Solar Energy 157 (2017) 10–19

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Modeling and experimental research of hybrid PV-thermoelectric system for high concentrated solar energy conversion

Khaled Teffah *, Youtong Zhang

Laboratory of Low Emission Vehicle, Beijing Institute of Technology, Beijing 100081, China

ARTICLE INFO

Article history:
Received 22 May 2017
Received in revised form 21 July 2017
Accepted 4 August 2017

Keywords:
Photovoltaic-thermoelectric (PV-TE)
Concentrated solar energy
Peltier effect
Seebeck effect
Solar energy conversion

ABSTRACT

An experimental research of a novel combination, within a photovoltaic-thermoelectric (PV-TE) system, for high concentrated solar energy (×300–1000) conversion to electricity is presented. Our hybrid system contains, at its core; a triple junction solar cell (TJSC); a thermoelectric cooler (TEC); a thermoelectric generator (TEG), all settled thermally in series respectively. The thermoelectric cooler enhances the solar cell efficiency by pumping its excess heat through the Peltier effect; the thermoelectric generator plays the role of a heat sink for the TEC, converting some of this waste-heat into electricity by means of the Seebeck effect. The basic steady state finite element modeling demonstrates the contribution of the TEC-TEG Module, inflating the overall efficiency of the hybrid system for high solar concentrated irradiation; the experimental and simulation results are matched. All of which evokes a new system that takes into consideration the PV electric power generation, without compromising the cooling potential and the immediate electric production of the thermoelectric devices.

1. Introduction

As the annual consumption of energy continues to increase at a drastic rate (Lewis and Nocera, 2006), the fossil energy has not been exhausted yet but it is not sustainable; one of the prevalent challenges the energy field encounters is to achieve an immediate transition technique, for the utilization of the renewable energy resources. While there are many friendly strategies (Grätzel, 2005; Reddy, 2017; Christopher and Dimitrios, 2012; Hocaoğlu et al., 2009; Saibi, 2009; Armaroli and Balzani, 2011), photovoltaic technology is the unparalleled approach to the exploitation of unlimited solar energy. Unfortunately, the efficient single solar cell so far is built of silicon and its efficiency is about 20.8–25.6% under the standard (AM1.5G) test (Green et al., 2015). To effectively maximize the harnessed free solar energy; the sun light concentration systems (Lee et al., 2016), and concentrator photovoltaic (CPV) (Guter et al., 2009; van Riesen et al., 2015; Cotal et al., 2009; King et al., 2007) sustain a very high belief to be the ultimate key. Furthermore, the multi-junction solar cell (MJSC) can reach in theory by using an unlimited amount of layers an efficiency of 86.8% (Beeri et al., 2015; De Vos and Pauwels, 1981).

A part of the incident solar radiation received by the multi-junction solar cell (MJSC) is converted into electricity, but a big part is transformed to heat. If this excess heat is not driven out of the system, that affects the efficiency of the solar cell and the output power drops by 0.45%/°C (Kane and Verma, 2013). However, a thermoelectric cooler (TEC) can be applied to the back of the multi-junction solar cell (MJSC); and be operated as a heat pump by the Peltier cooling effect. This conception is to develop a heat flux sandwiched between the cold side and the hot side of the thermoelectric cooler (TEC), reliant on the applied current direction. In addition, a thermoelectric generator (TEG) will be applied as a heat sink on the hot side of the thermoelectric cooler (TEC) by converting a part of the waste heat of this latter to electricity by the Seebeck effect, and contributes to enhance the overall efficiency of the whole system.

The concept of combining a photovoltaic with a thermoelectric cooler and a thermoelectric generator (PV-TEC-TEG) is a novel hybrid proposed model for the improvement of the overall system efficiency; but there are several other models in the domain such as PV-TEC or PV-TEG combination were published. Van Sark (Van Sark, 2011) developed theoretically an idealized PV-TEG model, by attaching the thermoelectric material (TEG) with typical figure of merit (Z) of 0.004 $K{-}1$ at 300 K to the back of PV module; and get an efficiency enhancement of 8–23%. Another experimental and theoretical research reported by Chávez-Urbiola et al. (2012) showing that a TEG in a discussed PV-TEG system, based on a previous properties and conditions achieved an efficiency of 4–6%, when the difference temperature between the hot side and the

* Corresponding author.
E-mail address: baronecrist@hotmail.fr (K. Teffah).

http://dx.doi.org/10.1016/j.solener.2017.08.017
0038-092X/

cold side of the TEG is about 150 K and 250 K respectively. An approach for the optimization of the PV-TEG for concentrated solar energy was suggested by Beeri et al. (2015) using commercially multi-junction solar cell and TEG, an overall efficiency of 22–32% was achieved; the efficiency of the TEG is directly proportional to the sun concentration, reaching a maximal value of almost 3.5% at sun concentration of 300. A mathematic modeling of PV-TEC system was developed by Kane and Verma (2013), in addition an experimental analysis reported by Benghanem et al. (2016) and Borkar et al. (2014) all suggest an application of the hybrid PV-TEC for the enhancement of efficiency and life time of module by the cooling effect.

To the best of our knowledge, neither of the previously mentioned hybrid systems PV-TEG or PV-TEC in the field has compromised between the cooling capability and electrical production of the TE modules.

In this paper, we propose a first model of its kind, that combines in a roof multi-junction solar cell (MJSC) with TEC-TEG module. We investigate the behavior of the MJSC under different high sun concentration factor using MATLAB/ SIMULINK software, similarly we demonstrate the ability of using the whole hybrid system to achieve a high efficiency using a finite eliminate method under a characterized simulation approaches on COMSOL Multiphysics software. Furthermore, this work will illustrate experimentally the cooling and the electric contribution of the TEC-TEG to the system overall efficiency.

