Shallow solar pond thermoelectric generators

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Abstract

This study introduces a new type of solar power generator by combining shallow solar ponds and thermoelectric generators. First, a mathematical model is presented for the combination using the modified version of the Hottel-Whiller-bliss equation. Then an analytical case study is also represented by solving the proper ODE. Results show a reasonable amount of power production and some interesting findings. This study used three different water bag heights of 4cm, 2cm, and 1cm. Results indicate growth in power production as a decrease happens in the water bag heights. Then the daily power production for one through one thousand parallel moduli was graphed. Total daily power production for one modulus generator was found to be about 0.1854 (Wh), 0.6070 (Wh), and 1.673 (Wh) for 4cm, 2cm, and 1cm, respectively.

Keywords: *Shallow solar pond – Thermoelectric generators – Flat plate solar collector – solar energy – Renewable energies*

1 Introduction

The sun is Earth's primary source of life and energy. We use energy primarily to power machines. The majority of energy in developed countries is used to power machines such as cars, planes, and computers. We require energy to run machines and produce food for a growing population. Because our current energy supply is insufficient to meet our needs, we must turn to alternative energy sources. Solar energy is one of the best alternatives. Photons are packets of energy that travel from the sun. Photons are energy carriers that travel at the speed of light. Photons travel in all directions through space. Sun photons also strike the Earth's surface. Flat plate collectors are a type of solar thermal collector that collects heat from the sun to heat a substance that can then be used in various applications, such as power generation.

Thermoelectric generators (TEGs) can directly transform thermal energy into electrical current through the use of the thermoelectric effect. They can also improve overall system efficiency in places where waste heat is readily available, such as cars. Thermoelectric generators have numerous uses, including those in the energy and cooling industries. The most common application is power generation in areas with limited access to grid electricity and a reliable heat source. Inefficient energy conversion is a significant problem for thermoelectric generators. The effectiveness is determined by the temperature gradient between the two sides of the TEG and the characteristics of the materials used. They function best when there is a sizable temperature gap between the two sides of the device. Thomas Johann Seebeck first identified the thermoelectric effect in 1821. It was found that a voltage difference was generated at the junction between two dissimilar metals when a temperature difference was applied across the joint. The Seebeck effect occurs when a thermoelectric device is subjected to a temperature gradient, resulting in an electric field's generation. The motion of charge carriers produces this electric field. In an electric field, charge carriers will flow from the warm side of the device to the cooler side. By raising the temperature of a conductor, the charge carriers within it can be "excited" to a higher energy level. When a conductor cools, the charge carriers revert to their initial energy state. Different charge carrier energies result from a temperature gradient across a joint between two conductors with different Seebeck coefficients. This results in a transfer of charge carriers from the conductor with the higher Seebeck coefficient to the conductor with the lower Seebeck coefficient. As a result, charge carriers will move from the warm side of the device to the cold side. An electric field is produced across the device by the net movement of charge carriers. Charge carriers are pushed from the device's warm to the cold side by the electric field. The electric field is no longer available when the energy gap between the charge carriers is equalized. Material types N and P are used to construct thermoelectric generators. The Seebeck coefficient is negative in N-type materials. Substances with a positive Seebeck coefficient are classified as P-type.

A shallow solar pond (SSP) is a non-convective pond that uses a thin layer of water—even as thin as 4 cm—and a transparent cover to retain heat rather than release it into the atmosphere. The translucent cover is constructed from polymer, plastic, or glass. The pond's bottom has been painted black to absorb the sunlight better. The SSP can be built in small packs of water bags, giving the idea of the benefits of the light travel weight and more flexible placement without incurring the cost of constructing a conventional solar pond. A shallow solar pond thermoelectric generator, or SSPTEG for short, is a system in which a small solar pond serves as the primary heat source for the thermoelectric generators. The water bag, which serves as the primary heat source for the thermal electric generators, warms up when solar radiation strikes the shallow solar pond. By establishing a controllable heat barrier between the water bag and the thermoelectric generator, this combination enables us to store solar energy for longer and use it when needed. In order to analyze the performance of a parallel thermoelectric generator, Liang et al.[1] developed an analytical model. The potential and various varieties of shallow solar ponds have been reviewed by Garg et al. [2]. Struckmann in [3] did the mathematical modeling of the flat plate solar collector. Regarding large-scale installations, A. I. Kudish and D. Wolf in [4] covered the idea of shallow solar ponds in great detail. An experimentally verified mathematical model of Tehran's shallow solar pond was presented by H. M. Ali and M. Akhlaghi [5]. The thermal performance of a shallow solar pond in the batch mode of heat extraction was examined by S. Aboul-Enein et al. in [6]. In shallow solar ponds, Sharma et al. [7] have established a relationship between the temperature rise of the water and the amount of solar radiation available on the horizontal surface, depth, and top area of the pond. Sodha et al. [8] developed a theoretical analysis of shallow solar ponds. In order to extract heat, El-Sebaii et al. [9] looked into the thermal performance of a shallow solar pond (SSP) in an open cycle continuous flow heating mode. A parametrical analysis of the design and functionality of a solar heat pipe thermoelectric generator unit was carried out by Wei He et al. [10]. Meng et al. [11] .'s investigation looked at how the performance of a thermoelectric heat pump powered by a thermoelectric generator device was impacted by the physical dimensions of the thermocouples. In [12], Daniel Champier reviewed thermoelectric generator applications.

