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Experimental investigation of passive water cooling in solar heating thermoelectric generator

Güneş enerjili termoelektrik jeneratörde pasif su soğutmanın deneysel incelenmesi

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Experimental Investigation of Passive Water Cooling in Solar Heating Thermoelectric Generator

Highlights

- *The heat pipe was investigated by solar power under three different conditions as non-reflector, semi-reflector and full-reflector.*
- *A Small capacity passive water cooler was used for 5 pieces thermoelectric generators (TEGs).*

Graphical Abstract

The heating required for the thermoelectric generator (TEG) system was provided by a solar powered two-phase closed thermosiphon (TPCT) type heat pipe, and the cooling was provided by a two-section passive water cooler.

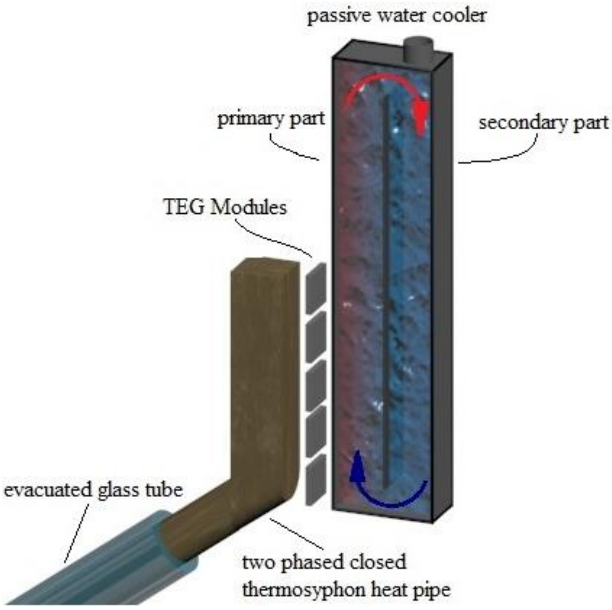

Figure. Passive water cooling for thermoelectric generators

Aim

Investigation of the effectiveness of a small capacity two-parts passive water cooler.

Design & Methodology

The system was designed, manufactured and experimentally investigated.

Originality

The efficiency of the two-parts passive water cooler was experimentally studied and calculated with the necessary measurements.

Findings

For non-reflector, semi-reflector and full-reflector, the highest open circuit voltage values in total are 4.38V, 7.53V and 8.20V, respectively.

Conclusion

For TEG's cold side, instead of a big, impractical passive cooler (water/air), with using a small, practical and simple passive water cooler could be provided an effective cooling without consuming additional energy.

Declaration of Ethical Standards

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Güneş Enerjili Termoelektrik Jeneratörde Pasif Su Soğutmanın Deneysel İncelenmesi

Araştırma Makalesi/Research Article

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ÖZ

Bu çalışmada, güneş enerjisinden elektrik üretmek için bir termoelektrik jeneratör (TEG) sistemi tasarlanmıştır. TEG'in sıcak yüzeyini ısıtmak için güneş enerjili iki fazlı kapalı termosifon (TPCT) tipi ısı borusu kullanılmış ve soğuk tarafı soğutmak için 1200 cc kapasiteli pasif su soğutmalı bir sistem tasarlanmış ve üretilmiştir. Soğutma sistemi, verimli bir soğutma sağlamak için doğal bir su sirkülasyonu sağlayan birincil ve ikincil bölümler olarak iki kısma sahiptir. Literatürdeki çalışmaların çoğunda tek bir TEG kullanılırken, bu çalışmada daha fazla elektrik üretmek için basit, kolay ve ucuz bir tasarım elde etmek amacıyla 5 TEG kullanılmıştır. Sadece pasif su soğutmanın etkisi değil, aynı zamanda reflektör kullanmanın sistem verimliliği üzerindeki etkisi deneysel olarak test edilmiştir. Sistem, reflektör olmayan, yarı reflektör ve tam reflektör olmak üzere üç farklı koşulda güneş enerjisi ile çalıştırılmıştır. Elektriksel ve termal veriler bir bilgisayara kaydedilir ve karşılaştırma ve hesaplamalar için 08:00-15:00 saatleri arasında elde edilen veriler kullanılmıştır. Sadece maksimum açık devre voltajına ulaşılan TEG-1 için, maksimum çıkış gücü, elektriksel verim ve Seebeck katsayısı hesaplamaları yapılmıştır. Sonuçlar, küçük kapasiteli pasif su soğutmalı bir ısı borusu kullanıldığında, elektrik üretmek için 5 adet TEG için gerekli sıcaklık farkına ulaşılabileceğini göstermiştir.

