

THE OPTIMAL FLAT PANEL SOLAR THERMOELECTRIC GEOMETRIES FOR HEAT AND ELECTRIC POWER PRODUCTION

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Abstract

A calculation technique provides direct calculation of the heat and electric power of flat panel solar thermoelectric system is established, this was in order to determine the optimum system size optimization for combined water heating and electricity generation. The system size optimization is trade-off between the thermoelement length, cross-section area and the solar absorber size. The technique is developed under the conditions of given solar irradiation, the thermoelectric (TEG) cold side temperature, cross-section area and number of thermoelements. The calculation technique is verified by experimental setup, which comprises of uncovered flat black painted solar absorber, a heat sink partly submerged on water system and TEG device which was sandwiched in between, 5 commercial TEG devices of different sizes were examined, the steady state TEG open circle voltage and temperatures were measured to evaluate the electric and thermal power experimentally. The data obtained through the calculation technique was validated against the experimental data. The results show that there is an optimum size of the system, decreasing or increasing the size further wouldn't achieve the optimum performance. The established calculation technique provide the designer (manufacturer) and users with good indication of what TEG size they should use, thus saving the user's time of examining different TEGs with different aspect ratios (sizes) and saving manufacturing cost by using less material.

Keywords: Combined Heat and Power, Solar Hot Water, Thermoelectric Generator, Seebeck effect, Conduction heat transfer, Aspect ratio

Nomenclature

- Q_{abs} The amount of heat absorbed by the solar absorber [Watt].
 Q_{Lost} The amount of heat emitted from the absorber to the surrounding [Watt].
 Q_{rad} The amount of heat emitted by radiation from the absorber [Watt].
 Q_{con} The amount of heat emitted by convection from the absorber [Watt].
 Q_{TEG} The amount of heat transferred through the thermoelectric generator [Watt]

C_p	Copper specific heat [$J.Kg^{-1}.K^{-1}$]
A_c	The absorber area [m^2].
σ	Steven and Boltzmann, Constant [$W.m^{-2}.K^4$]
ϵ	Absorber emissivity
T_h	Absorber and TEG temperature
T_c	Cold side temperature of TEG
T_a	Ambient temperature [room temperature]
h	Convection coefficient
TEG	Thermoelectric generator
A_{TEG}	TEG area [m^2]
L	Thermoelement length [m]
K	Thermal conductivity of TEG material[$Wm^{-2}.K^{-1}$]
N	Number of the thermo element in TEG
α	Seebeck coefficient
ρ	Electrical resistivity of the TEG material
l_c	Length of contacts layers [1mm]
r	Resistivity ratio
n	Conductivity ratio
R	The TEG internal resistance value
V	The voltage drops cross TEG

Introduction

Combined heat and power (CHP) is to generate heat and electric power from one system. CHP systems offer significant contribution to pollutant emissions reduction in addition to energy saving and high performances compared with the system in separate production (Ferreira et al., 2012). Recently, interest in CHP production based on solar system, especially for domestic application, has been expanded (Pearce, 2009). Generally, there are two different approaches for generating hot water and electricity based on roof top solar system; to benefit from photoelectric or Seebeck effect, by adding photovoltaic cell (PV) or Thermoelectric Generator (TEG) to solar hot water system, called either Solar Photovoltaic/Thermal (PV/T) or Solar thermoelectric (STEG).

Although CHP systems based on STEG technology are not widely commercialised, PV/T system is available (Herrando et al., 2014). Despite the fact that PV/T system has some advantages such as increasing the overall system efficiency, where the heat wasted from PV cells can be used to heat the water (Pearce, 2009), it also has few disadvantages. The key issue with this system is that it only works during day light (under appearance of the sun only) and the operation temperature needs to be kept at lower than 50°C. This due to the fact that the efficiency of PV cells decreases with increasing temperature (Mahtani et al., 2007). Such limitation may affect the hot water to reach the hygienic temperature (Watts, 2000), and consequently, a deployment photovoltaic in hot climate countries can tremendously decrease the system efficiency. While the later disadvantage is one of the advantages

of the solar thermoelectric (STEG) system, as the higher temperature is the better TEG performance, which indicate that it preforms even better in country with hot climate, even more, STEG system benefits of simple constructed, easy to control, easy to replace, high reliability, less maintenance, longer life operation, and the main advantage it does not depend on sunlight. Furthermore, the efficiency has the potential to be improved dramatically by using more efficient TEG material (Fleurial, 1999). Recent publications show that the electric conversion efficiency of STEG system increased to up to 5% instead of 2% previously recorded (Arturo et al., 2013; Kramer et al., 2011). The objective of this study is to investigate the optimal STEG size optimization based on flat panel system to achieve the maximum heat and electric power output.

