Design and Investigation of Solar Hybrid Electric/Thermal System with Sun-tracking Concentrator, Photovoltaic and Thermoelectric Generators

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Abstract: - We study solar hybrid system that includes Sun-tracking solar radiation concentrator, photovoltaic cell and thermoelectric generator with the heat extracting water-based thermosyphon unit, so that the system produces electric and thermal energy. Theoretical modeling was made, showing that the system has a great potential for development and application, with the ability to provide higher efficiency and thermal stability than traditional hybrid PV/Thermal systems. Experimental study was performed with Si monocrystalline photovoltaic cell and thermoelectric generator (TEG) using the classic Bi_2Te_3 material. The results obtained agree with theoretical predictions. The system studied can be efficient and economic, especially in countries with high insolation, like Mexico, China and Greece.

Key-Words: - Solar hybrid system, Electrical and thermal energy, radiation concentration, Photovoltaic cell, Thermoelectric generator

1 Introduction

It is now well-known and generally accepted that the energy production and consumption in the near future must be based upon the renewable energy sources (solar energy, first of all), and the efficiency of utilization of these sources is of great importance. In this aspect, the solar hybrid systems are most interesting because they are more efficient and more stable in relation to the variations of the source intensity than individual solar devices; that is why the great attention of scientists and technologists was focused on these systems during the last decades (see, for example, [1-10]).

The simplest of the hybrid systems, and the most widely used and studied, is the PV/Thermal (PVT) system consisting of photovoltaic (PV) panel coupled to heat extractor with running water or air. Usually PVT system employs crystalline Si solar PV module, taking advantage of its cooling by heat extracting unit thus increasing its efficiency, and produces 100 – 140 W/m^2 of electric energy at peak illumination, and 3 – 6 times as much thermal energy stored in water/air, heated up to 45 – 50 ^{o}C.

In several publications [10-13] studying was performed of the possibilities of use of thermoelectric generators (TEGs) in solar systems, with the conclusion that TEGs will bring new features in the field and can be successfully used in hybrid systems, instead of PV panels or together with them. It is important to mention an essential increase in thermoelectric conversion efficiency reached during the last decade and connected with the utilization of nanostructured materials for their production [14, 15].

In our previous papers [10, 16] the general analysis was made of the different geometries of solar hybrid systems employing TEGs. One of the schemes treated there, namely, the system with solar radiation concentrator, photovoltaic cell, TEG and water filled heat extractor using thermosyphon effect, was the subject of studying in this paper where theoretical estimations as well as experimental results are presented.

2 Description and Modeling of the System

All parts of the hybrid system studied are shown in Fig. 1 where solar radiation flux is denoted as 1. The radiation concentrator attached to the 2-axis Sun-tracking block (not shown) is represented by Fresnel lens 2 that with the help of the plain mirror 3 creates uniform illumination of the generating stage including PV cell 4, TEG 5 and water-filled heat extractor 6 which is a part of thermosyphon circuit (its other parts are the storage tank connected with the water tubes, as seen in the figure). We denote as C the radiation concentration degree that takes into account all optical losses in the concentrating system, so that the radiation intensity on the generating stage is IC where I is solar radiation