2 Working mechanism of the SSPTEGs

Fig.1 shows the schematic of SSPTEG introduced in this paper.

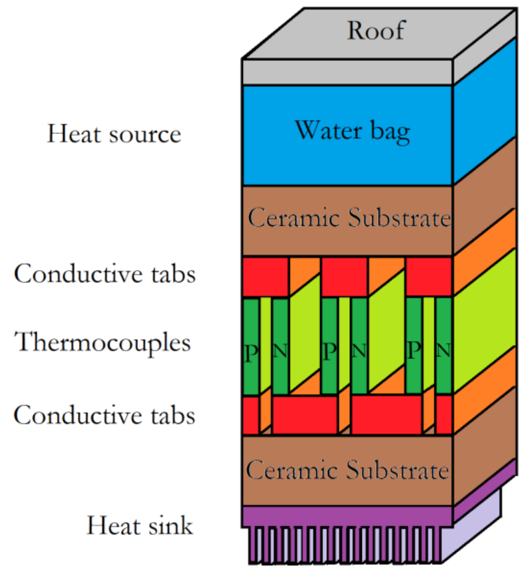

Figure 1: Schematic of SSPTEG

Under the shallow solar pond, the blackened surface of the modulus absorbs solar irradiance, heating the water bag, which will later be used as the thermoelectric generator's main heat source and produce power using the method described in [1]. Furthermore, by placing each modulus in a circuit in parallel, we can add up the output power. Regardless of whether the structure is static or dynamic, this setup can produce electricity on any surface exposed to solar radiation daily. This placement can be applied to vehicles like cars, spacecraft, and houses for industrial or commercial use.

3 Mathematical modeling of the SSPTEGs

3.1 Heat transfer of the SSPTEGs

We can use a modified version of the Hottel-Whiller-Bliss model of the flat plate collector to model the system [2] mathematically. That Fourier's law of heat transfer is used to model the flat plate collector's bottom heat loss coefficient for a variety of materials. In contrast, the flat plate collector's total heat loss coefficient only applies to the sides and top of the system. Assume that the inherent and external parameters of each SSPTEG's modulus are the same and that the top convection between the water bag and the trapped air is minimal.

In that case, the modified Hottel-Whiller-Bliss model can be expressed as:

$$Q_u = \left[(\bar{\tau}\alpha)I_{(t)} - U\left(T_{w(t)} - T_a\right)\right] - Q_{TE} \quad (1)$$

$$Q_{TE} = k_{hot\ \ side} + k_{cold\ \ side} \quad (2)$$

$$\frac{1}{k_{hot\ \ side}} = \frac{1}{k_{CS}} + \frac{1}{k_{CT}} + R_{HSO\to CS} + R_{CT\to TC} + R_{CS\to CT} \quad (3)$$

$$\frac{1}{k_{cold\ \ side}} = \frac{1}{k_{CS}} + \frac{1}{k_{CT}} + R_{HSI} + R_{CS\to HSI} + R_{CT\to CS} + R_{CT\to TC} \quad (4)$$

$$\bar{\tau}\alpha = 1.01\tau\alpha \quad (5)$$

Where Q_u is the useful energy gain of the shallow solar pond system (W/m^2), Q_{TE} is the downflow of the energy to the thermoelectric generator system (W/m^2), τ is the transmissivity of the shallow solar pond, α is the absorptivity, U is the overall heat loss of the shallow solar pond (W/m^2K), $I_{(t)}$ is solar radiation at any time (W/m^2) and $T_{w(t)}$ is the temperature of the water bag at any time, T_a is the ambient temperature. And $k\_\{CS\}$ $k\_\{CT\}$ are the thermal conductivity (W/K) of the ceramic substance and the conductive tabs, respectively. And R represents the thermal resistance (K/W), and subscripts 'HSO,' 'CS,' 'CT,' 'TC,' and 'HSI' refer to the heat source, a ceramic substrate, conductive tabs, thermocouples, and heat sink respectively. Assuming that the heat sink would bring its temperature of itself to the ambient temperature, we can write the equation as follows:

