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Published in:
Energy Procedia

DOI (link to publication from Publisher):
10.1016/j.egypro.2018.07.080

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Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Mahmoudi Nezhad, S., Cotfas, P. A., Cotfas, D. T., Rezaniakolaei, A., & Rosendahl, L. A. (2018). Performance evaluation of a high-temperature thermoelectric generator under different solar concentrations. *Energy Procedia*, *147*, 624-630. https://doi.org/10.1016/j.egypro.2018.07.080

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Energy Procedia 147 (2018) 624–630

Energy Procedia

www.elsevier.com/locate/procedia

International Scientific Conference "Environmental and Climate Technologies", CONECT 2018

Performance evaluation of a high-temperature thermoelectric generator under different solar concentrations

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Abstract

Due to some special features like being highly reliable and having long lifetime, solar thermoelectric generators (STEGs) are appropriate to convert solar energy into electrical energy directly. In this investigation, an oxide-based TEG is examined under different solar concentrations. To increase the energy absorbance by the TEG, a self-adhesive graphite sheet is attached to the surface of the TEG. For both STEG systems, the variation of the temperatures on the hot and cold sides of the TEG, open circuit voltage and short circuit current are obtained and compared. I-V-P curves for both STEG systems are achieved and discussed. The results indicate the significant effect of using graphite sheet in the STEG system on the power generation and all abovementioned parameters.

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Selection and peer-review under responsibility of the scientific committee of the International Scientific Conference 'Environmental and Climate Technologies', CONECT 2018.

Keywords: solar thermoelectric generator; experimental investigation; graphite sheet; solar concentration; power generation

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1. Introduction

Fast depletion of the fossil fuels makes clean and renewable alternative energies very important. Sun is an unlimited source of energy. Solar energy can be converted to electricity by different devices. STEGs are promising devices which can be used for harvesting solar energy. TEGs have no moving parts and working silently with high reliability, therefore, TEGs have been used in different applications like waste heat recovery [1, 2], low power remote applications [3, 4], space probes [5], hybrid solar-TEG systems [6–8] and so on. Using low-temperature TEGs in STEG systems have been investigated in many references but there are fewer studies on the application of high-temperature TEGs in STEG systems. One of the first studies with remarkable results has been presented by Telks [9]. The efficiency of the STEG system for the solar concentration less than 50 reached to 3.35 %. In the recent years, new investigations of different aspects of STEG systems have been done. Kraemer et al. [10] presented a STEG system which was arrived at 4.6 % conversion efficiency. This efficiency is more than 7 times higher than the formerly obtained maximum value for a flat-panel STEG. Later in another study, Kraemer et al. [11] suggested a numerical model and an optimization approach for the terrestrial STEGs. The conversion efficiency was reached to 5 % in the new design of the STEG system.

With the development of the high-temperature TEGs, the capability of using concentrated solar radiation has been investigated [12] and a new category of the STEG systems have been established. A general model for power generation and efficiency of the STEG systems has been offered by Cai et al. [13]. Impact of different parameters including input energy, the thermal conductivity, the absorptivity and emissivity of the heat collector, and the cooling water were investigated. The results illustrated that increasing input energy and absorptivity, enhance the performance of the STEG while low emissivity of the heat collector is beneficial to achieve a high-performance STEG system. Kutt et al. [14] optimized a concentrated STEG system. The optimum number of commercial TEGs that should be used in the STEG system is determined.

Baranowski et al. [15] divided the STEG into two subsystems including TEG and solar absorber in the modeling procedure. To achieve 85 % efficiency for the absorber they used two different methods that are using the solar selective absorber and thermally insulating cavities. The predicted efficiency for the used TEG materials and for solar concentration between 250 to 300 suns was 15 %. A SiGe-based STEG system was examined by Pereira et al. [16] under high solar concentration values (>100) and high-temperature condition (>450 °C). The maximum efficiency of the system was obtained 1.8 % which is for the lowest emissivity value. The feasibility of direct transformation of concentrated high-temperature solar radiation into electricity was investigated experimentally by Tomes et al [17]. The impact of coated graphite layer on the hot side of the TEG on the temperature difference, maximum power generation by the system and the efficiency of the system are also determined. The results showed that coating the graphite layer on the hot surface leads to having a higher temperature difference between hot and cold sides of the TEG and the maximum power and efficiency of the system improves substantially.

