THE STUDY OF THE THERMOELECTRIC GENERATOR DEPENDING ON THE LIGHTING LEVELS

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Abstract: *Whereas in the 20th century, scientists were concerned with the production of energy in huge quantities, regardless of the consequences, their interest later switched to the production of green energy from renewable sources. Nowadays, the interest has been directed towards increasing the efficiency of existent energy systems and finding other energy sources. A way to achieve these is to harvest energy from sources that generate small amounts of energy, but sufficient to power low-power devices, as well as to valorize residual energy (especially heat) that would otherwise be dissipated and lost. Since thermoelectric generators convert heat into electrical energy based on the Seebeck effect, this paper analyzes the important parameters of the TEC1-12706 thermoelectric generator, such as short circuit current, open circuit voltage, maximum power, and internal resistance in laboratory and natural conditions in function of different levels of irradiance. The performance of the thermoelectric generator is lower in real condition than under artificial light.*

Keywords: *thermoelectric generator (TEG), irradiance, comparison*

1. INTRODUCTION

Energy harvesting by thermoelectric generators plays an important role in environmental protection as a result of the possibility to recover the waste energy from automotive, furnaces, and photovoltaic panels. Moreover, by using the energy generated by them, the lifetime of the batteries used for powering the sensors, control the circuits, devices for data communications, and wearable technologies can be prolonged [1]. In this case, fewer batteries will have to be recycled. Two thirds of the energy produced by automotive is wasted in the environment [2], the photovoltaic panels convert between 10 and 24% in electric energy and the rest is the loss in thermal energy [3]. The thermoelectric generators can convert a part of this into electric energy and the quantity can be huge [2].

Bi_2Te_3 is the most widely used thermoelectric generator. It works at a low temperature and is the best for applications where the hot side temperature reaches a maximum of 250-300^{o}C. In case of applications where the hot side can reach a higher temperature $CoSb_3$-based skutterudite product by Shanghai Institute of Ceramics can be used [1], or PbTe, Tegma skutterudite [4], TEG-HH-8 from Evident Thermolectrics company [5]. For all, the values of the temperature of the hot side must be kept under 600^{o}C.

The thermoelectric generators based on oxide can be used for temperatures higher than 800^{o}C on the hot side. The representative modules are those from Calcium/Manganese oxide and Silicon/ Germanium. Cascade thermoelectric modules, such as Calcium/Manganese oxides, Bi2Te3 and BiTe–PbTe can be used to increase the performance and aria of application.

In security, military and chemical applications, especially for systems that work in severe conditions and generate a lot of heat that is dissipated, self-powering is a very good opportunity and this can be assured by the thermoelectric generators [2]. Because the thermoelectric generator harvests the waste heat and converts it into electricity, it can be used successfully due to its advantages to power the low power sensors, the smart network sensors and others.

For applications such as monitoring, following, and controlling, which use smart sensors or intelligent sensor networks, it is important to have power sources that have almost the same lifetime. Some devices which use thermoelectric generators as power supplies have been developed. Micropelt developed some systems to monitor the temperature and others to control electro-valves from a distance [6]. The systems have a Micropelt MPG-D751 thermoelectric generator module as power supply. This module can generate 1mW maximum power and 1V open circuit voltage if the temperature difference is 10^{o}C and a maximum power of 10mW and 3.7V open circuit voltage if the temperature difference is 30^{o}C [1].

The performance of the thermoelectric generators is studied in different conditions. Cotfas et al. studied the operation of Bi2Te3 thermoelectric module considering the difference of temperature between the hot side and cold side and also the effect of this on the Seebek coefficient [7]. The maximum power generated varies parabolically with the temperature difference between the hot and cold side of the thermoelectric generator. Also, a linear dependence between the open circuit voltage, V_{oc}, and the temperature difference was found. The efficiency of the Bi_2Te_3 thermoelectric module is low [7]. Cotfas et al. studied the response of thermoelectric generators to Bi2Te3 and Zn4Sb3 under different levels of solar radiation and dimensions, as well as the influence on the maximum power of adding a graphite layer on the hot side of the solar thermoelectric generator STEG (solar thermoelectric generator) [9]. The result shows that by adding a graphite layer on the thermoelectric generator, the power generated and the efficiency of the STEG increase significantly, around 2.5 times. In the case of a higher solar concentration ratio, STEG by Bi_2Te_3 had lower performances than $Zn_4Sb_{3,}$ but the figure of merit of the STEG by the Bi_2Te_3 is higher; also, the power performance of both STEGs is improved if the length of the semiconductors is increased [9].