Experiment system description

A module representing small scale solar thermoelectric system based on flat panel has been designed and constructed as shown in Fig. 1, aiming to evaluate the heat and electric power generated by the system, this by measuring the system temperatures (T_h , T_c and T_w) as well as the TEG voltage output at open circuit condition. The system consists of halogen lamp as solar source, a copper plate as solar absorber, heat exchanger immersed in water container, and TEG sandwiched between the heat absorber and the heat exchanger. The solar absorber measuring 0.13m x 0.13m x 0.001 m, was painted black at the top surface, high temperature black matt paint (pnm type) was used. A channel was machined on the back side of the absorber to accommodate a k-type thermocouple for measuring the temperature of the absorber, which also the hot side of the TEG (T_h). Another thermocouple is placed on a groove on the top of the aluminium heat exchanger in order to measure the TEG cold side temperature (T_c). The heat exchanger is submerged into 450 ml of water in plastic container, magnetic stirrer was used to improve the water heat transfer, and the temperature of the water (T_w) was measured by another thermocouple placed into the water. Due to the stability of the light radiation of the incident on the absorber, a halogen lamp with light intensity of 1.7 kw/m² was employed, since that halogen provides better approximation to the solar spectrum than their tungsten counterparts (Riffat and Mayere, 2012). The halogen lamp is placed 7.5 cm above the surface of the solar absorber.

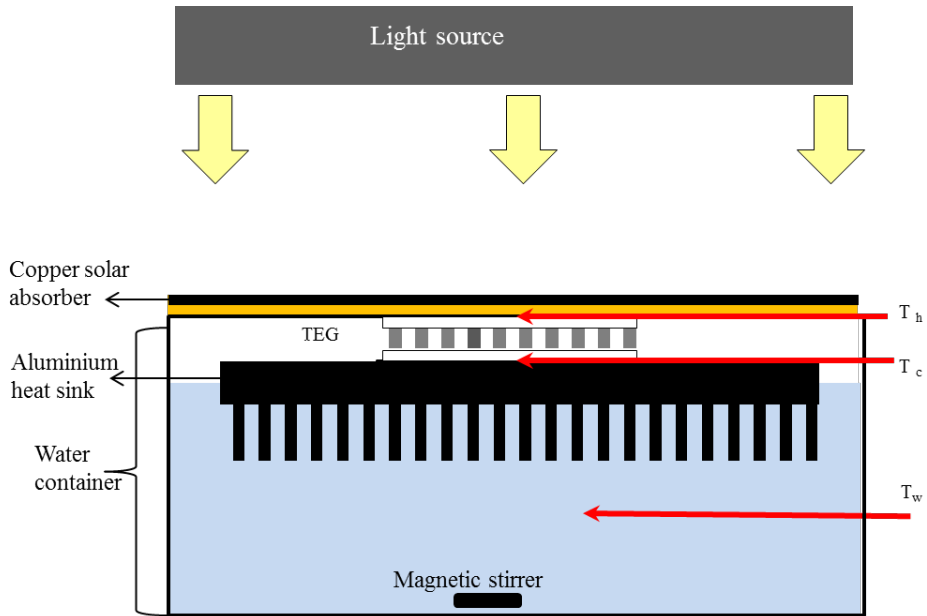


Figure. 1. System design and construction

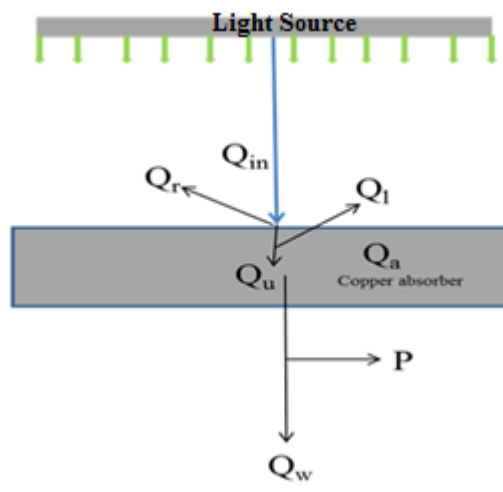


Figure. 1. Schematic diagram of the energy flow of the system shown in Fig. 1.