Anahtar Kelimeler: Güneş enerjisi, iki fazlı kapalı termosifon, temoelektrik jeneratör, pasif soğutucu.

Experimental Investigation of Passive Water Cooling in Solar Heating Thermoelectric Generator

ABSTRACT

In this study, a thermoelectric generator (TEG) system is designed to produce electricity from solar energy. Solar powered two-phase closed thermosiphon (TPCT) type heat pipe is used to heat the hot surface of the TEG, and a 1200 cc capacity passive water-cooled system is designed and manufactured to cool the cold side. The cooling system has two sections as primary and secondary sections which provide a natural water circulation to achieve an efficient cooling. A single TEG is used in most studies in the literature while 5 TEGs are used in this study to obtain a simple, easy and cheap design to generate more electricity. Not only the effect of passive water cooling, but also the effect of using a reflector on the system efficiency is tested experimentally. The system is operated by solar power under three different conditions as non-reflector, semi-reflector and full-reflector. Electrical and thermal data are recorded in a computer and data obtained from 08:00 to 15:00 is used for comparison and calculations. Maximum output power, electrical efficiency and Seebeck coefficient calculations are made for only TEG-1 in which the maximum open-circuit voltage is reached. Results showed that using a heat pipe with a small capacity passive water-cooling, the temperature difference for five TEGs can be reached to generate electricity.

Keywords: Solar energy, Two-phase closed thermosiphon, thermoelectric generator, passive cooling.

1. INTRODUCTION

Energy is one of the most important topics of this age. Although there are many sources of energy used by the human being throughout history, some of these energy sources are renewable energy sources. One of the renewable energy sources is solar energy. Solar energy is the largest and most widely used renewable energy source. It has applications such as water heating, photovoltaic electricity generation, energy production [1]. There are intensive studies and applications on electricity generation from solar energy. Solar photovoltaics and solar thermal applications are two main approaches to electrical power generation [2], [3].

Thermoelectric (TE) energy converters are very popular for producing electricity directly form solar energy. Thermoelectric generators (TEGs) are quiet, reliable and environmentally friendly solid-state electronic devices having no mechanically moving parts. TEG can convert heat energy to electricity. Defined by Seebeck effect in 1821, TEG produces electricity with temperature difference between two surfaces [4]. Any kind of heat including waste heat from automobile exhaust, geothermal and solar energy etc. can be used to heat the hot side of TEG [5], [6], [7], [8].

TEG using solar energy as the heat source can be called solar thermoelectric generator (STEG). The basic idea is to use solar energy as a heat source on the hot surface of the TEG. Three different methods can be used for this purpose. The first is the use of heat obtained by

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concentrating the solar flux with classical (parabolic) and optical (fresnel) methods. The second method is using the TEG as a heat exchanger in a combined heat and power (CHP) system. The third method is using waste heat from the fluid used for cooling photovoltaic (PV) panels [9].

TEG generates electricity from the heat flow from the hot side to the cold side of TEG. Therefore a temperature difference must be established between the two surfaces [10], [11]. Solar heat can be fed to the hot side of the TEG directly or indirectly. Direct solar heating includes lens (fresnel) or mirror (parabolic dish or trough) [11], [12], [13], [14], [15], [16]. Heat pipe systems placed in vacuum glass tubes, and systems utilizing waste heat obtained from PV are the most popular indirect solar heating methods [17], [18], [19], [20], [21], [22], [23].

While most of the studies focus on solar-powered heating, cooling the TEG is also a very critical subject of study. Sajid et al. classified the cooling mechanisms as passive air cooling, fan cooled, passive water cooling, forced water cooling and heat pipe cooling [24]. There are not so many studies in literature on passive water cooling in solar energy thermoelectric generator. Chávez-Urbiola et al. used passive water coolers to cool four different systems consisted of PV, TEG and concentrator [25]. Singh et al. designed a solar pond that the heat at the bottom of the pond was carried by a heat pipe and the top layer of the pond was used as a passive water cooler [26]. Deasy et al. designed a passive liquid thermosiphon cooling system which was a reservoir of water with a maximum capacity of 10 liters. They used the cooler for a thermoelectric generator and simulated the experimental results by calculation [27].

