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Performance Analysis of a Thermoelectric Cooler Placed between Two Thermoelectric Generators for Different Heat Transfer Conditions

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ABSTRACT

The thermoelectric cooler (TEC) and thermoelectric generator (TEG) modules have several appealing features, including fixed parts, high reliability, low maintenance costs, and seamless connection with other heating equipment, accompaniment, can be powered by a variety of low-energy renewable energy sources such as solar water/air collectors, ground heat exchangers or heat from biomass. The thermoelectric assembly was integrated into the TEC using the TEG in this study. A prototype was developed in which recently developed thermoelectric modules were integrated into a thermoelectric cooler. For this purpose, a TEC sandwiched between two TEGs with different heat transfer conditions was established, to simulate the heat transfer and thermoelectric behavior of both the TEG and the TEC system, and evaluate the effect of the combined TEG-TEC on the performance parameters of the good system by comparing different cooling modes ranging from natural convection, forced convection, and water-cooling tests. It was shown that to the natural convection of heat transfer, as the TEC voltage increases, the hot surface temperature of the upper TEG increases, and the cold surface temperature of the lower TEG decreases, where the lowest TEC temperature reaches 1.36 A. When using forced convection (by using a fan), the temperature profile decreases over time, starting at around 70 °C for 7V, and after almost 60 minutes, the temperature drops to around 45 °C for 3V. This turned out to be a match between experiment and theory in all traces shown, with a voltage difference of 25 mV for 3V TEC and ending at 70 mV for 8V TEC.

Keywords: thermoelectric cooler, sandwich TEC, TEG performance, heat transfer conditions, enhancing power generation, low energy harvesting, renewable energy induction.

INTRODUCTION

The current situation in terms of the increase in the growth rate of demand for electricity, which has an impact on the increase in the costs of its generation, is much greater than the intentions and orientations of the energy sector to develop strategies leading ultimately to maximizing the efficiency of current production sources (Alsaqoor et al., 2022; David et al., 2021; Khaled et al., 2022).

The rapid advancement of renewable energy technology at the industrial level has led to a lack of interest in the development of a system based on low-temperature renewable energy sources (Al-Manea et al., 2022). However, in recent years, there has been a growing interest in researching one of the systems referred to as a system that can be run on low renewable energy heat sources a semiconductor device, called a Thermoelectric Generator (TE). It is characterized by a quiet and environmentally friendly system ensuring an efficient conversion interface between thermodynamic and electric domains (Mansour et al., 2022). Thermoelectric devices are characterized by the ability to operate based on the conversion of thermal energy into electricity or the conversion of electrical energy into a temperature difference directly based on thermoelectric effects (Bell, 2008; Blatt, 2012; Skipidarov and Nikitin, 2016).

Similar to the concepts of electric motors and generators, thermoelectric generators (TEG) convert heat to electricity while thermoelectric coolers (TEC) convert electricity to heat. Thermoelectric generators are one of these low-heat energy sources. (Lyu et al., 2021) investigated a hybrid cooling system for the battery pack that included TEC, liquid cooling, and forced air cooling. Their work revealed that the voltage provided to the fan and pump influenced the effectiveness of the cooling system.They demonstrated that when powered by 40V heather, the BTMS based on TEC technology was able to retain the battery at a temperature of 20 °C lower than pure liquid cooling. Furthermore,the thermal model comprising the battery and the TEC thermal model demonstrated that the thermal behavior of the battery under TEC cooling settings effects the proper design and optimization of BTMS with acceptable accuracy (Liu et al., 2014).

TEG uses waste heat to generate energy, which can be described as a green energy source. From an economic point of view, waste heat or heat from renewable energy sources is a free source of electricity generation. Therefore, the use of TEG can be considered a renewable energy source (Mamur et al., 2021).