Five commercial TEG with different geometries and sizes (Table 1) were studied.

Table1:The TEG modules geometries

Sample ID	N	A (m ²)	L (m)	Module Size (Ax2N)/L (m)	R (Ω)
Sample 1	72	1.6x10 ⁻⁶	1.7x10 ⁻³	0.136	1.8
Sample 2	127	1x10 ⁻⁶	1.5x10 ⁻³	0.169	6.5
Sample 3	127	2x10 ⁻⁶	1.7x10 ⁻³	0.299	3.5
Sample 4	127	7.6x10 ⁻⁶	3.6x10 ⁻³	0.536	1.6
Sample 5	48	1.7x10 ⁻⁵	2.4x10 ⁻³	0.680	0.2

Mathematical analysis

As shown in Fig. 1 and 2, when the system expose to the radiation of the light source (Q_{in}), some of this radiation is reflected back from the top surface of the absorber (Q_r), and the remaining is received and converted into heat by the absorber (Q_a),

$$Q_{in} = Q_r + Q_l \quad (1)$$

The TEG is operated by the heat flow by Q_a , and when the proposed system reaches the heat equilibrium condition, Q_a is equal to its heat lost from the absorber (Q_l) in addition to the heat transferred through the TEG(Q_{TEG}):

$$Q_a = Q_l + Q_{TEG} \quad (2)$$

Q_l is mainly due to the convection (Q_{conv}) and radiation (Q_{rad}) effects, and therefore the total heat lost can be considered as:

$$Q_l = [h A_c (T_h - T_a)] + [\varepsilon \sigma A_c (T_h^4 - T_a^4)] \quad (3)$$

Where T_h is the measured absorber temperature, A_c is the measured absorber area, and T_a is the room temperature. While Stefan Boltzmann constant (σ), the convection coefficient (h) and the absorber's emissivity (ε) were obtained from the literature (Fan and Akbarzadeh 2011; Nellis and Klein 2008). The amount of heat lost from the absorber was obtained through equation 3. The system thermal power can be obtained by finding Q_{TEG} , by assuming that there is no heat lost, and all heat transferred though TEG (Q_{TEG}) is totally absorbed by water (Q_w), by other mean $Q_w \approx Q_{TEG}$.

Heat transferred through the TEG is mainly due to the conduction effect, and then the heat power production of the system can be determined by using Fourier law:

$$Q_{TEG} = \frac{KA_{TEG}(T_h - T_c)}{L} \quad (4)$$

Then heat transfer formula through the system at the steady state will be the combination between equation 2, 3 and 4, as follows:

$$Q_{abs} = h A_c (T_h - T_a) + \varepsilon \sigma A_c (T_h^4 - T_a^4) + \frac{KA_{TEG}(T_h - T_c)}{L} \quad (5)$$

Theoretically, to determine the best TEG geometry, where the optimum heat and electric power output can be obtained, different TEG length values investigated, based on equation 5, and at condition where the value of Q_{abs} and A_{TEG} are given as constant, each length value given will have its corresponded ΔT . As TEG ΔT is established for every given TEG length, the electric power can be calculated by using the following equation (Min, 2010):

$$P = \frac{N\alpha^2 A \Delta T^2}{2\rho(n+L)\left(1 + \frac{2rLc}{L}\right)^2} \quad (6)$$

All the parameters and values used in equation 6, excluding N , A , L and ΔT are obtained from the literature (Min, 2010). The α is the TEG material seebeck coefficient with a value of $=200\mu V/k$, ρ is the electrical resistivity with a value of $1 \times 10^{-5}(\Omega.m)$, Lc is the length of the TEG contacts layers with a value of $1mm$, r is the electrical resistivity ratio with a value of 0.2 , n is the thermal conductivity ratio with a value of $0.1mm$, and N represents the TEG thermo element numbers.