It is stated that the active cooling of TEG is a problem because mechanical devices such as pumps and fans consume power and the increase of the coolant reduces the gain. Passive air cooling can provide air resistance and reduces the efficiency, so passive water cooling is a good choice [26]. In this study, TEG and solar energy was considered together for an electric generator design. Hot side of TEG was heated by a solar-powered two-phase closed thermosiphon (TPCT) heat pipe. A passive water cooler was preferred for cooling the cold side of TEG. Unlike other studies in the literature, a small, practical and simple cooler design was used instead of a large and bulky cooler. On the other hand, while one TEG module was used in most studies, in this study, five TEG modules are connected to a single solar heater and a single passive water cooler at the same time. In order to see the efficiency of the designed cooler, the system has been compared in three different concentrators as non-reflector, semi-reflector and full-reflector.

2. EXPERIMENTAL SETUP

In this study, solar-powered two-phase closed thermosiphon (TPCT) heat pipe is used as the heater. TPCT evaporates the working fluid in its evaporation region and moves it to the condenser region where the working fluid condenses and returns back to the evaporation region by gravity [22], [23]. In this study, a TPCT type heat pipe is designed as 1800mm for the evaporation region and 190mm for the condenser region from iron material. One-third of the evaporation region is filled with distilled water. The heat pipe in this experiment is put into a solar collector tube which traps the heat concentrated onto heat pipe. Solar collector tube used in the system is 1800mm in length with 37mm inner diameter. Surface areas of the collector tube for non-reflector, semi-reflector and full-reflector are 0.1045m^2, 0.1567m^2 and 0.2090 m^2 respectively.

Condenser of heat pipe is designed as to heat five TEG modules, and all surfaces except the surface used for heating TEG modules are insulated against heat loss. Passive water cooler is preferred for cooling the surface of TEG. Cooler is manufactured from the same iron profile material as the condenser of TPCT, and dimensions of the condenser and cooler are given in Fig.1.

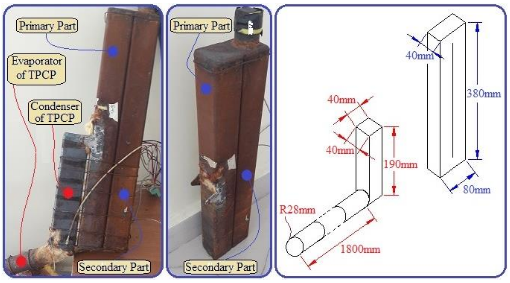

Figure 1. Heater and cooler parts with dimensions

Cooler is comprised of primary and secondary parts with 1.2lt capacity. Primary and secondary parts are internally separated and cooling water in both parts does not mix each other. Because of the separator the water heated in primary part moves upward and passes to the secondary section where it cools down and moves back downward. Therefore a natural circulation is accomplished inside a closed primary and secondary volume of the cooler which is filled up with water. Five TEG modules are installed between the solar powered heat pipe and the passive water-cooled system (Fig.2). Hot-side and cold-side temperature measurements and open circuit voltage measurements are performed for each TEG module.

Table 1. Snapshot specification for TEG1-1263-4.3 [30]

Hot side temperature (^oC)	300
Cold side temperature (^oC)	30
Open circuit voltage (V_{oc})	10.7
Matched load resistance (Ω)	5.4
Matched load output voltage (V)	5.3
Matched load output current (A)	1.0
Matched load output power (W)	5.2
Heat flow across the module (W)	≈115
Heat flow density (W/cm^2)	≈13

TEG1-1263-4.3 type module is used as thermoelectric generator. Table 1 gives the snapshot specifications of the module which is 30±5mm x 30±5mm in size. Open circuit voltage graphs of the module according to hot side and cold side temperature values are given in Fig.3.