Oxide-based STEGs are appropriate for working under high solar concentrations and high-temperature conditions. These materials are more efficient in the high-temperature ranges. In this study, an oxide-based STEG system is examined experimentally under different solar concentration values. In the next step, to increase the absorbance of the STEG system, a self-adhesive graphite sheet is attached to the top surface of the TEG. An inclusive evaluation of the performance of both STEG systems with and without graphite sheet is carried out. The temperature gradient between the hot and cold side of the TEG, open circuit voltage, short circuit current, and maximum output power are obtained and compared for both STEG systems.

2. Experimental setup

Flat plates, parabolic troughs, Fresnel lenses and parabolic dishes are mostly used as the solar collector in the experiments. In this investigation, a high-flux solar simulator consists of 10 xenon arc lamps cooled with high-pressure water (see Fig. 1) is used to provide the concentrated light. Very high solar concentration (until 11000 suns) can be simulated in the focal point [18, 19]. To deliver a uniform light over the surface of the TEG, an optical mixer located in front of the STEG system. In order to produce 0 to 338 suns, just 6 lamps are used in the experiments. All the experimental results are taken in Solar Technology Laboratory of Paul Scherrer Institute (PSI).

Before starting the experiments, a thermogage is used to measure and calibrate the distribution of the solar radiation. Thus, the most homogeneous heat flux over the area of 42 mm·42 mm can be found and TEG can be located in that area.

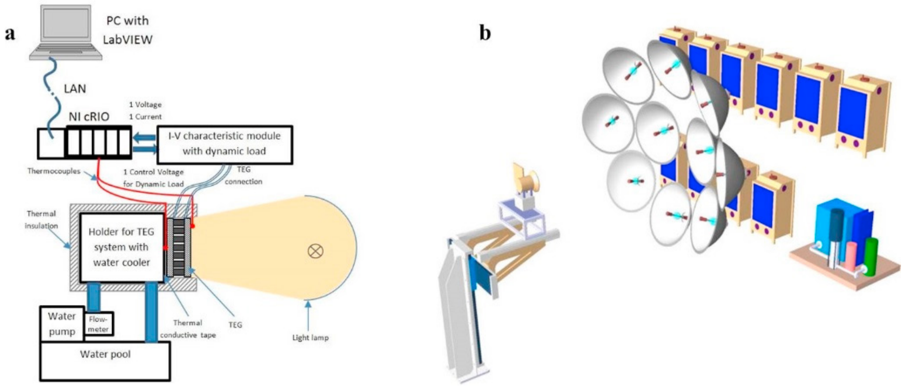


Fig. 1. (a) Schematic of experimental setup; (b) solar simulator used in this study [20].

A commercial oxide TEG model CMO-25-42S with 50 uni-couples and size of 42 mm·42 mm, Fig. 2(a), which the materials of N-Type and P-Type are $CaMnO_3$ (Mn-113) and $Ca_3Co_4O_3$ (Co-349) [21] respectively, is used in the experiments. In order to enhance the energy absorbed from the solar simulator, a self-adhesive graphite sheet [22] is attached to the surface of the TEG. Fig. 2(b) shows the schematic of the STEG system including TEG with graphite layer on top and heat exchanger with water, as the working fluid.