In order to increase the performance of thermoelectric generators, scientists have studied the effects of doping on the thermoelectric properties of Bi_2Te_3 with different materials such as $Se_{0.3,}$ Sb [12], Sr [13] or Cu [14].

There are also some studies that investigated the position of TEG in a thermoelectric module (TEM) in order to offer every TEG the possibility of having almost the same temperature gradient and to minimize mismatch power loss. [10][11]

The contributions of this paper are:

- Comparison of the TEC1-12706 thermoelectric generator performance in laboratory and natural conditions in function of different levels of irradiance.
- Analysing the important parameters of the thermoelectric generator, such as short circuit current, open circuit voltage, maximum power, internal resistance and efficiency

The paper is structured as follows: the thermoelectric generator model is presented in the second section, the experimental setup is described in the third, the results in the fourth one, and the conclusions and the future work are presented in section five.

2. THE THERMOELECTRIC GENERATOR MODEL

The thermoelectric generator is composed from a number *n* of thermoelectric elements, which are connected electrically in series and thermally in parallel [7].

The thermoelectric element contains of a pair of P and N type thermoelements, also known as legs. These are positioned between two ceramic plates manufactured from Al_2O_3. The Seebeck coefficient is negative for the N leg, whereas for the P leg it is positive. The legs are interconnected using a thin copper plate. The load resistance, noted R_L is connected in series with the TEG, Fig. 1 [8].

The functionality of the TEG is given by the conversion of thermal energy into electrical energy when there is a temperature difference between the hot end the cold sides (Seebeck effect).

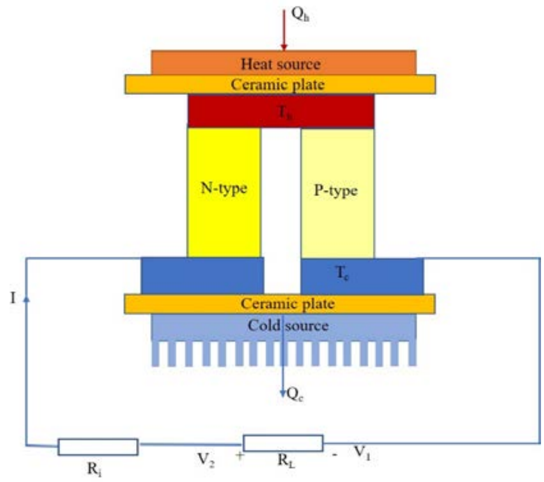


FIG. 1 The structure of TEG with a single thermoelectric element

The circuit voltage is calculated using the following relation:

$$V = \alpha(T_h - T_c) - IR_i \tag{1}$$

where α is the Seebeck effect, T_h is the temperature of the thermoelectric element's hot side, T_c is the temperature of the thermoelectric element's cold side, I is the current in the circuit, R_i is the internal resistance of TEG.

The circuit current is given by equation 2:

$$I = \frac{\alpha(T_h - T_c)}{R_i + R_L} \tag{2}$$

where R_L is the load resistance.

The power generated by the TEG is given by equation 3:

$$P = IV = R_L \frac{\alpha^2 (T_h - T_c)^2}{(R_i + R_L)^2} \tag{3}$$

3. THE EXPERIMENTAL SETUP

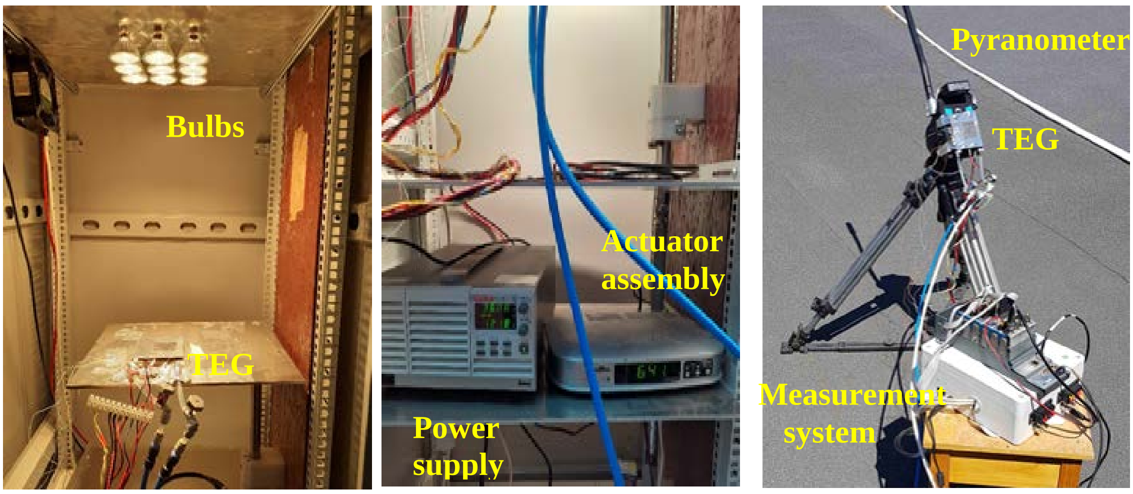
The goal of this study is to analyze the performance of the thermoelectric generator TEC1-12706, in the laboratory, under artificial light and in natural sunlight conditions, in function of different levels of irradiance.

TEC1-12706 thermoelectric generator is based on Bi_2Te_3, with 40 mm x 40 mm x 3.8 mm sizes. A graphite sheet is stuck on the hot side of the thermoelectric generator.

The illumination system for the laboratory consists of nine bulbs powered by a programmable power supply and an actuator that allows varying the distance between the bulbs and the thermoelectric generator. The actuator assembly has 20 memory positions. This allows that once the system was calibrated in irradiance, it can be used whenever needed, Fig. 2a. A tripod with manual sun tracker was used for the measurements in sunlight. The same pyranometer which was used for the calibration of the illumination system from the laboratory is placed in the same plane with the thermoelectric generator to measure the sunlight intensity.

The cold side of the thermoelectric generator is placed on the cooling system which consists of a copper parallelepiped with milled channels cooled with water.

The measurement system is created using a cRIO NI platform. The current voltage characteristic is measured using a system developed by the authors using the capacitor technique [15]. Five K thermocouples are used to measure the temperature, two of them of the hot side, and the other three of the cold side. The thermal grease is used between the cold side and the cooling system to keep the temperature of the cold side at quasi constant temperature.



(a) (b)

FIG. 2 Experimental setup a) TEG under artificial illumination; b) TEG under sunlight illumination

4. RESULTS AND DISCUSSIONS

In case of the laboratory, the measurements are made at different levels of radiation, from 600 W/m^2 to 1280 W/m^2. The first goal is to determine the necessary time for the TEG to reach a steady state which according to the analysis of the measurements is 5 minutes. After that, there are some minor variations. They are higher for the higher level of irradiance considered. This behavior is caused by the fact that the hot side of the thermoelectric generator reaches a high temperature and then due to the effects which are in TEG, the temperature difference decreases.

The behavior of the maximum power generated by the TEG on 14 minutes duration is presented in Fig. 3.

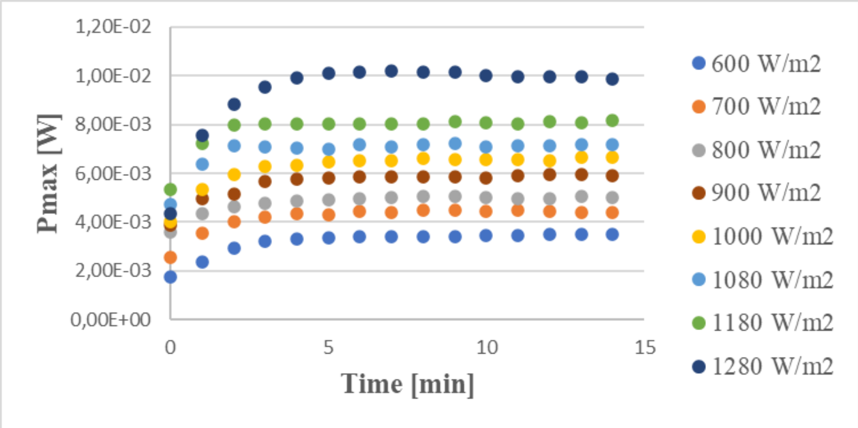


FIG. 3 Behavior of the maximum power in function of time in lab

The average of maximum power generated by TEG considered after five minutes depends linearly on the irradiance, less for the 1280 W/m^2, Fig. 4.