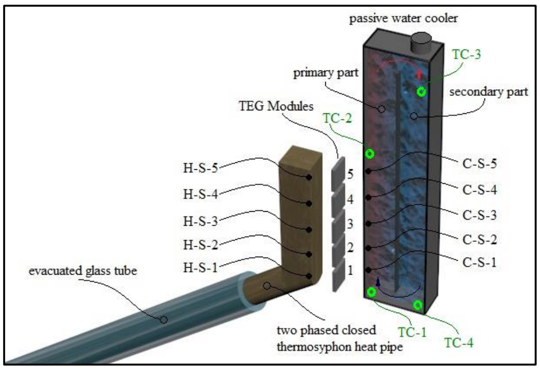

Figure 2. Location of TEG modules and temperature measurement points

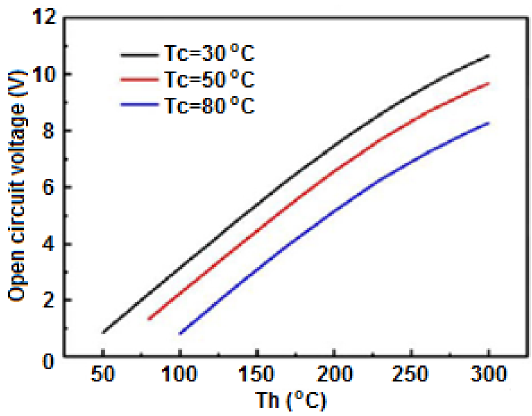

Figure 3. Open circuit voltage chart for TEG1-1263-4.3 versus temperature [30]

All temperature measurements are conducted by K-type thermocouples placed at appropriate locations. DeltaOhm LP PYRA 02 pyranometer is used for measuring incident solar radiation. All experimental data (temperatures, open circuit voltages and solar radiation) is recorded in real time with one second intervals by ORDEL UDL100 universal Data Logger with 0.2% accuracy.

3. EXPERIMENTAL RESULTS

Fig.4 shows the experimental setup. The experiments were carried out in the northern coast of Turkey, city of Samsun with latitude of 41°14'N. Collector angle is set to 26° which is optimum for summer conditions of the experimental site. To determine the effect of passive water cooler on the experimental setup, tests are conducted for three different conditions as non-reflector, semi-reflector and full-reflector.

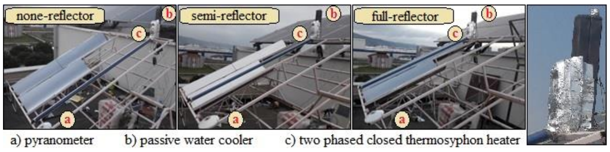

Figure 4. Experimental setup

Fig.5 shows the solar radiation distribution for non-reflector, semi-reflector and full-reflector taken for six subsequent days. To evaluate the results, data recorded at 30th of March, 2nd of April and 3rd of April are chosen for non-reflector, semi-reflector and full-reflector respectively.

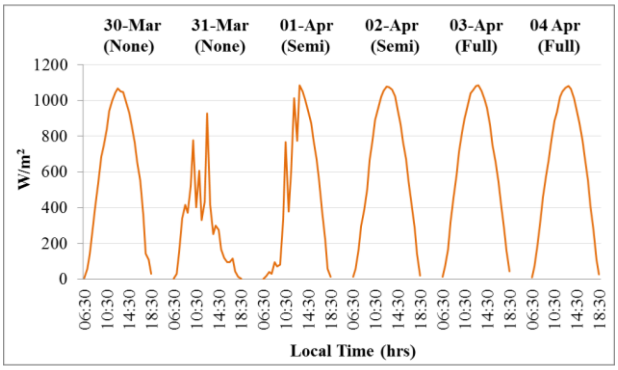

Figure 5. Distribution of solar radiation

Data recorded from 08.00 to 15.00 are chosen for the evaluation. Solar radiation is measured by pyranometer.

Primary and secondary parts of the cooler containing and circulating 1200 cc water is equipped with temperature measurement at four different points (TC1, TC2, TC3 and TC4), which are shown in Figure 2. From the Figures 6, 7 and 8 which show the temperature variations in these points, it can be understood that the water is circulating in the cooler.

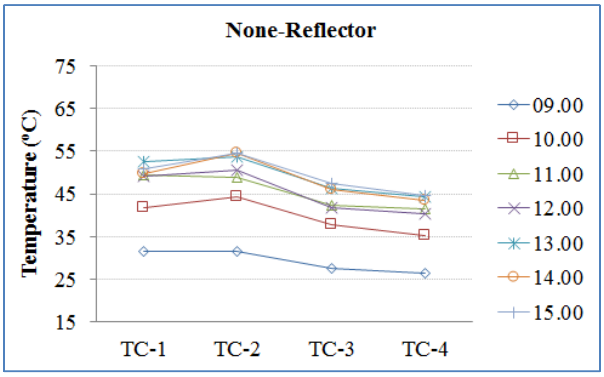

Figure6. Temperature distribution of passive water cooler for none-reflector system

