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Comparative Study of Conventional and Water Circulating-Heat Sink Cooling Base Thermoelectric Generator System for Optimum Solar Thermal Waste Heat Recovery

*[1]YUSUF, A; [2] ALI, MH

*[1]*Department of Physics, Kaduna State University, Kaduna State, Nigeria*
[2]*Department of Physics, Bayero University Kano, Kano State, Nigeria, Email: alim@buk.edu.ng*
**Corresponding Author Email: yusuf.aliyu@kasu.edu.ng*

ABSTRACT: A novel technique for waste heat recovery in solar thermal power generation is investigated through experimentation and systematically presented. Power generation using Thermoelectric Generator (TEG) is a promising technique in waste heat recovery application. In this topology, TEG array is directly attached to the back of the solar Photovoltaic panel (model AP-AM15) to receive the transmitted heat at the back of the PV panel as waste heat. More so, a circulating water-heat sink is attached to the TEG cold side to improve the temperature gradient. Base on Seebeck effect, the TEG directly converts the temperature difference into electricity. The experimental result shows that efficiency between the range of 2.1% and 4.7% for the conventional cooling system while the output power approximately ranges between 0.05W and 0.47W, the circulating water-heat sink technique has efficiency ranging between 2.9% and 10.3% with output power between the range of 0.10W and 2.2W. The daily average increase in efficiency was found to be 263.76%. This shows that the daily average power is improved by a factor of 2.6376 with the water circulating water-heat sink technique. This is an indication of waste heat recovery from the solar thermal power generation.

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Recently, the demand for new energy resources improved the growing concerns due to rising energy prices. The utilization of new alternative sources for the recovery of waste energy gained tremendous attention in the research community (Hoang et al. 2019). The energy recovery from waste sources is considered as the vital key technology targeting to satisfy the approaches of both the efficiency enhancement in energy use and the reduction of pollutants. In recent years, the use of renewable energy and the recycle of waste heat are paid great attention to by several researchers and research institutions. Some technologies for the waste heat recovery have been applied to the reality such as exhaust gas recirculation (Shen, Tian, and Liu 2019), organic Rankine cycle (ORC)-based systems (turbine and boiler) (Wang et al. 2016), and thermoelectric generation (TEG) (Fan et al. 2016; Naphon, Wiriyasart, and Hommalee 2019; Attar, Lee, and Snyder 2020; Du et al. 2015). Among the aforementioned approaches for recovering waste heat, TEG is considered as the promising, possible, and practicable technology harvesting waste heat based on the direct conversion of thermal energy into electrical energy with distinguished characteristics (Wiriyasart et al. 2019). Being highly consistent, low noise, zero emission of environmental pollutant and no operational cost, no moving parts and can directly convert heat into electricity (Al-nimr, Tashtoush, and Hasan 2020). Moreover, the major characteristics advantages of TEGs as compared to ORC-based systems include easy installation and small sizes. In fact, TEGs have been applied to some producing industries, military, transportation sectors, and the life of the human (Wang et al. 2013). Though, some previous research showed the feasibility of TEGs in the waste heat recovery, additional design optimization of such TEG system is needed (Fan et al. 2016; Naphon, Wiriyasart, and Hommalee 2019; Attar, Lee, and Snyder 2020; Du et al. 2015; Wang et al. 2016; Zhang et al. 2015). Mostly, there are two methods of the optimization of TEG systems: One is to optimize the TEG module for the development of new thermoelectric materials and structure design optimization (Su et al. 2014); and the other is to enhance the heat transfer from heat source to TEG module hot side and from TEG module cold side to heat sink (e.g. air or coolant) (Abdo, Ookawara, and Ahmed 2019). To gain a comprehensive understanding of the transport phenomena in the TEG systems, some mathematical models have been established by researchers coupling the heat

**Corresponding Author Email: yusuf.aliyu@kasu.edu.ng*

source/sink flow and TEG modules. Sornek, Filipowicz, and Rzepka in (Sornek, Filipowicz, and Rzepka 2016) developed a numerical model for TEG modules with a parallel-plate heat exchanger. This model was used to predict the fluid temperatures and the temperatures in the TEG modules. In previous studies, the design optimization of TEG systems mainly focused on conductive systems, convective systems or radiative systems (Huang et al. 2016; Shu et al. 2018; Su et al. 2014).In this study, the effects of cooling design both convective and radiative systems where employed, whereby a coolant liquid (water) is pumped from reservoir by a regulated water pump circulating inside a piped heat sink and passed through a regulated cooling radiator. As this process continues from a free defined temperature, it shows that the TEG cold side temperature can be reduced thereby improving heat transfer. Hence, the output power can be significantly improved by the design optimization of cooling channel. However, the detailed coolant channel design effect and the mass/volume flow rate were largely ignored.