Thermoelectric devices are broadly applied, particularly in military equipment, aviation, medicine, and industry (Chen et al., 2016; Kane et al., 2017; Riffat and Ma, 2003). Self-propelled thermoelectric coolers (TEC-TEG) were suggested by (Lin et al., 2019). Single and two-stage TEC-TEG systems were designed and thoroughly tested. Their work proposed a novel design of combined TEC-TEG systems that separated hot and cold TEC feeds using two single-stage TEGs. The advantage of the new design is the distinct setup of the electric current. They developed a three-dimensional thermoelectric model to compare the performance of new and original designs for different ratios of thermocouple numbers and operating conditions. The advantage of the new design is the distinct setup of the electric current. Their design demonstrated that the new design not only improves system cooling efficiency but also boosts the maximum temperature drop throughout the TEC. TEG can convert heat into electricity thanks to the Seebeck effect and therefore has great potential for the use of solar energy(Singh et al., 2011; Suter et al., 2011).

Based on the Peltier effect, TEC can utilize electricity to elevate heat to high-temperature heat sources. Therefore, it is extensively employed in different cooling, freezing, and temperature control technologies (Huang and Duang, 2000; Zhao and Tan, 2014).

Presented in (Olabi et al., 2022) the applications of TEG for WHR (waste heat recovery) in various applications, and also presented the barriers and challenges associated with TEG in WHR, so they concluded that the combination of waste heat recovery with TEG in different thermal systems is more likely to will be accepted with high efficiency.

In this work (Teffah et al., 2018) a module containing TEC, TEG, and total copper heat sink connected in series was tested; investigated the cooling behaviour during electricity generation by TEC and TEG and found that TEG production increases with increasing TEC input voltage to about 0.5V at 5V input voltage.

In (Bayendang et al., 2022), thermoelectricity is proposed as an alternative energy source (TEG) as well as an energy-saving load (TEC) for many applications requiring low DC power, cooling, and heating. It has been found that the output current from the TEG or the input current to the TEC initially increases the TEG output power and the TEC cooling power, respectively.

The SP1848 thermoelectric generator was tested with series and parallel circuits in (Susanto et al., 2021), and the maximum efficiency values were achieved with a 5 kΩ resistor, achieving 5.38% of the left TEG.

In the case of TEGs, the efficiency of the right side of the generator is usually stable. It was also observed that the highest value of right-hand TEG generator efficiency is attained at 0.48% at 2kΩ.

In work (Jouhara et al., 2021), they found that if it is to achieve the effect, regardless of the cost, this effect can be achieved by using thermoelectric devices and producing cold if electricity is available, or generating electricity if heat is available, inattentively low COP and efficiency of thermoelectric devices. In this study, an experimental investigation for sandwiched TEGs (TEG1-12611-08) with TEC (TEC1-12706) is performed to visualize the double TEG performance under precisely controlled temperature differences created by TEC with different ambient conditions. The experimental investigation is a part of a project simulating the use of TEG to produce electricity all day and night depending on sky temperature and ground temperature.

In (Alahmer et al., 2022) have been experimentally tested and compared with liquid evaporation mode with different heat fluxes using free and forced convection, so the results revealed that when compared to free convection without fins, adopting forced steam convection would improve the TEG voltage fluctuations 435.9%.

In (Mamur and Ahiska, 2014) was presented and described the role of thermoelectric generators (TEG) in the conversion of geothermal energy into electricity, and the TEG structures used for electricity production. It was confirmed that the conversion efficiency of commercially used thermoelectric modules (TEM) is less than about 10%.

EXPERIMENTAL SETUP

For the process related to TEG, we have various options for selecting the system drive, these can be conventional sources, such as heat of combustion or electricity, they can also be renewable sources, such as solar hot water collectors, geothermal sources, etc.

As illustrated in Figure 1, the Thermoelectric Generator TEG encounters several energy conversions processes between temperature difference and energy; Seebeck voltage, Julian, Peltier, conduction, and Thomson heat flow.

The setup used in this work consists of one TEC sandwiched between two TEG, where Voltage is supplied to the TEC to control its hot and cold surface temperatures touching the hot surface of the upper TEG and the cold surface of the lower TEG. The upper TEG is provided by an industrial heat sink for natural and forced convection heat transfer to room temperature. The lower TEG is provided with only fins for natural convection and is able to be inserted in water to simulate the geothermal water temperature Figure 2.