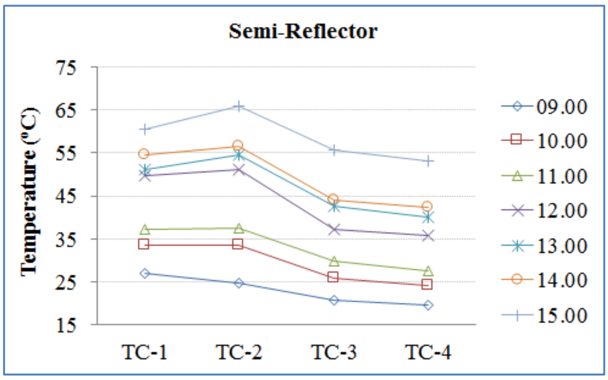

Figure 7. Temperature distribution of passive water cooler for semi-reflector system

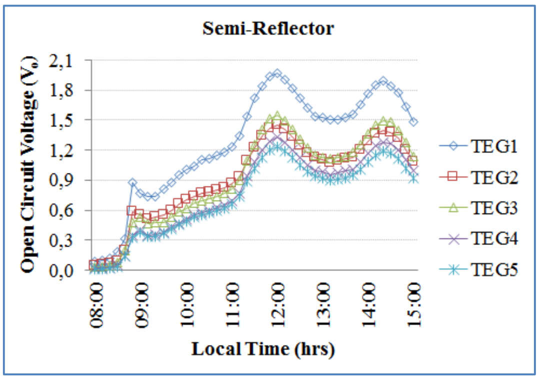

Figure10. Open circuit voltage distribution produce by TEGs for semi-reflector system

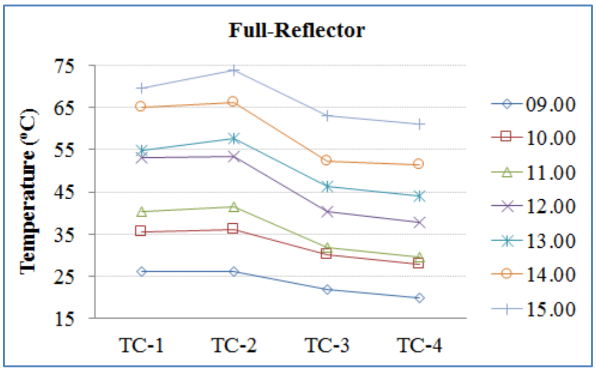

Figure 8. Temperature distribution of passive water cooler for full-reflector system

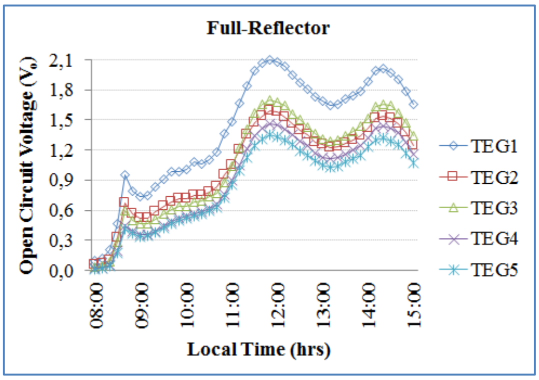

Figure 11. Open circuit voltage distribution produce by TEGs for full-reflector system

Figures 9, 10 and 11 show the variation of generated open voltage based on the reflector use. Full reflector version produced the maximum open circuit voltage value. TEG1 module which is the nearest module to the heat pipe reached the maximum open circuit voltage and the other TEGs came next according to their distance to the heat pipe.

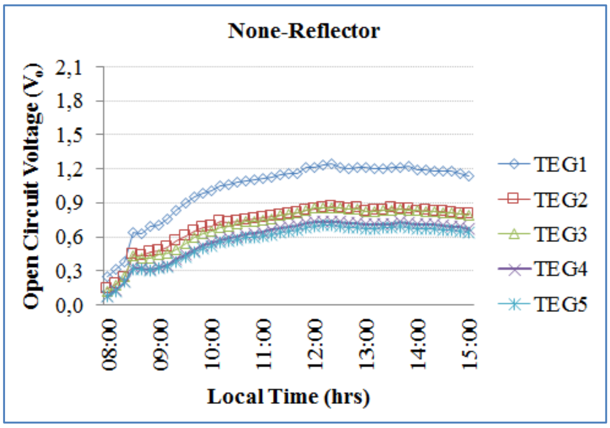

Figure 9. Open circuit voltage distribution produce by TEGs for none-reflector system

Figure 12 shows the total amount of open circuit voltage generated at none, semi and full reflector systems. Open circuit voltage which is a maximum of 4.38V in total for non-reflector is 7.53V for semi-reflector and 8.20V for the full-reflector.