MATERIALS AND METHOD

TEG System Design: TEG array is an arrangement of TEG modules in series and parallel combinations which are connected thermally in parallel and electrically in series. Each module has large number, N of thermocouple pairs, with an internal resistance of $R_{\text{int},N}$. A series connected TEG forms a string and parallel arrangement of strings form the array of TEGs with total internal resistance of R_T given as (Dalola et al. 2009);

Where n_s is the number of TEG in a string, n_p is the number of strings in parallel.

The corresponding internal resistance of a TEG with N number of thermocouple pairs is given by (Verma, Kane, and Singh 2016);

$$R_T = \frac{n_s}{n_p} R_{\text{int},N} \qquad (1)$$

$$R_{\text{int},N} = N \cdot \left[\frac{2\rho h}{A} + \frac{2\rho_c l_c}{A_c} \right] \qquad (2)$$

Where ρ is the electrical resistivity of the thermoelectric element, TE, h is the height of the TE leg, ρ_c the electrical resistivity of the copper contact, l_c the length of the copper contact, A is the cross sectional area of the TE leg, A_c cross sectional area of the copper contact, From figure 1, Using Ohm's Law the circuit current, I_{TE}, is given as (Carmo et al. 2011);

$$I_{TE} = \frac{V_{oc,n}}{R_T + R_{TE}} \qquad (3)$$

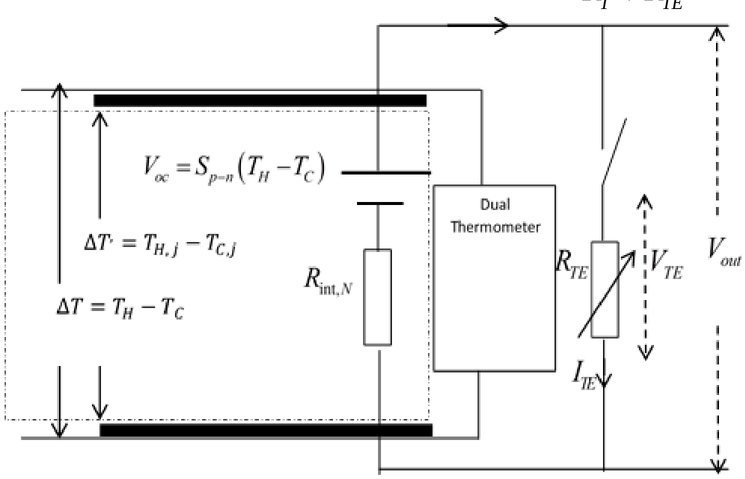

Fig 1: Circuit schematic for measuring the output signals of the thermoelectric generator

And $V_{oc,n} = n_s V_{oc} = n_s N S_{p-n}\left(T_{H,j} - T_{C,j}\right)$ (4)

Where $V_{oc,n}$ is the open circuit voltage of the TEG, V_{oc} is the open circuit voltage of the thermocouple single pair, R_{TE} is the load resistance across the TEG and S_{p-n} is the Seebeck coefficient of a thermoelectric p-type and n-type single pair. $T_{H,j}$ and

$T_{C,j}$ are temperature of the hot and the cold junctions respectively (Carmo et al. 2011).

Electrical Potential, V_{TE} at the output circuit across the load resistor R_{TE} is given by (Dalola et al. 2009).

$$V_{TE} = n_s S_{p-n} N\left(T_{H,j} - T_{C,j}\right)\cdot\frac{R_{TE}}{R_T + R_{TE}} \quad (5)$$

The electric power generated at the output, P_{TE}, by the thermoelectric generator array can be found using equation (3), (4) and (5)

$$P_{TE} = I_{TE}V_{TE} = R_{TE}\cdot\left[\frac{n_s S_{p-n} N\left(T_{H,j} - T_{C,j}\right)}{\left(R_T + R_{TE}\right)}\right]^2 \quad (6)$$

For maximum output power simulation at matched load condition $\left(R_{TE} = R_T\right)$, the maximum Power, $P_{TE,\max}$ can be obtained from equation (6) using equation (1) and (2) as (Carmo et al. 2011);

$$P_{TE,\max} = \frac{n_s n_p N\cdot S_{p-n}^2\left(\Delta T'\right)^2}{8\cdot\left(\frac{\rho h}{A} + \frac{\rho_c l_c}{A_c}\right)} \quad (7)$$