Properties of the used TEG and TEC are given in Table 1. The setup was provided with six thermocouples to measure the temperatures at all surfaces and ambient temperature, two multimeters to measure the voltage created by the upper and lower TEGs used, and a power supply to control the voltage and current supplied to the TEC between the two TEG. Results of all thermocouples were collected using a USB TC-08 8-channel thermocouple logger with PicoLog Data Logging Software and recorded on a PC. The current and voltage were recorded manually with time for each specific test.

Performed experiments

The experimental setup which has been prepared was used to perform different experiments. The performance of the TEG 1 and TEG 2 were tested under 1-variable temperature differences for natural heat transfer from the upper and lower surfaces, 2- forced convection from the upper surface, and 3- natural convection with liquid water from the lower surface.

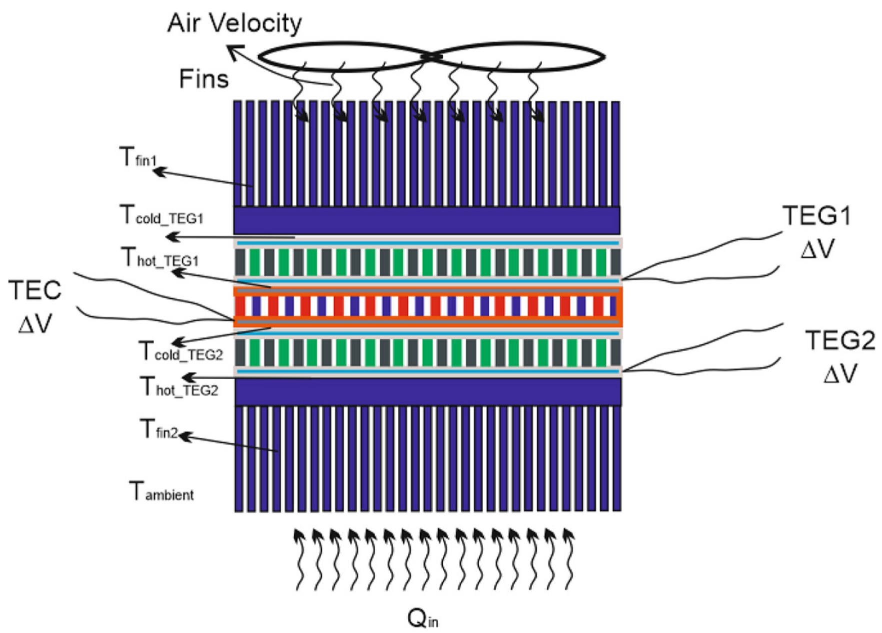

Figure 1. Schematic diagram of the sandwiched TEC between two TEGs working principle

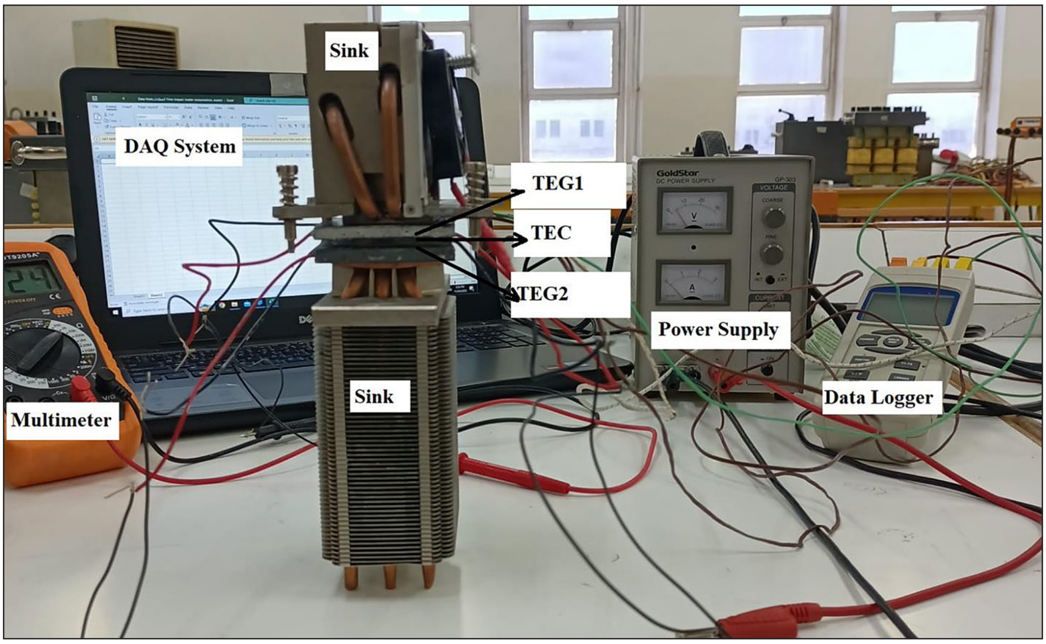

Figure 2. Experimental setup used to test the performance of a sandwiched TEC-TEGs system