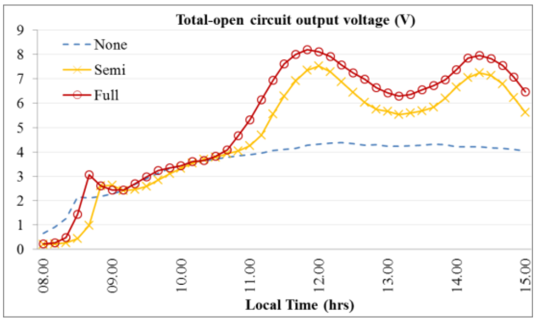

Figure 12. Distribution of total open circuit voltage produces by TEGs

To utilize the collected data, Seebeck coefficient (α_{TEG}), maximum power (P_{max}) and electrical efficiency (η_e) can be calculated. Effective Seebeck coefficient, maximum power output obtained at the matched load of the module could be calculated by using equations below [22], [23]:

$$\alpha_{TEG} = \frac{V_{OC}}{T_{HS}-T_{CS}} \tag{1}$$

where α_{TEG} is the Seebeck coefficient and V_{oc} is the open circuit voltage of used TE module. In this condition maximum power output is:

$$P_{max} = \frac{V_{OC}^2}{4R} \qquad (2)$$

where R is internal resistance (5.4 Ω) of the used TE module. By using obtained and calculated values electrical efficiency can be computed by:

$$\eta_e = \frac{P_{max}}{I_{st}} x100 \qquad (3)$$

According to the calculations made for TEG-1, Seebeck coefficient (α_{TEG}), maximum power (P_{max}), electrical efficiency (η_e) and temperature difference (ΔT) distribution for non, semi and full reflector are shown in Figure 13, 14 and 15.

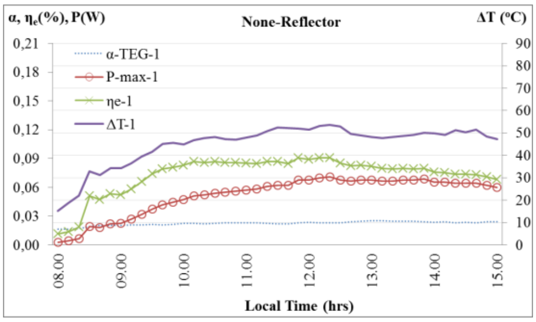

Figure 13. Distribution of the calculated values for none-reflector system (TEG1)

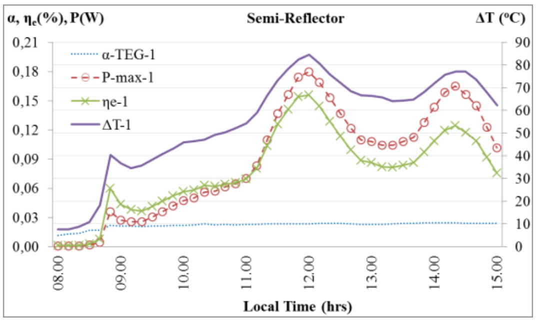

Figure 14. Distribution of the calculated values for semi-reflector system (TEG1)

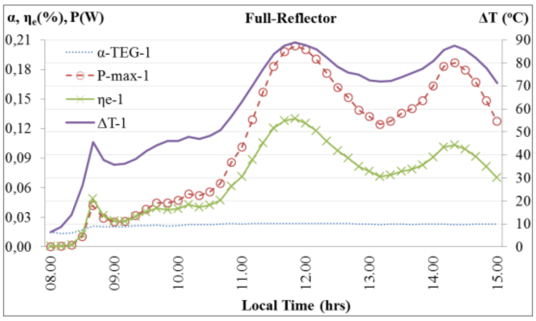

Figure 15. Distribution of the calculated values for full-reflector system (TEG1)

Figure 16 shows the electrical efficiency (η_e) distribution of TEG-1 module at different reflector conditions. The highest efficiency values obtained for non-reflector, semi-reflector and full-reflector are 0.090, 0.156 and 0.130 respectively.