Thermal analysis shows that the rates of flow of heat from the waste heat source to the hot junctions through the upper ceramic plates Q_H, and from the cold junctions to the environment through the lower ceramic plates Q_C due to the thermal conduction are respectively given as (Dalola et al. 2009)

$$Q_H = \left(T_H - T_{H,j}\right)K \quad (8)$$

$$Q_C = \left(T_{C,j} - T_C\right)K \quad (9)$$

Where T_H and T_C are respectively the temperatures of the hot and the cold sides of the substrates, and K is the thermal conductance of the substrates.

This exchange of heat rate at the hot and the cold junctions is the sum of the Peltier effect, the thermal conduction through the couple according to Fourier law and the Joule heat loss due to the flow of current (Dalola et al. 2009; Verma, Kane, and Singh 2016). As a result, Q_H and Q_C can also be expressed as (Verma, Kane, and Singh 2016)

$$Q_H = n_s N S_{p-n} T_{H,j} I_{TE} + n_s n_p N k_{\text{int}}\left(T_{H,j} - T_{C,j}\right) - \frac{1}{2} I_{TE}^2 R_T \quad (10)$$

$$Q_C = n_s N S_{p-n} T_{C,j} I_{TE} + n_s n_p N k_{\text{int}}\left(T_{H,j} - T_{C,j}\right) + \frac{1}{2} I_{TE}^2 R_T \quad (11)$$

where k_{int} is the internal thermal conductance $\left[WK^{-1}\right]$ of the couple, K is the thermal conductance of the substrates, It can also be seen from equation 8,9, 10 and 11 that,

$$\frac{\Delta T'}{\Delta T} \cong \frac{K}{K + 2n_s n_p N k_{\text{int}}} = \beta \quad (12)$$

Where $\Delta T = T_H - T_C$, is the temperature difference between the hot and the cold substrates and β is the ratio between the temperature gradients between the substrate and temperature gradient between the TE elements (Manikandan and Kaushik 2015).

A useful parameter for the performance assessment of a TEG is the power factor, PF and efficiency, η (Montecucco, Siviter, and Knox 2015). Montecucco et al. in (Montecucco, Siviter, and Knox 2015) defined PF as the power in matched-load conditions per unit squared temperature gradient per unit module area A_m. According to this definition and considering equation 7 and equation 12, the power factor of the array can be described by the following equation (Montecucco, Siviter, and Knox 2015):

$$PF = \frac{P_{TE,\max}}{\left(\Delta T\right)^2 A_m} = \frac{n_s n_p N S_{p-n}^2 \beta^2}{8A_m\left(\frac{\rho h}{A} + \frac{\rho_C l_C}{A_C}\right)} \quad (13)$$

$$\text{Efficiency, } \eta_{TE} = \frac{\textit{Output Power}}{\textit{Input power}} = \frac{P_{TE}}{Q_H} \quad (14)$$

Using equation 6, 8 and 11, the efficiency can be well-defined as (Montecucco, Siviter, and Knox 2015);

$$\eta_{TE} = \frac{P_{TE}}{Q_H} = \frac{R_{TE}\cdot\left[\frac{n_s n_p N\cdot S_{p-n}\left(\Delta T\right)\beta}{\left(R_T + R_{TE}\right)}\right]^2}{n_s N S_{p-n} T_{H,j} I_{TE} + n_s n_p N k_{\text{int}}\left(T_{H,j} - T_{C,j}\right) - \frac{1}{2} I_{TE}^2 R_T} \quad (15)$$

Where k_{int} is the thermal conductance given as (Montecucco, Siviter, and Knox 2015);

$$k_{\text{int}} = \frac{2\lambda A}{h} \qquad (16)$$

And λ is the thermal conductivity of the TE material $\left[W/(Km)\right]$ (Dalola et al. 2009) .

At matched load condition, the maximum efficiency can be found as (Dalola et al. 2009).

$$\eta_{TE,\max} = \frac{n_p^2 \Delta T \beta}{2T_{H,j} + \frac{16\lambda A}{S_{p-n}^2 h}\left(\frac{\rho h}{A} + \frac{\rho_c l_c}{A_c}\right) - \frac{\Delta T \beta}{2}} \qquad (17)$$

The daily average increase in efficiency η_{avg} can then be estimated as (Motahhir et al. 2019);

$$\eta_{avg} = \frac{\sum\left(P_{C,sys} - P_{NC,sys}\right)}{\sum P_{NC,sys}} x100\% \qquad (18)$$

Where $P_{C,sys}$ is the daily average output power of the TEG with cooling system and $P_{NC,sys}$ is the daily average output power of the TEG when there is no cooling system (Motahhir et al. 2019).