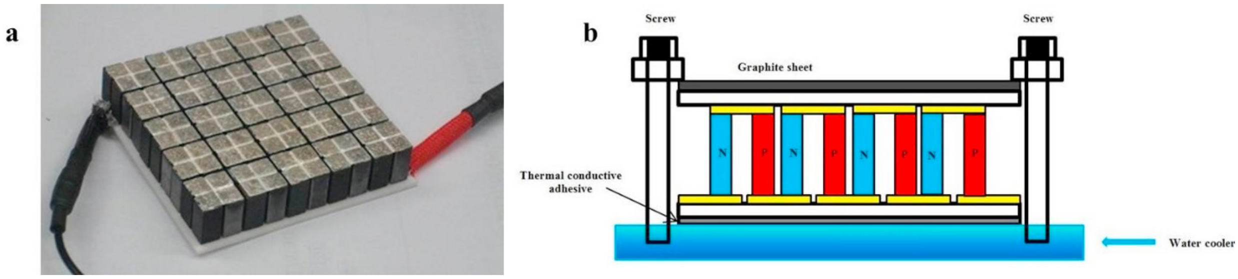


Fig. 2. (a) Oxide TEGs used in experiments; (b) physical model of the STEG system.

The mass flow rate of the water in the heat sink is 5 Lit/min that is constant during all experiments. All the temperatures and I-V-P curves are recorded with a data acquisition and control systems based on National Instruments cRIO. 2 T-type thermocouples are used to measure the temperatures on the hot side. For the cold side and ambient temperature, 3 and 1 T-type thermocouples are used, respectively.

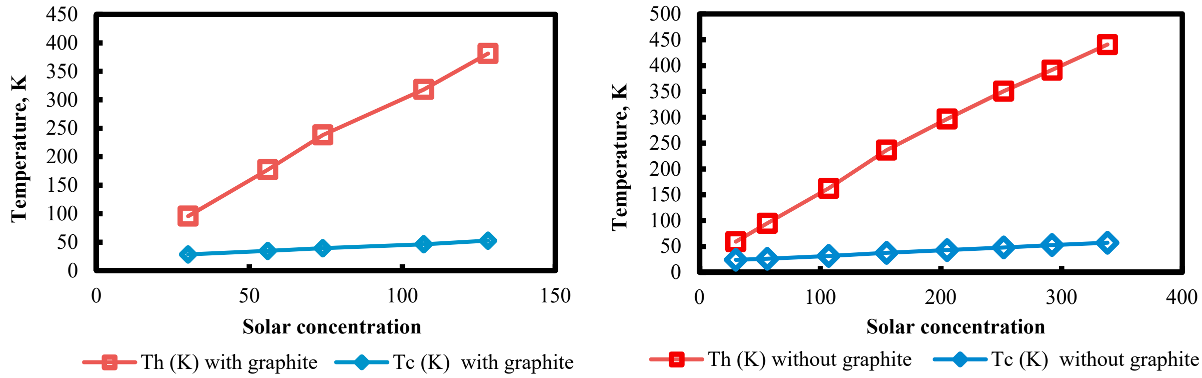
3. Results and discussion

The temperature gradient across the TEG and figure of merit of the TEG are two main parameters in power generation by the TEG. In the first step of experiments, TEG without graphite layer on top is examined. In this condition due to having more reflection from the top surface of the TEG, less input energy can be absorbed; therefore, higher solar radiation can be applied to the STEG system. In the next step, a self-adhesive graphite sheet is attached to the hot side of the TEG and consequently, TEG has more absorbance rather than when there is no graphite sheet. In this situation, the solar radiation that can be applied to the system is less than STEG system without graphite sheet. As mentioned before, 6 lamps are used in the experiments that all of them are kept on during the tests and the magnitude of the solar concentration is controlled by a shutter that is located in front of the lamps. Table 1 shows the values of the solar concentrations that are applied to the both STEG systems along with the open-rate percentage of the shutter.

Table. 1. Solar radiation on the TEGs versus open-rate percentage of the shutter.