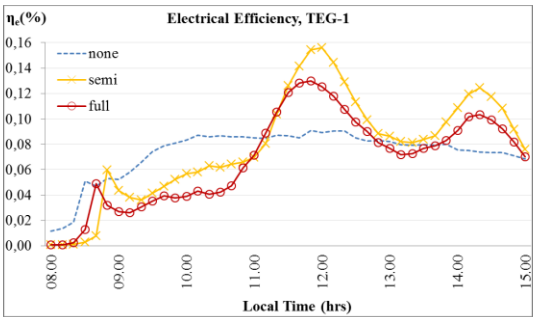

Figure 16. Distribution of electrical efficiency (η_e) (TEG1)

4. CONCLUSION

In this study, a small, practical and simple passive water cooling system is used for cooling a thermoelectric generator (TEG), which generates electricity by the temperature difference between the surfaces. Five TEGs are used in the system and their hot sides are heated by solar-powered two-phase closed thermosiphon (TPCT) tipi heat pipe. A 1200 cc passive water cooler with primary and secondary sections is used to cool the hot side of the TEGs by natural circulation. System is operated as non-reflector, semi-reflector and full-reflector, and the temperature values on passive water cooler and heat pipe are recorded along with open circuit voltage values. The results below are obtained by calculations based on the data gathered from the tests of non-reflector, semi-reflector and full-reflector:

- The highest temperatures for the passive water cooler are 54.5ºC, 66.0ºC and 73.9ºC,
- The highest temperatures reached at the condenser part of TPCT type condenser are 102.3ºC, 137.3ºC and 156.0ºC,
- The highest temperature difference between the hot-side and cold-side are 53.5ºC, 84.6ºC and 88.9ºC,
- The highest open circuit voltage values in total are 4.38V, 7.53V and 8.20V,
- Maximum power values for the first Thermoelectric Module (TEG-1) in the experiment are 0.071W, 0.179W and 0.204W, and their efficiency values are 0.090, 0.156 and 0.130.

The results of this study showed that instead of a big, impractical passive cooler (water/air), a small, practical and simple passive water cooler can provide an effective cooling without consuming additional energy. Besides, instead of using a single TEG, multiple TEGs are used to generate more electricity. Comparison of non-reflector, semi-reflector and full-reflector systems revealed that full-reflector gives the highest open circuit voltage, and semi-reflector gives the best efficiency.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

REFERENCES

[1] Jian L., Tianjun L., Bihong L. "Performance analysis and load matching of a photovoltaic–thermoelectric hybrid system", ***Energy Conversion and Management***, 105: 891–899, (2015).

[2] Tian Y., Zhao C.Y. "A review of solar collectors and thermal energy storage in solar thermal applications", ***Applied Energy***, 104: 538–553, (2013).

[3] Mills D., "Advances in solar thermal electricity technology", ***Solar Energy,*** 76: 19-31, (2004).

[4] Pandey A.K., Tyagi V.V., Selvaraj J.A/L., Rahim N.A., Tyagi S.K. "Recent advances in solar photovoltaic systems for emerging trends and advanced applications", ***Renewable and Sustainable Energy Reviews***, 53: 859-884, (2016).

[5] He W., Zhang G., Zhang X., Ji J., Li G., Zhao X. "Recent development and application of thermoelectric generator and cooler", ***Applied Energy***, 143: 1-25, (2015).

[6] Jarman J.T., Khalil E.E., Khalaf E. "Energy analyses of thermoelectric renewable energy sources". ***Open J. Energy Efficiency***, 2: 143-153, (2013).

[7] Angeline A.A., Jayakumar J., Asirvatham L.G., Marshal J.J., Wongwises S. "Power generation enhancement with hybrid thermoelectric generator using biomass waste heat energy", ***Experimental Thermal and Fluid Science***, 85: 1–12, (2017).

[8] Gao H.B., Huang G.H., Li H.J., Qu Z.G., Zhang Y.J. "Development of stove-powered thermoelectric generators: a review", ***Applied Thermal Engineering***, 96: 297-310, (2016).

[9] Orr B., Akbarzadeh A., Mochizuki M., Singh R. "A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes", ***Applied Thermal Engineering***, 101: 490-495, (2016).

[10] Suman S., Khan M.K., Pathak M. "Performance enhancement of solar collectors – A review", ***Renewable and Sustainable Energy Reviews***, 49: 192–210, (2015).

[11] Champier D. "Thermoelectric generators: A review of applications", ***Energy Conversion and Management,*** 140: 167–181, (2017).