Method: The experimental set up is as shown on plate 1, plate 2 shows the developed series and parallel arrangement of the TEG. The schematic on figure 2 was used to explain the experimental procedure. The Rheostat was adjusted to obtain the current-voltage characteristics of the TEG model (SP1848-SA27145), using digital multimeters (SD9205A).

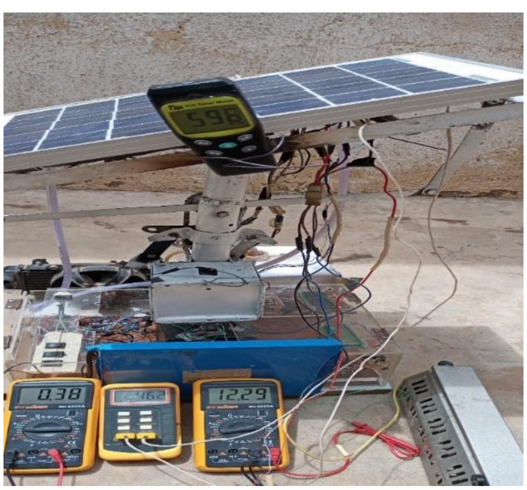

Plate 1: Real time Experimental setup, Currents and Voltages measurements

The amount of irradiance and temperature profile of the PV panel, TEG and the ambient were taken using solar radiation meter (Model pi 510) and dual digital thermometer (model 6802II TWOK-TYPE) respectively. The experiment was conducted at different time of the day under natural convection when there is no cooling of the TEG. When the cooling was introduced similar electrical parameters were also recorded. This procedure was followed in order to get the load current, I_L and voltage, V_L characteristics with the cooling and without cooling of the TEG cold side, it also allowed to develop P_L-V_L and P_L-I_L characteristics of the TEG (Ali and Yusuf 2017). The positions of the maximum power point were located on the plots in MATLAB environment.

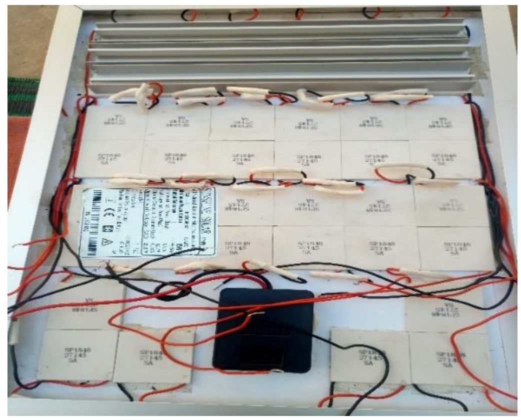

Plate 2: Series and parallel arrangement of TEGs at the back of the panel

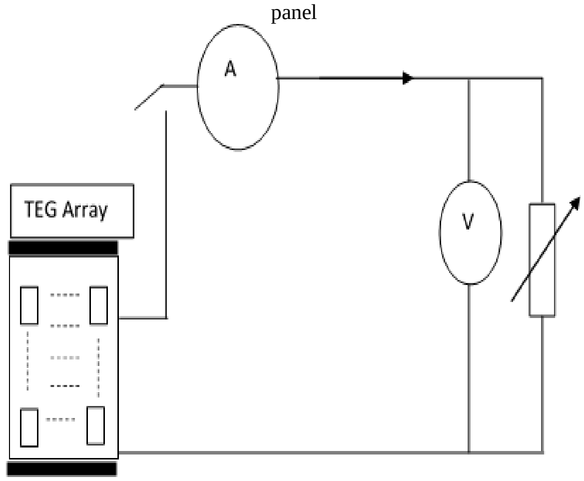

Figure 2: Experimental schematics for measuring the Currents and Voltages

RESULTS AND DISCUSSION

The characteristics behaviors of both the I-V and P-V characteristics curves for both the convectional and the cooling systems models obtained and the known parameters from the datasheet as well as the unknown parameters obtained from MATLAB simulation for the TEG model (SP1848-SA27145) were recorded by employing the method in (Ali and Yusuf 2017). The measured data were plotted in figure 1 and 2, the measurement was done hourly from 8am to 5pm for both the conventional and the cooling system Adopted on 16th February 2020. The position of the maximum power point MPP on the plots where located and recorded. Table 1 presents the important output parameters obtained from the I-V characteristics of the TEG on 26th February 2020 using the conventional cooling method, and table 2 presents the same parameters extracted when the cooling system was introduced.