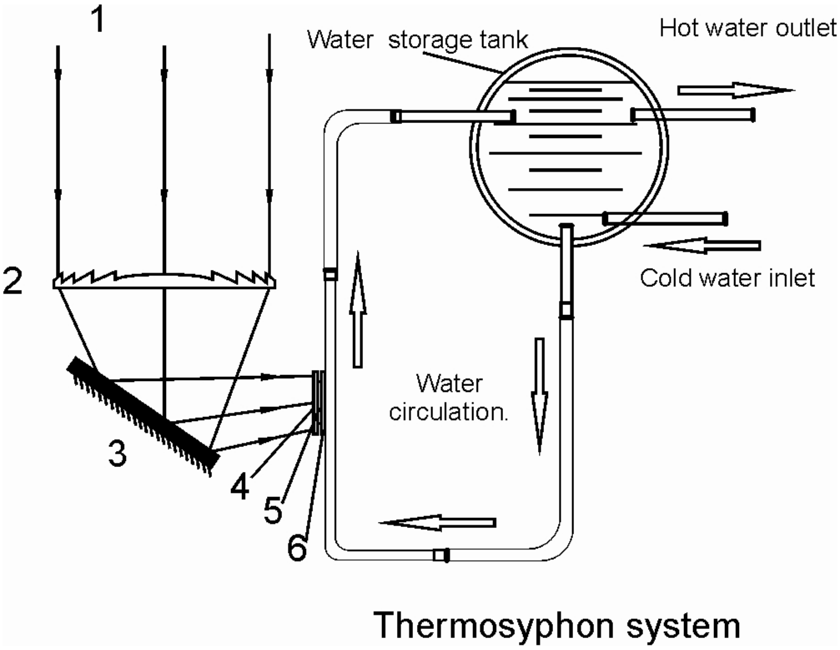

Fig. 1. Scheme of the hybrid system.

intensity at the entrance

It is known [17] that radiation concentration causes increase of the PV cell efficiency with practically linear growth of short circuit current I_{SC} and logarithmic increase of open circuit voltage V_{OC}; on the other hand, it leads to an increase of the cell's temperature that reduces V_{OC} and the efficiency. These variations are dominated by the changes of V_{OC} value; for this, in a good approximation we can use the expression (see [17])

$$V_{OC} \approx \frac{kT}{e} \ln \frac{C I_{SC}^1}{I_0} \quad (1)$$

Here k is the Boltzmann constant, e - electron's charge, I^1_{SC} - short circuit current without concentration (C = 1), I_0 – cell's saturation current having exponential dependence upon the band gap E_g and temperature T: I_0 = A exp ($-E_g/kT$), A = constant (actually, it has a weak temperature dependence that is neglected here). Having introduced the formulae for I_0 in (1), we can obtain an approximate expression for the temperature dependence of V_{OC} for relatively small variations of temperature in relation to the ambient temperature T_0 = 300 K, assuming that $T = T_0 + \Delta T = T_0\,(1+ \Delta T/T_0)$, $\Delta T << T$.

$$V_{OC} \approx \frac{kT}{e} \ln \frac{C I_{SC}^1}{A \exp(-E_g / kT)} = \frac{kT}{e} \ln \frac{C I_{SC}^1}{A \exp \dfrac{-E_g}{kT_o (1 + \Delta T / T_o)}} \quad (2)$$

Taking into account that $(1+\Delta T/T_0)^{-1} \approx (1-\Delta T/T_0)$ when $\Delta T << T$, we proceed in the following way:

$$V_{OC} \approx \frac{kT}{e} \ln \frac{C I_{SC}^1}{A \exp\left[-\dfrac{E_g}{kT_0}\left(1 - \dfrac{\Delta T}{T_0}\right)\right]} = \frac{kT}{e} \ln \frac{C I_{SC}^1}{A \exp(-E_g / kT_0)} \exp\left(-\frac{E_g}{kT_0} \cdot \frac{\Delta T}{T_0}\right) \quad (3)$$

One can see that the first part of the last logarithmic expression actually defines initial value of V_{OC} (without concentration) multiplied by C, so that we finally obtain:

$$V_{OC}(C,T) = \frac{T}{T_0}\left(V_{OC}(1,T_0) + \frac{kT_o}{e} \ln C - \frac{E_g}{e} \cdot \frac{\Delta T}{T_0} \right) \quad (4)$$

This expression clearly shows the tendencies of variation of the open circuit voltage (and the cell's efficiency) with changes of concentration degree and the cell's temperature: since the temperature increase ΔT has approximately linear dependence upon C value (see experimental data in Fig. 2), the second (positive) term in (4) increases with concentration degree in logarithmic way, whereas the third, negative term, is the linear function. Therefore, one should observe increase of V_{OC} for small concentrations when the third term is negligible, and the decrease at larger C values. The Fig. 2 shows such a dependence calculated according to (4) with the initial voltage $V_{OC}(1,T_0)$ equal to 0.52 V that corresponds to the c-Si cell used in experiments; besides, the Si band gap value

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was taken for calculations. The dependence found exactly corresponds to the predictions.