[12] Sun D., Shen L., Yao Y., Chen H., Jin S., He H. "The real-time study of solar thermoelectric generator", ***Applied Thermal Engineering,*** 119: 347-359, (2017).

[13] Baranowski L.L., Snyder G.F., Toberer E.S. "Concentrated solar thermoelectric generators", ***Energy & Environmental Science,*** 5: 9055-9067, (2012).

[14] Lertsatitthanakorn C., Jamradloedluk J., Rungsiyopas M. "Electricity generation from a solar parabolic concentrator coupled to a thermoelectric module", ***Energy Procedia,*** 52: 150-158, (2014).

[15] Date A., Date A., Dixon C., Akbarzadeh A. "Theoretical and experimental study on heat pipe cooled thermoelectric generators with water heating using concentrated solar thermal energy", ***Solar Energy,*** 105: 656-668, (2014).

[16] Date A., Date A., Dixon C., Singh R., Akbarzadeh A. "Theoretical and experimental estimation of limiting input heat flux for thermoelectric power generators with passive cooling", ***Solar Energy***, 111: 201-217, (2015).

[17] Chávez-Urbiola E.A., Vorobiev Y.V. "Investigation of solar hybrid electric/thermal system with radiation concentrator and thermoelectric generator", ***International Journal of Photoenergy,*** 1-7, (2013).

[18] Sundarraj P., Taylor R.A., Banerjee D., Maity D., Roy S.S. "Experimental and theoretical analysis of a hybrid solar thermoelectric generator with forced convection cooling", ***Journal of Physics D: Applied Physics***, 50: 1-11, (2017).

[19] Bjørk R., Nielsen K.K. "The performance of a combined solar photovoltaic (PV) and thermoelectric generator (TEG) system", ***Solar Energy***, 120: 187-194, (2015).

[20] Makki A., Omer S., Su Y., Sabir H. "Numerical investigation of heat pipe-based photovoltaic–thermoelectric generator (HP-PV/TEG) hybrid system", ***Energy Conversion and Management,*** 112: 274-287, (2016).

[21] He W., Su Y., Riffat S.B., Hou JX., Ji J. "Parametrical analysis of the design and performance of a solar heat pipe thermoelectric generator unit", ***Applied Energy***, 88: 5083-5089, (2011).

[22] Li G., Zhang G., He W., Ji J., Lv S., Chen X., Chen H. "Performance analysis on a solar concentrating thermoelectric generator using the micro-channel heat pipe array", ***Energy Conversion and Management,*** 112: 191-198, (2016).

[23] Zhang M., Miao L., Kang Y.P., Tanemura S., Fisher C.A.J., Xu G., Li C.X., Fan G.Z. "Efficient, low-cost solar thermoelectric cogenerators comprising evacuated tubular solar collectors and thermoelectric modules", ***Applied Energy,*** 109: 51-59, (2013).

[24] Özdemir A.E., Köysal Y., Özbaş E., Atalay T. "The experimental design of solar heating thermoelectric generator with wind cooling chimney", ***Energy Conversion and Management***, 98: 127-133, (2015).

[25] Atalay T., Köysal Y., Özdemir A.E., Özbaş E. "Evaluation of energy efficiency of thermoelectric generator with two-phase thermo-syphon heat pipes and nano-particle fluids", ***International Journal of Precision Engineering and Manufacturing-Green Technology***, 5 (1): 5-12, (2018).

[26] Sajid M., Hassan I., Rahman A. "An overview of cooling of thermoelectric devices", ***Renewable and Sustainable Energy Reviews***, 78: 15-22, (2017).

[27] Chávez-Urbiola E.A., Vorobiev Y.V., Bulat L.P. "Solar hybrid systems with thermoelectric generators", ***Solar Energy***, 86: 369-378, (2012).

[28] Singh R., Tundee S., Akbarzadeh A. "Electric power generation from solar pond using combined thermosyphon and thermoelectric modules", ***Solar Energy***, 85: 371-378, (2011).

[29] Deasy M.J., Baudin N., O'Shaughnessy S.M., Robinson A.J. "Simulation-driven design of a passive liquid cooling system for a thermoelectric generator", ***Applied Energy,*** 205: 499-510, (2017).

[30] TECTEG, https://thermoelectric-generator.com/wp-content/uploads/2014/04/SpecTEG1-1263-4.3Thermoelectric-generator1.pdf