Table 1: Electrical characterization of TEG without cooling fluid dated 16th February, 2020

Time/H	T1/°C	T2/°C	DT/°C	Isc/A	Voc/V	Imp/A	Vmp/V	Pmp/W	Pin/W	Efficiency/%
8	30.1	33	2.9	0.306	0.768	0.153	0.383	0.059	2.7236	2.1560
9	34.6	37.9	3.3	0.348	0.874	0.174	0.436	0.076	3.3338	2.2807
10	37.6	41.2	3.6	0.380	0.953	0.190	0.476	0.090	3.7767	2.3959
11	40.3	46.2	5.9	0.622	1.563	0.312	0.779	0.243	6.5619	3.7039
12	46.0	52.7	6.7	0.707	1.774	0.354	0.885	0.313	8.0691	3.8843
13	52.7	60.1	7.4	0.780	1.960	0.391	0.978	0.382	9.6499	3.9621
14	46.2	54.4	8.2	0.865	2.172	0.433	1.083	0.469	9.9991	4.6952
15	45.0	51.1	6.1	0.643	1.616	0.322	0.806	0.260	7.2258	3.5955
16	40.8	45.8	5.0	0.527	1.324	0.264	0.661	0.175	5.5705	3.1335
17	37.1	41.1	4.0	0.422	1.059	0.211	0.528	0.112	4.1990	2.6605

Table 2: Electrical characterization of TEG with cooling fluid dated 16th February, 2020

Time/H	T1/°C	T2/°C	DT/°C	Isc/A	Voc/V	Imp/A	Vmp/V	Pmp/W	Pin/W	Efficiency/%
8	29.2	33.1	3.9	0.411	1.033	0.206	0.515	0.106	3.661	2.901
9	31.5	37.9	6.4	0.675	1.695	0.338	0.846	0.286	6.382	4.481
10	32.4	37.5	5.1	0.538	1.351	0.270	0.674	0.182	5.080	3.575
11	34.5	42.9	8.4	0.886	2.225	0.444	1.110	0.493	8.905	5.532
12	35.9	49.8	13.9	1.466	3.681	0.735	1.836	1.349	15.810	8.533
13	37.1	54.6	17.5	1.845	4.635	0.925	2.312	2.138	20.860	10.251
14	36.9	52.8	15.9	1.677	4.211	0.840	2.101	1.765	18.641	9.469
15	38.5	48.7	10.2	1.076	2.701	0.539	1.348	0.726	11.577	6.275
16	33.9	42.8	8.9	0.939	2.357	0.470	1.176	0.553	9.407	5.879
17	32.8	39.7	6.9	0.728	1.827	0.365	0.912	0.332	7.042	4.720

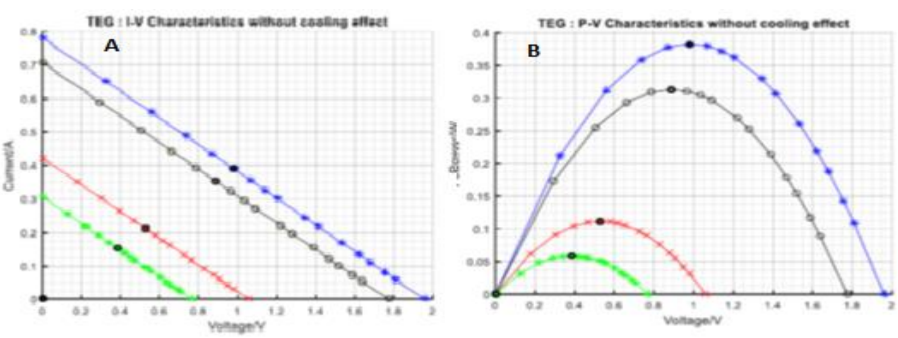

Fig 3: Electrical Characteristics of TEG arrays without cooling (a) I-V Characteristics (b) P-V Characteristics