The results of the temperature difference and the electric power obtained by theory were compared with the measured results obtained by experiments using the same system conditions (geometries), in order to validate the theatrical technique. In order to measure the maximum electrical power, the open circuit voltage and the TEG internal resistance were measured, and the electric power was determined by the following equation which obtained from the literature (Min, 2010):

$$P = \frac{V^2}{4R} \quad (7)$$

Results and discussion

The heat and electric power of the system is largely reliant on the TEG ΔT , and its sizes (geometries). The approach of the proposed technique is to estimate the TEG ΔT at different sizes, under the condition that the input heat remains constant for all sizes (equation 5). The ΔT of 5 flat panel solar TEG systems, with different sizes, have been experimentally measured and theoretically calculated in order to obtain the measured and the calculated

heat and power for each system. The results of TEG ΔT as function of the module size in both methods at the steady state condition are compared, and shown in Fig. 3.

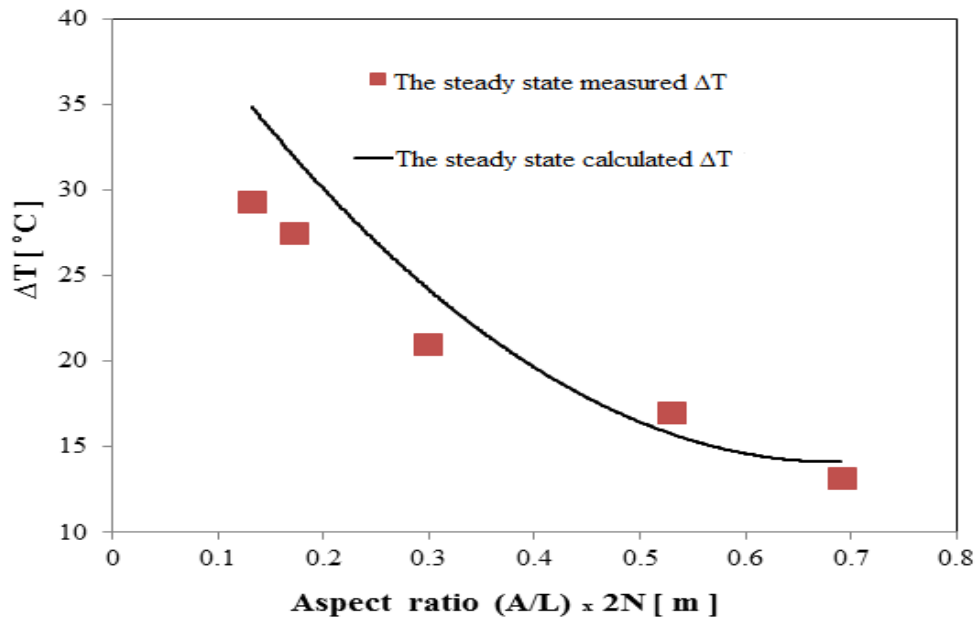


Figure. 3. Comparing the ΔT experimentally and thematically obtained by the developed technique.

Comparing the ΔT gained by the different approaches shows a good agreement. The maximum deviation between the two methods was around 16%, occurring at the system with the smallest size (module with size of 0.132). These results indicate that the calculation technique to predict ΔT is effective; consequently, the results are applied to calculate the heat and electric power. The results of the measured and calculated heat and electrical power were also compared to each other, and both results as function of the module size are shown in fig 4 and 5.