Table 1. Technical specifications for TEG1-12611-08 and TEC1-12706

TEG1-12611-08 technical specifications	
Hot side temperature	300 °C
Cold side temperature	30 °C
Open circuit voltage	9.5 V
Matched load resistance	1.8 Ohms
Matching load output voltage	4.8 V
Matching load output current	2.7 A
Matching load output power	13 W
AC resistance at 27 °C and 1000Hz	0.7–1.0 Ohms
TEC1-12706 technical specifications	
Hot side temperature	138 °C
Cold side temperature	-17 °C
Max voltage	16.4 V
Matching load output current	6.4 A
Matching load output power	60 W
Modul resistance	2.3 Ohms

The governing equations of the TEG are derived using Figure 1, in order to comprehend the system performance. Performing energy balance for the hot portion of the TEG yields.

$$\dot{Q}_h + \frac{1}{2} R\, I^2 - K(T_h - T_c) - \alpha\, T_h I = 0 \quad (1)$$

where: $\dot{Q}_h$ – the heat transfer rate from the TEG hot surface;

R, K, α, I, T_h and T_c – TEG electrical resistance, thermal conductivity, Seebeck coefficient, current, hot and cold surface temperaturesrespectively. For the bottom portion of the TEG as:

$$-\dot{Q}_c + \frac{1}{2} R\, I^2 + K(T_h - T_c) + \alpha\, T_c I = 0 \quad (2)$$

where: $\dot{Q}_c$ – the heat transfer rate from the TEG cold surface.

Because the TEG module is side-by-side insulated and mostly represents a modest value, it should be noted that the Thomson heat was ignored. The TEG is seen as a heat engine, producing power (P) equal to the difference between the energy provided and rejected (Goupil et al., 2011):

$$P = \alpha\, I\, (T_h - T_c) - R\, I^2 \quad (3)$$

RESULTS AND DISCUSSION

TEGs variable surface temperature with natural heat transfer

In order to determine the performance of the combined TEG-TEC system; the system was operated with natural convection on both sides and a variable TEC voltage.

Moreover, Figure 3 shows that the heat transfer from the TEG2 decreases after 1.36 A, reaching zero temperature difference between the hot TEG temperature and fins temperature. This results in a zero-power generation from the lower TEG. There is a need to increase heat transfer from the TEG.

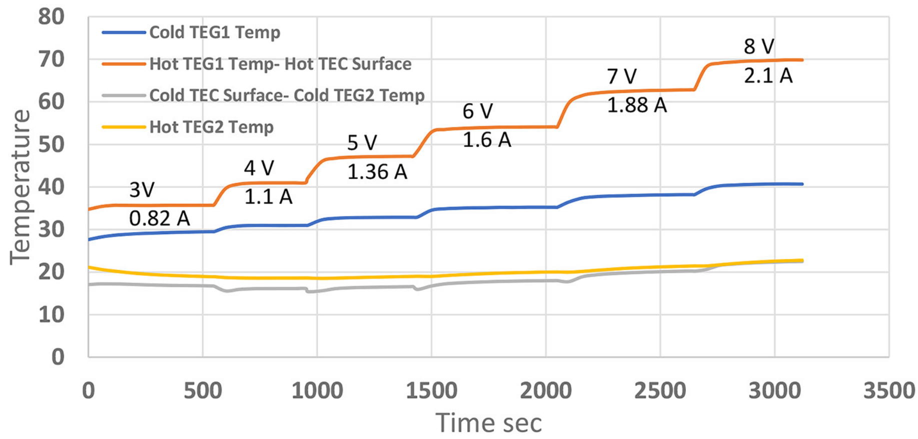

Figure 3. The system temperatures and behavior at different TEC voltage (3-8 V),a fan at ta the bottom of TEG2

Effect of forced heat transfer

At 8 volts, the lower TEG (LTEG) shows almost zero power generation, and the effect of the back heat flow from the hot TEC surface on the cold TEC surface needs to be investigated. A fan mounted on the upper TEG (UTEG) fins was switched on to do so. As shown in Figure 4, forced convection increased the heat transfer from the hot TEC (HTEC) surface.