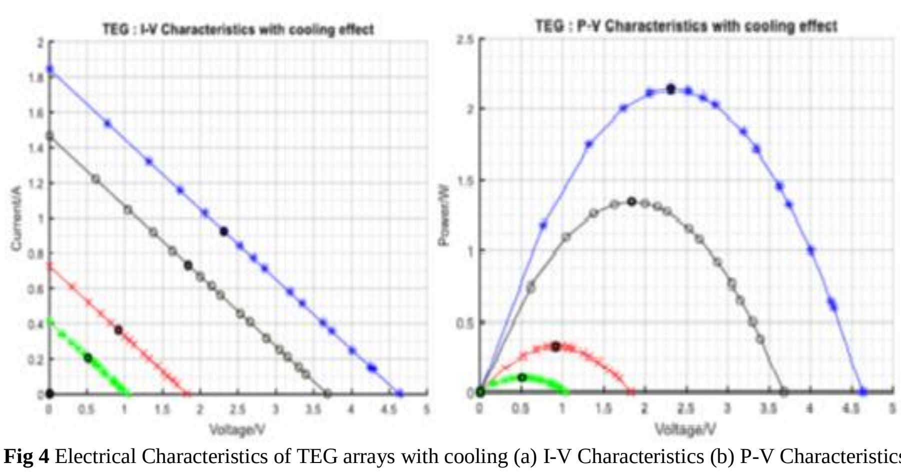

Fig 4 Electrical Characteristics of TEG arrays with cooling (a) I-V Characteristics (b) P-V Characteristics

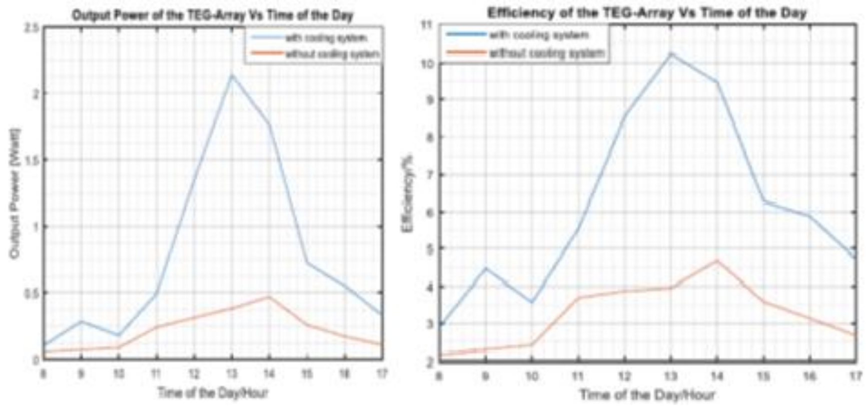

Fig 5: (a) Output power of the TEG with and without cooling system Vs time of the day (b) Efficiency of the TEG with and without cooling system Vs time of the day

The daily average efficiency of the TEG with the conventional cooling was found as;

$$\frac{0.218}{6.111} x100\% = 3.568\%$$

The daily average efficiency of the TEG with cooling technique was found as;

$$\frac{0.793}{10.737} x100\% = 7.386\%$$

The daily average increase in efficiency of the TEG with cooling system as compared to TEG with the conventual cooling system was found as;

$$\frac{0.793 - 0.218}{0.218} x100\% = 263.76\%$$

Figure 3 and 4 depicted the I-V and P-V characteristics plots for the TEG array from which the maximum power point MPP were located by simulation in MATLAB environment. Figure 5 and 6 depicted the plots of output power and efficiency variation with respect to time of the day. The maximum power was seen to be around the noon from 12pm up to 2pm of figure 5. Similarly, the maximum efficiency was seen to be around the same time interval, which is the period were infrared radiation from the sun seems to be maximum in a day. The daily average efficiencies obtained from the conventional and cooling method adopted were 3.568% and 7.386% respectively. The daily average increase in efficiency of this cooling technique as compared to the conventional one is 263.76%. This shows that the daily average power is improved by a factor of 2.64. This is an indication that cooling the TEG with a coolant (water in this case) increases the temperature gradient of TEG, thus, higher amount of power can be recovered and hence improved the performance of the TEG for waste heat recovery application.

*Conclusion***:** Characteristics behavior of both the TEG system with convectional cooling and water circulating-heat sink cooling techniques were studied in this work. The MPPs were located to investigate the maximum power for both the systems. The daily maximum power for both the systems were found to be around the midday. The proposed water circulating-heat sink technique has a higher output power and efficiency than that of the conventional cooling system. This indicates that the proposed method can enhance the TEG power generation system, hence, the performance of TEG in thermal waste heat recovery application can be improved.

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