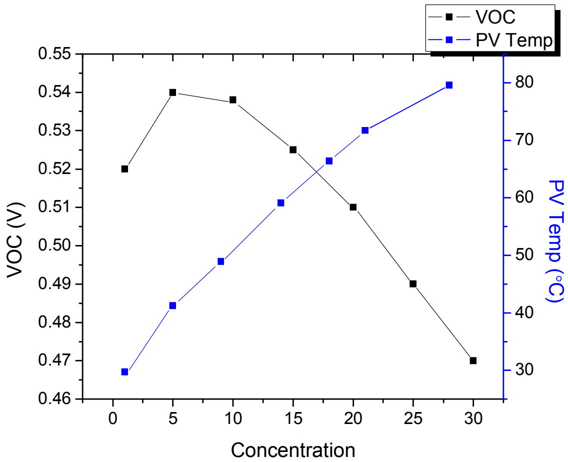

Fig. 2. Effects of concentration (see text).

Under assumptions made, the expression (4) also will give the temperature/concentration dependence of the solar cell efficiency $\eta(C,T)$, if we multiply it by $\eta_0/V_{OC}(1,T_0)$:

$$\eta(C,T)=\eta_0\frac{T}{T_0}\left(1+\frac{kT_o}{eV_{OC}(1,T_0)}\ln C-\frac{E_g}{eV_{OC}(1,T_0)}\cdot\frac{\Delta T}{T_0}\right) \quad (5)$$

Here η_0 is the cell's efficiency without concentration at ambient temperature.

The TEGs efficiency η^* (see [10, 16]) is the function of temperature difference between its plates that we take equal to ΔT, assuming a good thermal contact between PV cell and TEG's hot plate and efficient cooling of its cold plate by heat extracting system, as well as of the thermoelectric figure of merit ZT of TEG's material:

$$\eta^*=\frac{\Delta T}{T_h}\frac{\sqrt{1+ZT_M}-1}{\sqrt{1+ZT_M}+T_c/T_h} \quad (6)$$

Here T_h and T_c are the temperatures of the TEG's hot and cold plates correspondingly (thus we assume that $T_c = T_a$, and $T_h = T_a + \Delta T$), and index "M" at figure of merit means that it corresponds to the average TEG's temperature. As it was pointed out in [16], the classic thermoelectric material Bi_2Te_3 used in our experiments has the ZT value of 0.7, whereas the highest value found in the literature is 4; here we shall use both values for the discussion.

Taking into account that TEG absorbs thermal energy from PV cell that is less than the incident solar energy (part of that is reflected and another transformed into electricity), we shall write for the efficiency of TEG as a part of the hybrid system η_{TH} the following expression:

$$\eta_{TH} = \eta^*(1-R)(1-\eta) \quad (7)$$

Here R is cell's reflection coefficient, and η its electrical efficiency, so this parameter characterizes additional electrical efficiency given by the TEG; the total electric power generated by the system will be equal to the sum $\eta + \eta_{TH}$ multiplied by the incident energy. Figure 3 presents temperature dependence of the cell's efficiency calculated after (5) (curve 1) and of the η_{TH} values after (6, 7) for both values of ZT above (curve 2 for $ZT = 0.7$, and curve 3 for $ZT = 4$; value of R is taken as 0.9 assuming the antireflection coating). Curves 4 and 5 give summary system's efficiency for these 2 types of TEGs. It can be seen that in both cases the system's efficiency in certain temperature interval is higher than the efficiency of PV cell alone, thus showing the thermal stability of parameters and increase of the electric power generation.

The thermal efficiency of the system will not be much different from that of traditional PVT system.

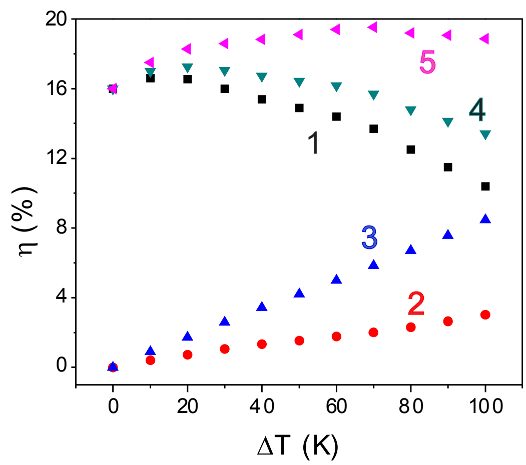

Fig. 3. Calculated electrical efficiency of hybrid system.