Enhancing the heat transfer from the HTEC lowered the temperature of the cold TEC (CTEC)

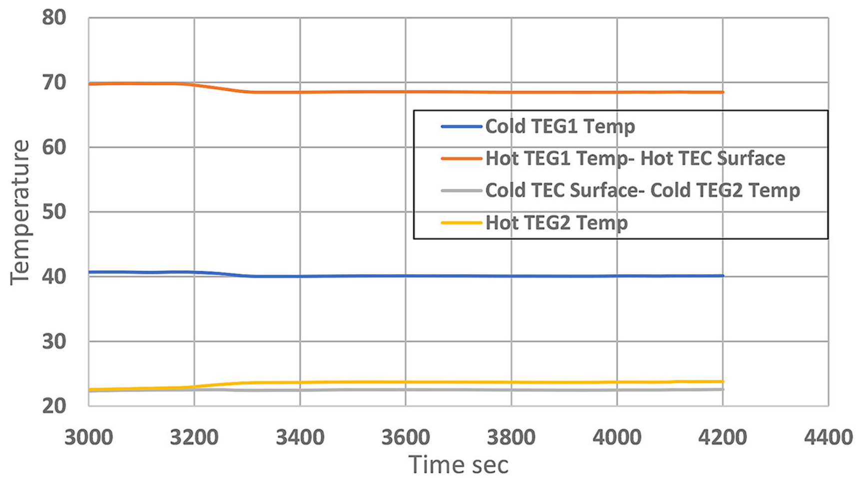

Figure 4. The effect of increasing heat transfer with a top fan

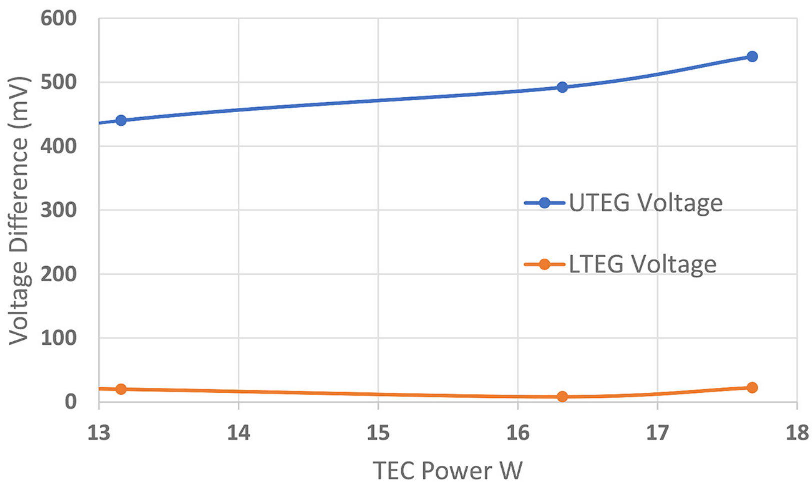

Figure 5. The effect of Enhancing heat transfer with a top fan

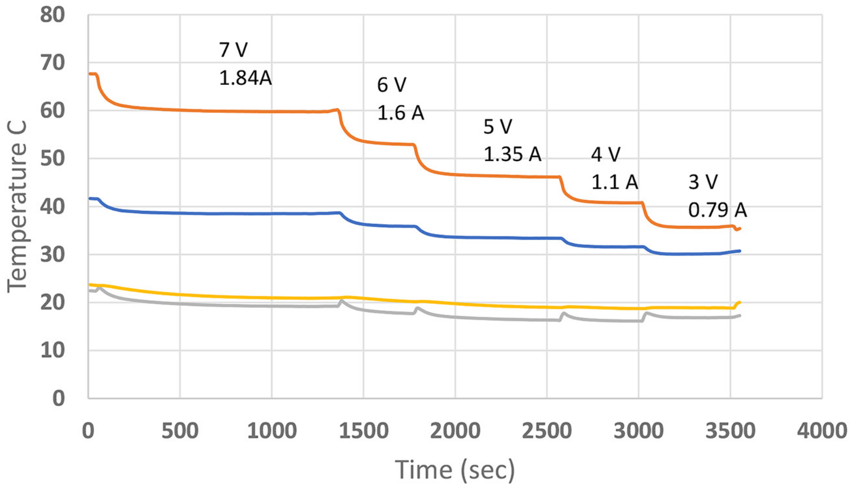

Figure 6. The system temperatures and behavior at different TEC voltage (3-8 V). a fan at ta the Top of TEG2

surface and assisted LTEG in generating power again. This indicates the importance of having an effective heat transfer medium when using thermoelectric elements.

Figure 5 indicates the power generation values from the UTEG and LTEG when a fan is switched on. It is clear from the figure that both TEGs produce higher power if the heat transfer is facilitated. An important phenomenon that should be noted from Figure 5 is that, unlike the HTEC surface that drops down uniformly when TEC power is reduced, the temperature of the CTEC surface increases instantly and then drops down to a steady state. This phenomenon needs more investigation, but it might be due to