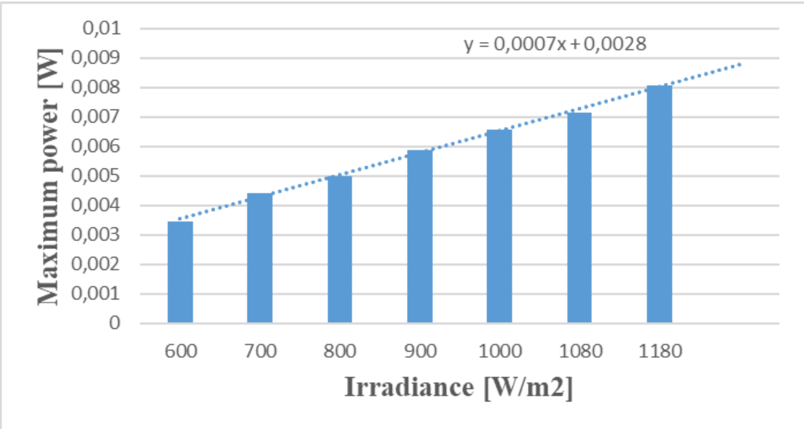


FIG. 4 Maximum power in function of the level of illumination in lab

In case of the sunlight, the measurements are made for three levels of radiation, 800, 900 and 950 W/m^2. The necessary time as the TEG reaches the steady state regime in sunlight conditions is the same with the one for TEG in the lab. The behavior of the maximum power generated by the TEG in sunlight condition on 14 minutes duration is presented in Fig. 5.

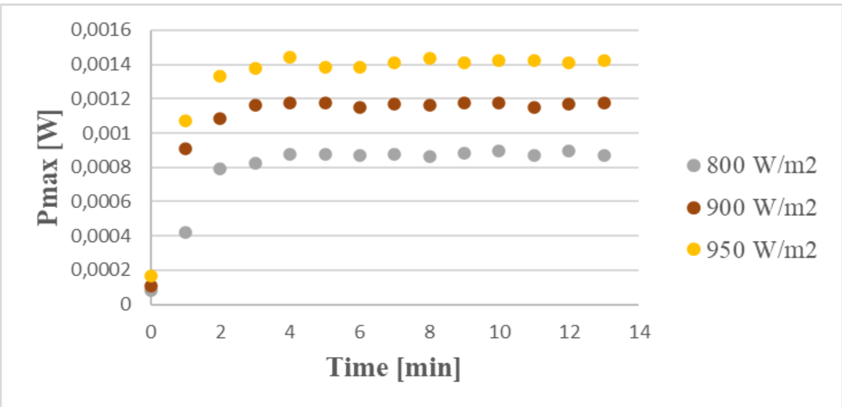


FIG. 5 Behavior of the maximum power in function of time in sunlight conditions

Table 1 presents the values for the parameters of the thermoelectric generator, such as: maximum power P_{max}, short circuit current I_{sc}, open circuit voltage V_{oc}, and internal resistance R_i, in both conditions, lab and sunlight conditions.

Table 1. Example of table

Iradiance [W/m^2]	P_{max} [mW]		I_{sc} [A]		V_{oc} [V]		R_i [Ω]	
	Lab	Sun	Lab	Sun	Lab	Sun	Lab	Sun
600	3.346	-	0.104	-	0.132	-	1.264	-
700	4.434	-	0.119	-	0.149	-	1.250	-
800	5.006	0.878	0.126	0.056	0.158	0.064	1.248	1.349
900	5.881	1.167	0.138	0.061	0.170	0.076	1.245	1.336
1000/950	6.564	1.413	0.145	0.064	0.181	0.089	1.240	1.320

There are notable differences between the maximum power generated under artificial light in the laboratory and under sunlight at the same level of illumination. The TEG generates around five times more under artificial than natural light. This difference decreases when the irradiance increases, at 800 W/m^2 it is 5.7 and decreases at around 4.3 for 1000 W/m^2 if the slope of the decrease is considered. The same behavior is observed for the short circuit current and the open circuit voltage. This high difference can be explained by the fact that halogen bulbs have more infrared radiation than sunlight and there are differences between the measurement conditions. The ambient temperature is lower than the temperature in the laboratory and the wind can reduce the temperature of the hot side of the thermoelectric measurements. At 900 the difference in temperature between the hot and cold sides of the thermoelectric generator is 6^{o}C for laboratory conditions and 4^{o}C under sunlight.