3 Experimental: methods, results and discussion

Experimental investigations were carried out with the model using mirror mosaic concentrator having 55 mirrors, each one of the size of the PV cell and positioned in a manner to reflect the solar light to the generating unit; varying a number of mirrors open for illumination, we can change concentration degree from 1 to 55 (see photo Fig. 4). One can see that the model has all the elements present in a scheme of Fig. 1.

The concentrator was made in our laboratory. The c-Si PV cell 8 X 8 cm^2 used in the experiments was elaborated by factory "Krasnoe Znamya" (Moscow, Russia); 4 TEGs 4 X 4 cm^2 each of the type TGM-127-1.4-2.5 were made by Kryotherm, Saint Petersburg, Russia.

Fig. 4. Photo of experimental model of the hybrid system.

To provide a good thermal contact between the elements of the energy generating stage, special thermal paste was used (for this and the other experimental details, see [16, 18]). The construction of thermosyphon heat extracting circuit was chosen after calculation of the water flux parameters corresponding to the laminar flow and efficient heat exchange between the copper rear wall of the energy generating stage and running water in the circuit; heat exchanger design was made on the basis of finite element computer simulation model in commercial software (COMSOL Multiphysics 4.2a, www.comsol.com) [18].

The characteristics of the PV cells at different concentration degrees are presented in Fig. 5. It is seen that the open circuit voltage behaves, in the first approximation, as it was predicted in section 2: it increases at initial small concentrations, and then decreases, as the temperature grows. The short circuit current increases with concentration, as expected, although not in the linear manner. We ascribe this discrepancy to our choice of the PV cell, and hope to get more linear dependence with the other cells in the nearest future.

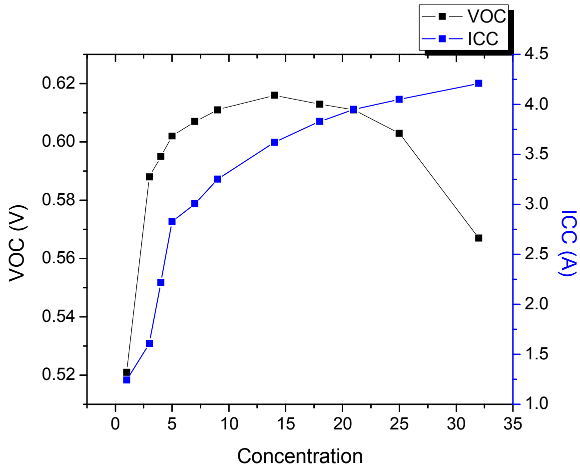

Fig. 5. Concentration dependencies of open circuit voltage V_{OC} and short circuit current I_{SC} of the PV cell.

The electric power generated by the system as a function of concentration is shown in Fig. 6. Here we see that the generation by TEGs is practically linear function of concentration (i.e. of temperature), exactly as it should be expected. Generation of the PV part of the system agrees with the data of Fig. 5, showing saturation at C from 15 to 30, thus giving a modest increase of the total electric power generated.

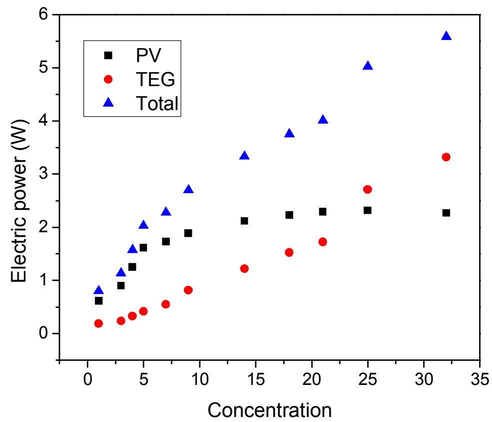

Fig. 6. Electric power generation at different concentrations.