2. Modeling of triple junction solar cell in MATLAB/SIMULINK (TJSC)

2.1. Triple junction solar cell (TJSC)

Multijunction solar cells (MJSC) for concentrated sun energy applications are increasing in the last few years for their high efficiencies and the ability of converting a large amount of the sun spectrum into electricity, by absorbing different light wavelengths corresponding to the used sub cells bandgap energy (Rabady, 2014; Braun et al., 2013). Triple junction solar cell (TJSC) is a multijunction cell composed of three layers (sub cells) with different bandgap energy, for our case are $GaInP_2/GaAs/Ge$; all the sub cells are interconnected by additional junction called tunnel junction. The Fig. 1 illustrates the structure of TJSC and the band gap energy of the three junctions.

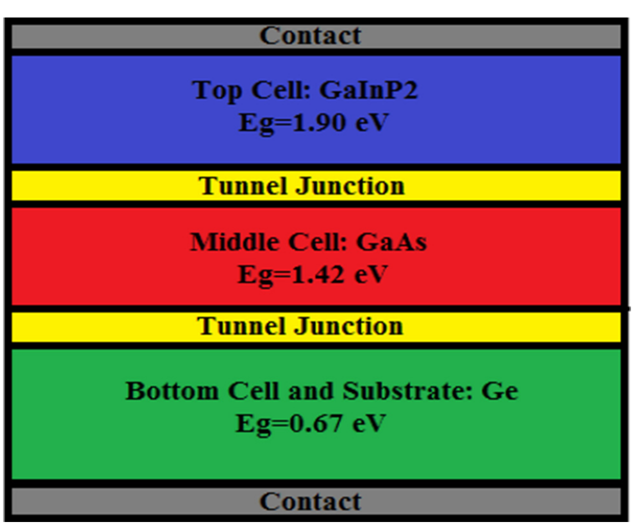

Fig. 1. Structure of triple junction cell based on $GaInP_2/GaAs/Ge$.

2.2. Equivalent circuit diagram of the TJSC

The equivalent circuit diagram of the TJSC is represented in Fig. 2. This circuit is composed of three sub cells connected in series and every sub cell has the same conventional circuit of single solar cell. Furthermore, the sub cell is characterized by a current source (I_{phi}) parallelly connected to a rectifying diode (Di) and parallel resistance (R_{pi}) (shunt), and connected in series with a series resistance (R_{si}). The developed blocks model in MATLAB/SIMULINK is based on the scheme in Fig. 2 below.

From Fig. 2 it is apparent that the current generated by each sub cell $I_{i(i=1,2,3)}$ using Kirchhoff law is given as follow:

$$I_i = I_{phi} - I_{Di} - I_{pi} \tag{1}$$

where I_{Di} is the diode current and I_{pi} is the parallel resistance (shunt) current in each sub sell, they can be calculated with the followed formulas:

$$I_{Di} = I_{si}(\exp^{(q(Vi+IiRsi)/NiKT)} - 1) \tag{2}$$

$$I_{pi} = (V_i + I_i R_{si})/R_{pi} \tag{3}$$

where I_{si} is the saturation current of certain diode, q is the constant charge in an electron $q = 1.602 \times 10^{-19}$ [C], V_i is the cell operating output voltage, R_{si} is the series resistance, R_{pi} is the parallel resistance, N_i is the quality factor of diode, K is Stephan Boltzmann constant $K = 1.38064852 \times 10^{-23}$ [$m^2 kg\ s^{-2} K^{-1}$], T is the cell operating temperature.

By using the Eqs. (2) and (3), the Eq. (1) becomes:

$$I_i = I_{phi} - I_{si}(\exp^{q(Vi+I_iR_{si})/NiKT} - 1) - (V_i + I_i R_{si})/R_{pi} \tag{4}$$

As the parallel resistance R_{pi} (shunt) is much higher than the series resistance R_{si} the Eq. (4) can be simplified as:

$$I_i = I_{phi} - I_{si}(\exp^{q(Vi+IiRsi)/NiKT} - 1) \tag{5}$$

The efficiency η_{PVmax} of the TJSC is the ratio of the its maximum electric generated power P_{PVmax} relative to the incident solar power P_{in}, it can be calculated as follows

$$\eta_{PVmax} = P_{PVmax}/P_{in} = V_{mpp} I_{mpp}/P_{in} \tag{6}$$

where V_{mpp} and I_{mpp} are the cell voltage and current at maximum power point, correspondently.

The incident solar power P_{in} is transformed into two kinds of energy, a part is converted into electrical energy P_{PVmax} by the triple junction solar cell (TJSC), and the remain part is transformed into heat Q_{cold} on the cold side of the thermoelectric cooler (TEC). Thus, the incident solar power P_{in} can be described as:

$$P_{in} = P_{PVmax} + Q_{cold} \tag{7}$$

The absorbed heat Q_{cold} by the TEC is in details described in COMSOL MULTIPHYSICS simulation section of the whole hybrid system.

2.3. SIMULINK/MATLAB developed model

For the purpose of studying the TJSC's behavior in different high sun concentration factor (×300–1000), MATLAB/SIMULINK blocks model is developed based on the scheme shown in Fig. 2, Eqs. (1)–(6). Moreover, the model permits to look closely to the performance of every sub cell of the TJSC subsystem at different operating temperature corresponding to different sun concentration ratio. In this model, in different sun irradiance energy we get the I-V and P-V curve of the cell and also its temperature at the corresponding sun concentration factor, the used parameters are in Table 1 above. The simulation model is demonstrated in Fig. 3 below.