Shutter percentage, %	5	10	15	20	25	30	40	50	60	70
Solar radiation for STEG without Gr, kW/m^2	30	56	-	107	-	155	205	252	292	338
Solar radiation for STEG with Gr, kW/m^2	30	56	74	107	128	-	-	-	-	-

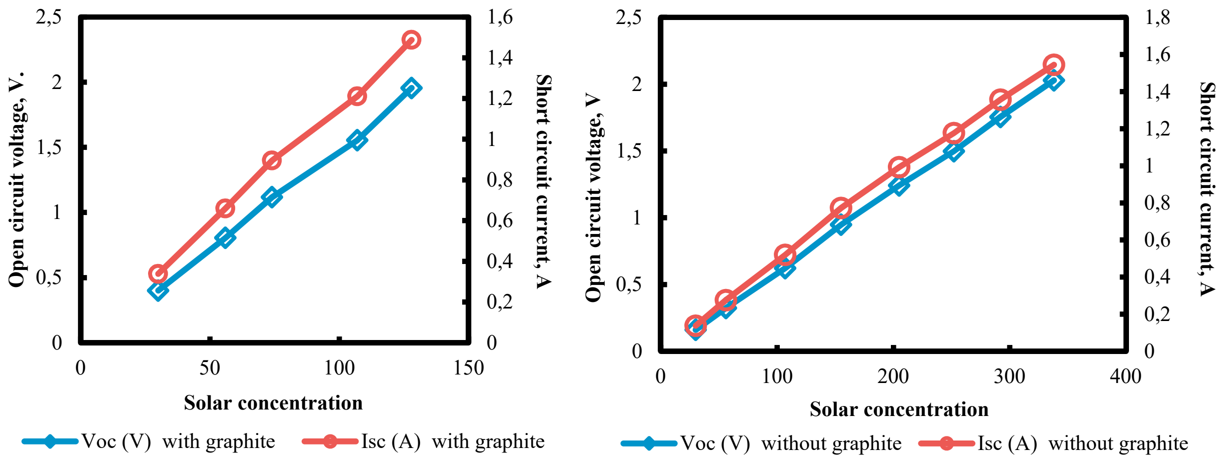
The maximum solar concentration that is applied to the STEG system with graphite layer is 128 suns. The reason is that the maximum temperature that the graphite sheet can tolerate to stay attached to the hot surface of the TEG is 400 °C. Fig. 3 illustrates the hot and cold side temperatures of the TEG in both STEG systems.



(a) (b)

Fig. 3. Hot and cold side temperatures of the STEG: (a) with graphite sheet; (b) without graphite sheet, versus solar concentration.

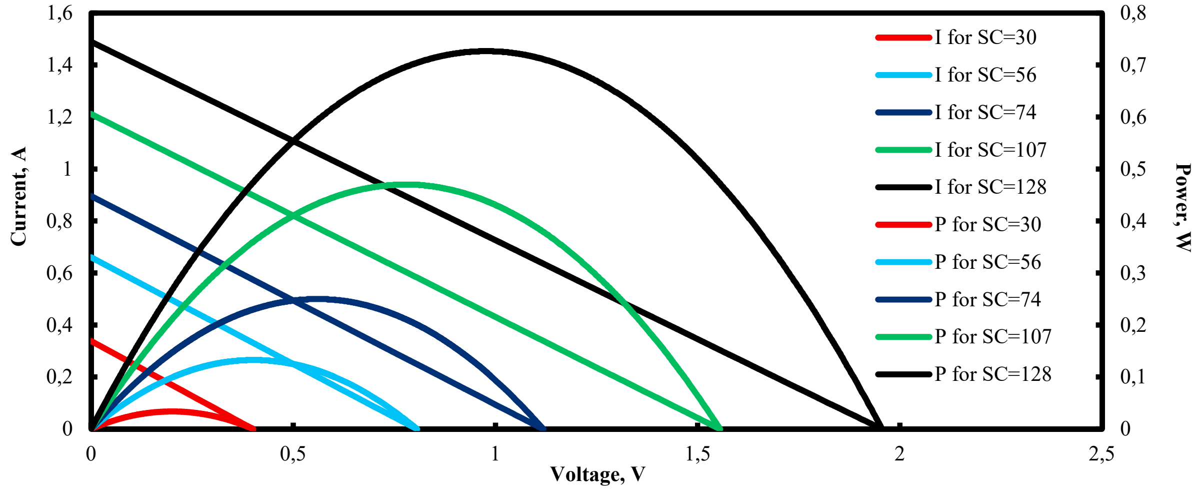
With increasing the solar radiation and therefore the heat flux through the TEG, the temperature of the hot and cold sides will enhance. The rate of increment of the hot side temperature is more than cold side temperature, therefore, the temperature difference increases as well. Due to the higher rate of energy absorbed from the simulator and consequently higher heat flux across the TEG, the temperature of the STEG system with graphite layer increases in the lower solar concentrations. For solar concentration 128 suns, the temperatures of the hot and cold sides of the TEG in the STEG system with graphite sheet is almost the same with STEG system without graphite sheet and solar concentration 292 suns.