The saturation of electric power generation in PV cell indicates that the c-Si module used in our experiment is far from ideal choice for this system; it gives expected growth of generation up to $C = 5$ that corresponds to the incident solar power of 30 W

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and the cell's efficiency of around 6% (the total system's electric efficiency at this concentration degree is 7.3%). Thus we see that our experimental model works better at small concentrations than at large ones, which is rather unusual. It is easy to show that with GaAs-type of PV cell, the results for electric efficiency will be much better, and with concentration degree of 30 - 50 it will be possible to obtain total electric efficiency of order of 20% or more (for this estimation, we use the data for GaAs solar cell treated in [10], and extrapolate the obtained TEG's efficiency to higher concentrations and temperatures; we might also note that the more efficient materials for TEG can be used).

Besides, it must be mentioned (see [16]) that the optimal use of TEGs in hybrid systems demands reasonable increase of temperature and therefore higher concentrations, so it is not practical for northern latitudes; however, in countries with high insolation (Mexico, India, China, Greece, Turkey etc.) it will be quite efficient.

The thermal power generated by the hybrid system and stored in hot water tank as function of concentration is presented in Fig. 7. The dependence is almost linear which is quite normal. The thermal efficiency defined as ratio of the generated thermal power to the incident solar radiation power is given by Fig. 8.

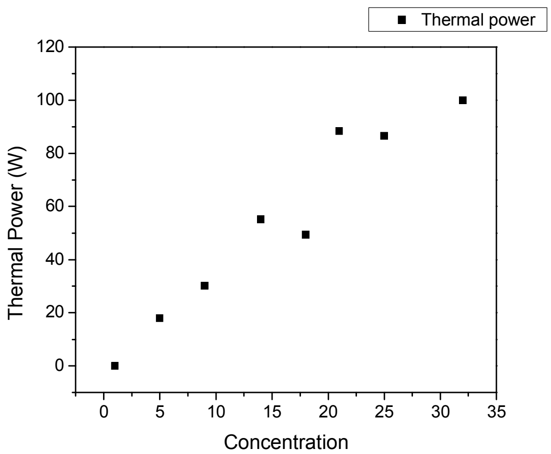

Fig. 7. Thermal power generation in the system.

It is seen (Fig. 8) that starting from concentration degree C = 5, the thermal efficiency is almost constant, staying at the level of around 45%, which is standard for the majority of PVT hybrid systems.

The relation between the thermal and electric power generated in our hybrid system model is larger than that in traditional PVT, and changes with concentration: it is 9 at C = 5, and 30 at C = 25. As it was mentioned above, this is a consequence of the behavior of c-Si PV cell at higher concentrations, and could be different for other cells.

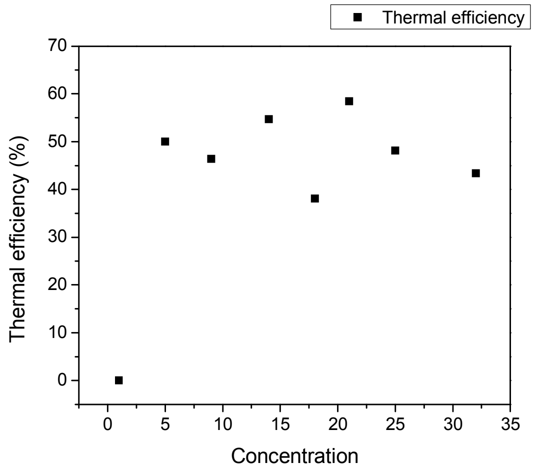

Fig. 8. Thermal efficiency of the hybrid system.

4 Conclusion

Theoretical modeling and experimental study of the solar hybrid electric/thermal system with concentrated radiation, PV cell and TEG prove that it can be a good alternative to the traditional PV/Thermal hybrid systems. With our experimental model we have shown that the system's electrical efficiency is comparable with that of traditional system, and its thermal efficiency is practically the same, with larger amount of energy generated.

The use of concentration allows employments of more expensive and efficient PV cells like GaAs or the tandem cells without essential increase in system's cost; thus the system studied can be both efficient and economic, and therefore is promising for development and applications.

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