unbalance between the different effects included in thermoelectric elements. To ensure the achieved data, the device was tested with lowering power supplied to the TEC and found the same results Figure 5.

Figure 6 shows that for both the cooled surfaces of UTEG and HTEC, the temperature profile decreases with time, starting at about 70 °C for 7V, and after almost 60 minutes, the temperature is reduced to around 45 °C for 3V. For the cold part of LTEG, the temperature within 60 minutes decreases by 10 °C, starting from 40 °C to 7V and ending at 30 °C for 3V.

Effect of water cooling

As the heat transfer from the fins of the system shows valuable increments in the TEGs power generation, the system is tested with heat transfer from the LTEG fins to water. Figure 7 shows the system behavior when run with fins in water under variable power supply to the TEC element and thus variable temperatures. The system was again tested for TEC voltage from

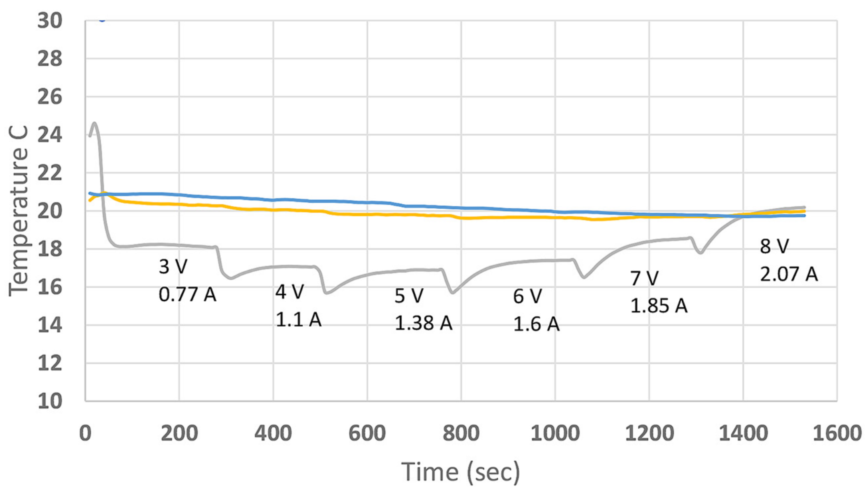

Figure 7. The system temperatures and behavior at different TEC voltage (3-8 V). a fan at ta the Top of TEG2 bottom water cooling