$$Q_u = \left[(\bar{\tau}\alpha)I_{(t)} - \left(U + \frac{1}{A}(k_{hot\ \ side} + k_{cold\ \ side})\right)\left(T_{w(t)} - T_a\right)\right] \quad (6)$$

Where A is the area of the water bag (m^2). On the other hand, we have the following:

$$Q_u = \frac{m.C_p}{A}\frac{\mathrm{d}T_w}{\mathrm{d}t} \quad (7)$$

Where m refers to mass (Kg), and C_p refers to the specific heat capacity ($J/Kg.K$). The main parameter of concern is the height of the shallow solar pond, so we can rewrite the equation as follows:

$$m = \rho V \quad (8)$$

$$V = A \times h_w \quad (9)$$

Where the ρ is the density (Kg/m^3) and h_w is the hight of the water bag. Then the main differential equation can be written as:

$$\frac{\mathrm{d}T_w}{\mathrm{d}t} = \frac{(1.01\tau\alpha)I_{(t)} - \left(U + \frac{1}{A}(k_{hot\ \ side} + k_{cold\ \ side})\right)\left(T_{w(t)} - T_a\right)}{\rho.h_{SSP}.C_p} \quad (10)$$

By solving this differential equation, we can reach the $T_{w(t)}$ At any desired moment.

3.2 Power generation of the SSPTEGs

In a study by Liang et al. [1], the parallel systems of TEGs were investigated. Assuming the shot side of the TEG modulus has the water bag temperature and the cold side of the TEG modulus have the ambient temperature, the power generated by "n" number of TEGs can be calculated using the equation below [1]:

$$P = [\frac{nm\alpha_s\left(T_{w(t)} - \mathrm{T_a}\right)}{r + r_L}]^2 \times r_L \quad (11)$$

Where m is the number of thermocouples in the modulus, α_s being the Seebeck coefficient, r and r_L being the internal resistance of all thermocouples (Ω) and load resistance (Ω), respectively.

4 Case study

The ODE is solved using the input data given in Tab.1 and Tab.2 and solar radiation and hourly temperature of the hottest day in Boushehr. The TEG modulus surface of the SSPTEG is assumed to be $5cm \times 5cm$ with a height of $2cm$. The hourly temperature and solar radiation for the hottest day of the year (July 21_{st}) is given in Fig.2.

Table 1. The inherent parameters of SSP for each modulus

inherent parameters of SSP				
τ	α	ρ	C_p	$U + \frac{1}{A} \times (k_{hotside} + k_{coldside})$
0.88	0.94	$1\,\frac{Kg}{m^3}$	$4200\,\frac{J}{Kg}$	$4\,\frac{w}{m^2K}$

Table 2. The inherent parameters of TEG modulus

inherent parameters of TEG			
m	α_s	r	r_L
126	0.000375	3 Ω	0.1 Ω

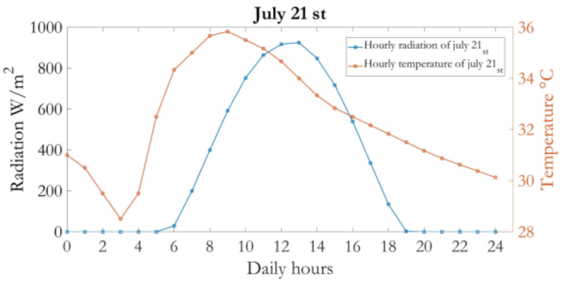

Figure 1: Solar radiation and ambient temperature of Boushehr on July 21

By solving the ODE equation using the given data the hourly temperature of one of the water bags is given in Fig.3. It shows that the highest temperature of the water bag is achieved at the peak of the solar radiation and the temperature of the water bag is near the temperature of the ambient air when the solar radiation is not available.