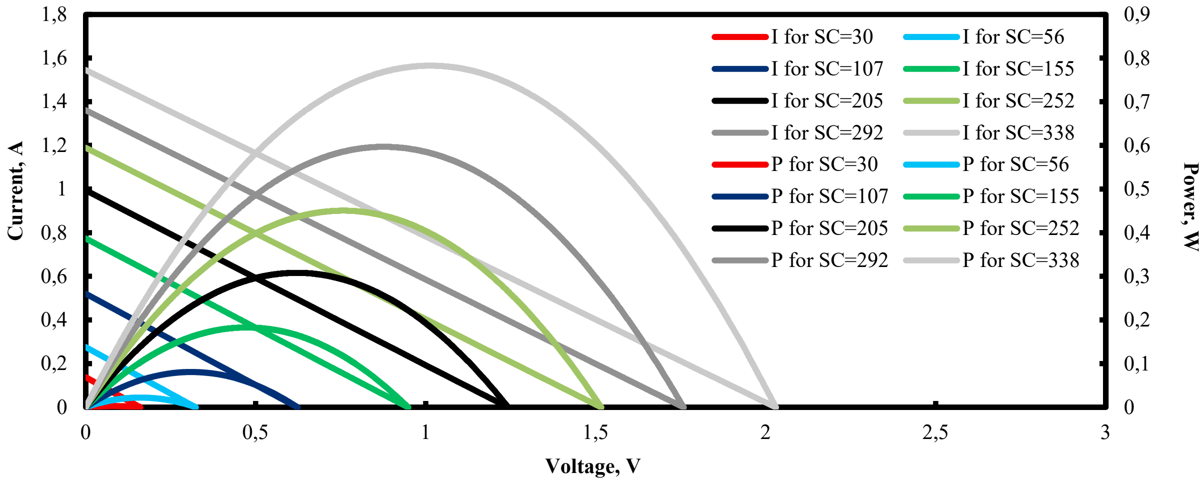
(a) (b)

Fig. 4. Open circuit voltage and short circuit current versus solar concentration for STEG: (a) with graphite sheet; (b) without graphite sheet.

Fig. 4 illustrates open circuit voltage and short circuit current for both STEG systems. As can be seen, for both with and without graphite sheet systems, open circuit voltage and short circuit current have the same linear trend and with increasing the solar concentration, the open circuit voltage and short circuit current are enhancing as well. Due to the higher energy absorbed by the TEG when graphite sheet is attached, in lower solar concentration the value of open circuit voltage and short circuit current are almost the same with open circuit voltage and short circuit current without graphite layer and in higher solar concentrations. The value of the open circuit voltage and short circuit current in STEG system with graphite sheet and solar concentration 107 are 1.56 V and 1.21 A, respectively while these values for the system without graphite sheet and solar concentration 252 are 1.5 V and 1.18 A.



(a)



(b)

Fig. 5. I-V-P curves for the STEG system: (a) with graphite sheet; (b) without graphite sheet, and different solar concentrations.

