPV/T collector.

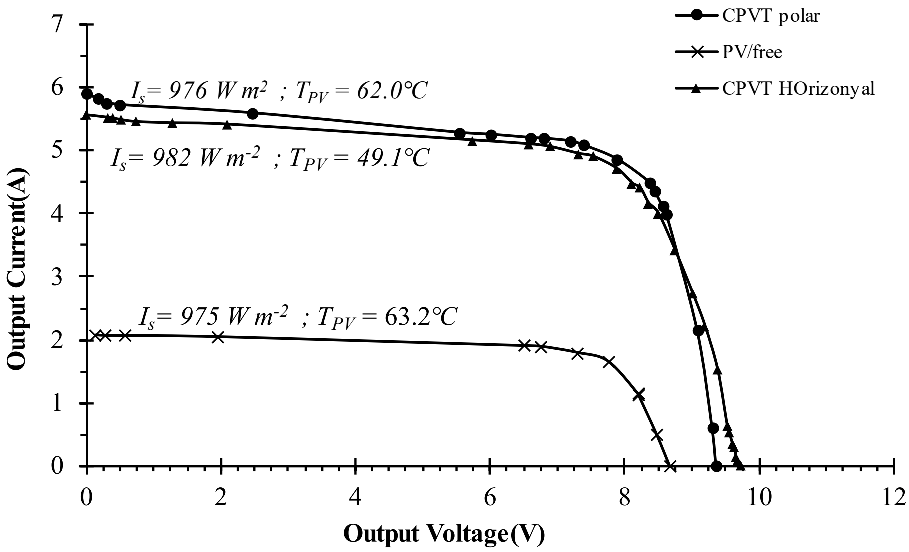


Figure 3. Measurement results of the I-V characteristic curves of photovoltaic modules in PV/free and CPV/T hybrid systems.

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