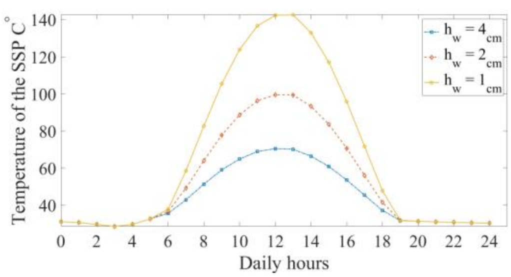

Figure 3: water bag hourly temperature for different water bag hights

Now the power production of one modulus with three different water bag heights is given in Fig.4. As shown in Fig.4, the SSPTEG modulus would only produce power in the presence of a temperature difference between the water bag and ambient air, which concluded that it would only happen when solar radiation is present.

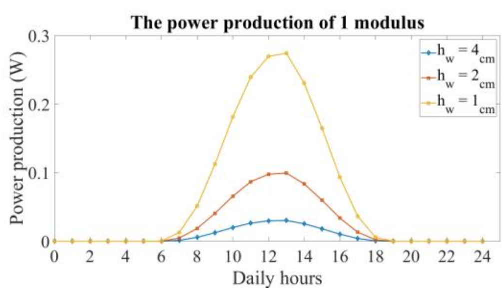

Figure 4: power production of one modulus with three different water bag heights

The power production for 100 and 1000 modulus are given in Fig.5 and Fig.6, respectively. As apparent from the two figures, the number of moduli has increased by a power of ten, yet the maximum power production has not raised as much.

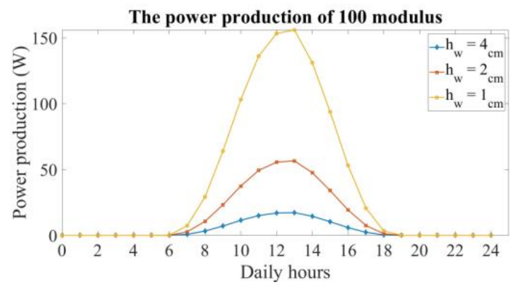

Figure 5: power production of one hundred moduli with three different water bag heights

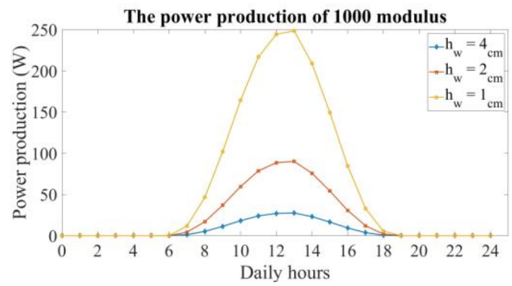

Figure 6: power production of one thousand moduli with three different water bag heights

The total daily power production (Wh) to the number of modulus for different water bag's height is given in Fig.7. And as was predicted from Fig.5 and Fig.6, the rise in the power production does not have a linear relation with the rise of the number of moduli. Moreover, as shown in Fig.7, the number of modulus and power production would have logarithmic relation.

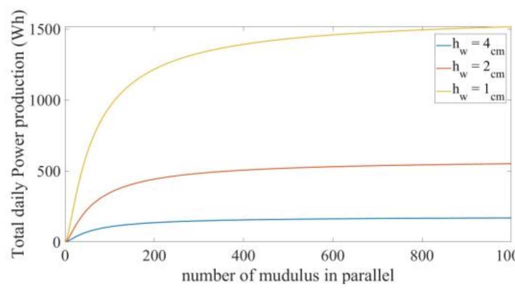

Figure 7: total daily power production (Wh) with respect to the number of moduli

The main findings from the case study can be written as two main points. First, the power production of the SSPTEGs is restricted by the sun, meaning there would be no power when solar radiation is unavailable, and the peak of power production is reached when the solar radiation is at its highest. Second, the total daily power production vs. the number of moduli have a logarithmic relationship meaning that adding more moduli opposite common sense would not linearly increase the power production. Knowing that an optimum point can be assigned for the modulus that can be in a parallel arrangement with each other.

6 Conclusion

This study looked into the possibility of developing a new kind of flat plate solar power generator by fusing a shallow solar pond with a thermoelectric generator. The SSPTEGs were mathematically modelled using the modified Hottel-Whiller-Bliss model. The SSPTEG modulus circuit for power generation was then combined in parallel. The case study result showed that by lowering the shallow solar pond height, the combination could generate a more perceptible amount of energy. The results also showed a logarithmic relationship between the rise in total daily power production and the quantity of parallel modulus. As a result, an optimal number of moduli in the parallel arrangement can be determined, which is extremely fascinating given that logic would suggest that power production would increase linearly. We can be very optimistic about the findings of the case study, but more research is required to fully explore the potential of these kinds of power generators.

7 References

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