The variation of the power and current versus voltage for different solar concentration are shown in Fig. 5. It can be seen that for the same solar concentration the power generated from the TEG with attached graphite is much higher that TEG without graphite sheet. It shows the substantial effect of the graphite sheet on the power generation by the system. This technique is very useful in the low concentration applications to compensate the low amount of input energy. Comparing Fig. 5(a) and Fig. 5(b) shows that for the same solar concentrations, the power generation by the system with graphite sheet is much more than the system without graphite sheet. Fig. 6 illustrates that by increasing the solar concentration, the ratio of the maximum power of the system with graphite sheet to the system without graphite sheet is decreasing slightly but this amount for the solar concentration 107 is still 5.8 and it shows the significant effect of the graphite sheet.

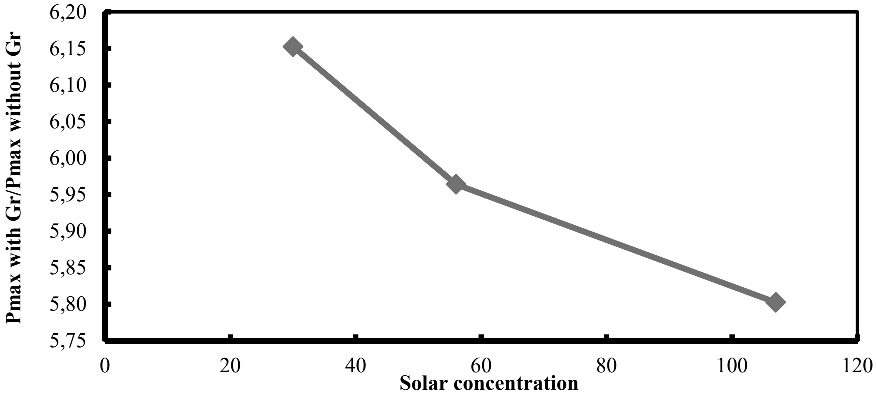


Fig. 6. The ratio of the maximum power for the STEG with graphite sheet to the STEG without graphite sheet versus solar concentration.

4. Conclusion

The performance of an oxide-based STEG system is examined under different solar concentrations. The temperature of the hot and cold sides of the TEG, open circuit voltage, short circuit current, and I-V-P carves are obtained. In the next step of the experiments, a self-adhesive graphite sheet is attached to the hot side of the TEG and all abovementioned are obtained and compared with the TEG without graphite sheet. The results show the huge impact of using the graphite sheet in the STEG system which plays the role of an absorber to increase the amount of absorbed energy from the solar simulator. Furthermore, the ratio of the maximum power in the system with graphite sheet to the system without graphite sheet decreases with increasing the solar concentration.

Acknowledgements

The authors would like to acknowledge financial support from Access to Research Infrastructures activity under 7th Framework Programme, SFERA 2, Grant Agreement n. 312643. The authors are thankful to the team from the Solar Technology Laboratory of Paul Scherrer Institute, Villigen, Switzerland (Ms.Y. Baeuerle, Mr. D. Wuillemin, Mr. V. Schnetzler and Mr. C. Wieckert), where all the measurements of this study were performed.

References

[1] Rahbar N, Esfahani JA, Asadi A. An experimental investigation on productivity and performance of a new improved design portable asymmetrical solar still utilizing thermoelectric modules. Energy Conversion and Management 2016;118:55–62.
[2] Nezhad SM, Rezaniakolaei A, Rosendahl LA. Experimental Study on Effect of Operating Conditions on Thermoelectric Power Generation. Energy Procedia 2017;142:558–63.
[3] Singh R, Tundee S, Akbarzadeh A. Electric power generation from solar pond using combined thermosyphon and thermoelectric modules. Solar Energy 2011;85:371–8.
[4] Stevens JW. Performance factors for ground-air thermoelectric power generators. Energy Conversion and Management 2013;68:114–23.
[5] Kimura R, Yoshida T. Design study of molten-salt-type reactor for powering space probes and its automated start-up. Journal of Nuclear Science and Technology 2013;50(10):998–1010.
[6] Mahmoudinezhad S, Rezania A, Rosendahl LA. Behavior of hybrid concentrated photovoltaic-thermoelectric generator under variable solar radiation. Energy Conversion and Management 2018;164:443–52.
[7] Rezania A, Rosendahl LA. Feasibility and parametric evaluation of hybrid concentrated photovoltaic-thermoelectric system. Appl Energy 2017;187:380–9.
[8] Mahmoudinezhad S, Qing S, Rezaniakolaei A, Rosendahl LA. Transient Model of Hybrid Concentrated Photovoltaic with Thermoelectric Generator. Energy Procedia 2017;142:564–9.