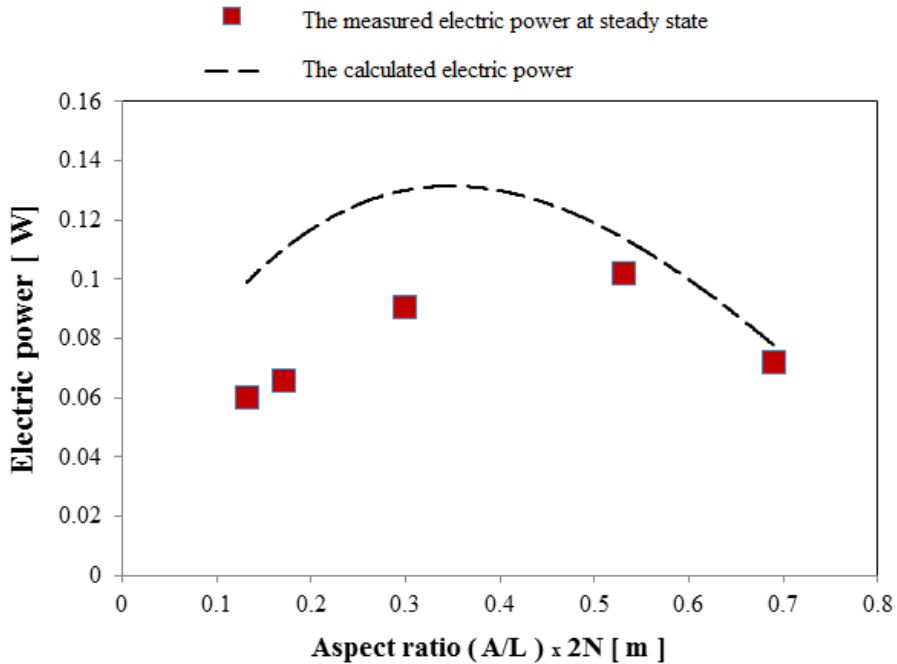


Figure 4. The measured and calculated results of the electric power as function of the TEG aspect ratio.

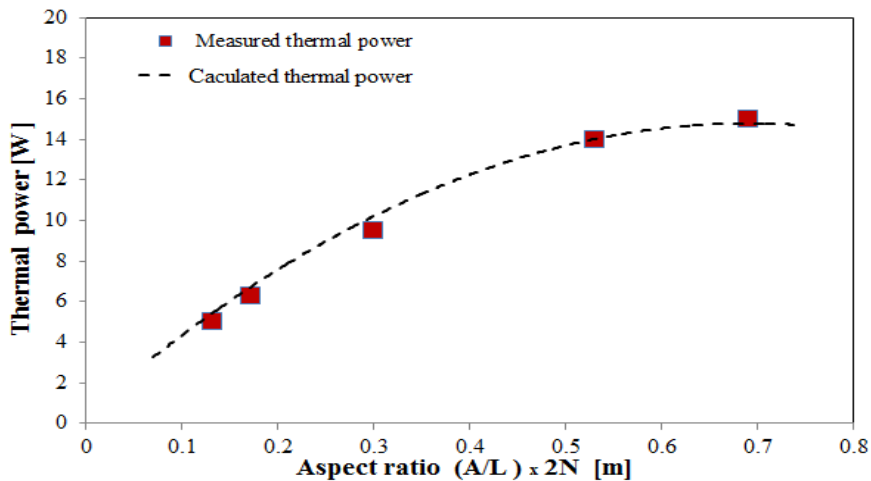


Figure 5. The measured and the calculated results of the heat power as function of the aspect ratio.

Comparison between the results gathered by experiment and by calculation based on the calculated ΔT was carried out. The results of both methods on heat power based on the steady state (Q_{TEG}) shows variation of less than 10%, while maximum variation between the results of the electric power in the two methods was around 20 %, which recorded at the smaller module

size. Fig. 4 and 5 show that the optimal heat and electric power value resulted by calculation and the measured are matched, module with geometries (size) of 0.53 achieved the best results among the remaining geometries investigated, indicating that there is a certain geometries where the maximum heat and electric power could be obtained. These findings agreed with previous studies, which concluded that the optimal power can be achieved when the right TEG geometry is applied (Rowe and Min, 1996; Omer and Infield, 1997). It is evident from the Fourier law that the TEG size and ΔT have significant effect on heat production. In principle, an increase of the TEG length will decrease the heat flow and electric power output for a given temperature difference cross TEG and its area. Previous studies have shown that an increase in the TEG length will increase the electric power output to reach its maximum at certain length value, and then the electric power output starts to decrease when increasing the length further for given TEG ΔT and area (Rowe and Min, 1996; Omer and Infield, 1997; He et al., 2011; Du et al., 2011). In fact by increasing the TEG length, ΔT will not be constant when the input heat and TEG area considerable unchanged (Equation 5), and therefore, ΔT has to be estimated based on TEG size change.

Conclusion

Calculation procedure verified by experiments to find out the optimal STEG size optimization, which generate the best value of heat and electric power, has been presented. The calculation technique was verified by comparing the estimated results to the measured results which obtained by experimental procedure, which examine 5 different commercial TEG sizes and both results shows good agreement. The established technique calculating the electric and heat power as function of TEG geometries ($\frac{A}{L}$) at its corresponded ΔT . The ΔT is changed along with the TEG size change, the estimated ΔT is compared to the measured ΔT at same condition and it shows good agreement. Consequently, the heat and electric power between calculated and measured methods are compared too and results shows good agreement.

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