5. CONCLUSIONS

TEC1-12706 thermoelectric generator, based on Bi_2Te_3, is studied under artificial light in the laboratory and in natural conditions. The study was made for different levels of illumination. The following parameters were extracted using the measured current voltage characteristic: maximum power, short circuit current, open circuit voltage, and internal resistance.

The maximum power depends linearly on the irradiance. The linearity is kept up to 1200 W/m^2.

The comparison between the parameters studied under artificial light and under sunlight shows a better response for the first method of illumination. This conclusion shows that thermoelectric generators need to be tested under natural conditions before they are used to generate energy for different systems.

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REFERENCES

[1] D. Champier, Thermoelectric generators: A review of applications, *Energy Conversion and Management*, vol. 140, pp. 167–181, 2017;
[2] W. Yongjia, L. Zuo, J. Chen and J. A. Klein, A model to analyze the device level performance of thermoelectric generator, *Energy*, vol. 115, no. 1, pp. 591-603, 2016;

[3] D. T. Cotfas, A. M. Deaconu, P. A. Cotfas, Hybrid successive discretisation algorithm used to calculate parameters of the photovoltaic cells and panels for existing datasets, *IET Renewable Power Generation* vol. 15, no. 15, pp. 3661-3687, 2021;

[4] Tegma n.d. http://tegma.no/, accessed 2. Apr. 2023;

[5] TEG-HH-8_module_spec_sheet, http://www.evidentthermo.com/, accessed on 2. Apr. 2023;

[6] https://www.micropelt.com/produkte/lorawan/mlr003, accessed on 10. Apr. 2023;

[7] P.A. Cotfas, D.T. Cotfas, O. Machidon, C. Ciulavu, *Performance evaluation of the thermoelectric generator*. Proc. of Scientific research and education in the air force-AFASES, Brasov, **2**, 239-246 (2016);

[8] D. Enescu, Thermoelectric energy harvesting: basic principles and applications, Green energy advances ebook (pdf) ISBN 978-1-83962-051-5 (2019), https://www.intechopen.com/chapters/65239;

[9] S. Mahmoudinezhad, P. A. Cotfas, D. T. Cotfas, L. A. Rosendahl, A. Rezania, Response of thermoelectric generators to Bi_2Te_3 and Zn_4Sb_3 energy harvester materials under variant solar radiation, *Renewable Energy* vol. 146, pp. 2488-2498, 2020;

[10] T. Choi, T. Y. Kim, Current harmonized improvement method: A concept of the optimal electrical array configuration of thermoelectric modules for minimizing the mismatch loss of a thermoelectric generator, *Energy Conversion and Management* vol. 286, pp. 117036, 2023;

[11] B. Bijukumar , A. G. K. Raam, V. Sukanya , C. M. N. Mukundan , A. Al-Durra, Investigation on arrangement of thermoelectric modules based on exhaust gas flow direction to minimize mismatch power loss in TEG arrays, *Applied Thermal Engineering* vol. 221, pp. 119853, 2023;

[12] Y. Saberi, S. A. Sajjadi, A comprehensive review on the effects of doping process on the thermoelectric properties of Bi_2Te_3 based alloys, *Journal of Alloys and Compounds* vol. 904, pp. 163918, 2022;

[13] A. Ashfaq, M. M. Sabugaa, M. B. Moussa, N. Almousa, E. A. Shokralla, R. Y. Capangpangan, A. C. Alguno, M. A. Hossain, A. M. Alanazi, M. Abboud, High thermoelectric power factor of Sr doped Bi_2Te_3 thin film through energy filtering effect, *International Communications in Heat and Mass Transfer* Volume 143, April 2023, 106719;

[14] S. H. Chung, J. T. Kim, H. Kim, J. Kim, D. H. Kim, High-temperature Bi_2Te_3 thermoelectric generator fabricated using Cu nanoparticle paste bonding, *Journal of Alloys and Compounds* vol. 896, pp.163060. 2022;

[15] P. A. Cotfas, D. T. Cotfas, Comprehensive review of methods and instruments for photovoltaic–thermoelectric generator hybrid system characterization, *Energies* vol. 13, pp. 6045, 2022.