[9] Telkes M. Solar thermoelectric generators. J. Appl. Phys. 1954;25:765.
[10] Kraemer D, Poudel B, Feng H-P, Caylor JC, Yu B, Yan X, Ma Y, Wang X, Wang D, Muto A, McEnaney K, Chiesa M, Ren Z, Chen G. High-performance flat-panel solar thermoelectric generators with high thermal concentration. Nat. Mater. 2011;10:532–53.
[11] Kraemer D, McEnaney K, Chiesa M, Chen G. Modeling and optimization of solar thermoelectric generators for terrestrial applications. Sol. Energy. 2012;86:1338–50.
[12] Weidenkaff A, Robert R, Aguirre MH, Bocher L, Lippert T, Canulescu S. Development of Thermoelectric Oxides for Renewable Energy Conversion Technologies. Renewable Energy 2008;33:342–7.
[13] Cai Y, Xiao J, Zhao W, Tang X, Zhang Q. A General Model for the Electric Power and Energy Efficiency of a Solar Thermoelectric Generator. Journal of Electronic Materials 2011;40(5):1238–43.
[14] Kutt L, Millar J, Lehtonen M, Marss M. Optimization of concentrated solar thermoelectric generator system for highest yearly electric output. The 56th international scientific conference on power and electrical engineering of Riga Technical University, Latvia, Riga, October 14, 2015.
[15] Baranowski LL, Warren EL, Toberer ES. High-Temperature High-Efficiency Solar Thermoelectric Generators. Journal of Electronic Materials 2014;43(6):2348–55.
[16] Pereira A, Caroff T, Lorin G, Baffie T, Romanjek K, Vesin S, Kusiaku K, Duchemin H, Salvador V, Miloud-Ali N, Aixala L, Simon J. High temperature solar thermoelectric generator – Indoor characterization method and modeling. Energy 2015;84:485–92.
[17] Tomes P, Trottmann M, Suter C, Aguirre MH, Steinfeld A, Haueter P, Weidenkaff A. Thermoelectric Oxide Modules (TOMs) for the Direct Conversion of Simulated Solar Radiation into Electrical Energy. Materials 2010;3:2801–14.
[18] Petrasch J, Coray P, Meier A, Brack M, Haberling P, Wuillemin D, Steinfeld A. A novel 50 kW 11,000 suns high-flux solar simulator based on an array of xenon arc lamps. ASME Journal of Solar Energy Engineering 2007;129(4):405–11.
[19] Alxneit I, Schmit H. Spectral characterization of PSI's high-flux solar simulator. J. Sol. Energy Eng 2012;134(1).
[20] Cotfas DT, Cotfas PA, Floroian DI, Floroian L. Accelerated Life Test for Photovoltaic Cells Using Concentrated Light. International Journal of Photoenergy 2016.
[21] TEC. Solidstate Power Generation. Part# CMO-25-42S. Available: http://espressomilkcooler.com/wp-content/uploads/2014/06/CMO-25-42S-OXIDE-NEW.pdf.
[22] RS. Selvklæbende Termisk kontaktfladeark, Grafit, 1000W/m·K, 115x90mm. Available: http://dk.rs-online.com/web/p/varmeledende-spaltefyldende-underlag/7123920/?searchTerm=712-3920&relevancy.