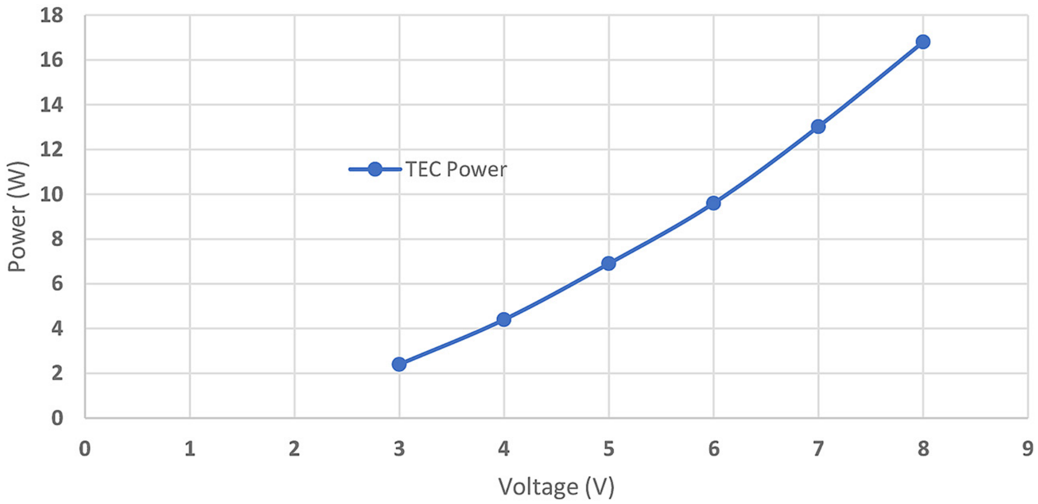

Figure 8. The relationship between voltage and power for TEC

3-8 Volts (2.5-16 W). Figure 6 shows a valuable improvement in LTEG performance. The water and fins temperatures decreased steadily and slowly, but the CTEC temperature dropped more than that of natural convection, even with a fan on. Higher temperature differences mean higher power production from the LTEG, which is favorable.

Figure 8 shows the power supplied to the TEC to generate the temperature differences for TEGs under the different voltages (3-8 Volts). As it is expected, the power increases with increasing voltage. The current also changes according to the resistance of the TEC and working temperature.

Figure 9 shows the power produced by the UTEG versus the TEC power for the three cases studied. Figure 9 indicates the maximum voltage achieved when forced convection is used at the upper fins. Water cooling of lower fins enhanced the power generation from the UTEG more than that of natural convection. This study focuses on the importance of heat transfer from the TEGs to achieve valuable values power. It is clear from both TEGs that as the heat transfer was enhanced, the power generated was also enhanced. The impact of the combined TEG-TEC on the performance parameters of the borehole system was comprehensively analyzed and compared in various cooling modes. It ranged from natural convection, forced convection, and water-cooling tests, including TEG output, conversion efficiency, TEC cooling capacity, that the system was operated with natural convection on both sides, and variable voltage TEC. Finally, a comparative study and numerical assessment of the increase in efficiency of various cooling modes in the TEG and TEC systems were conducted.

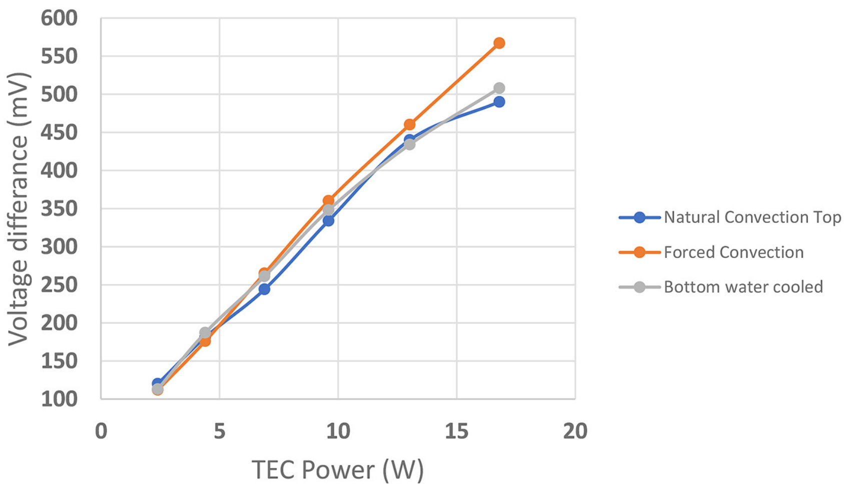

Figure 9. Power Produced by the UTEG versus TEC power

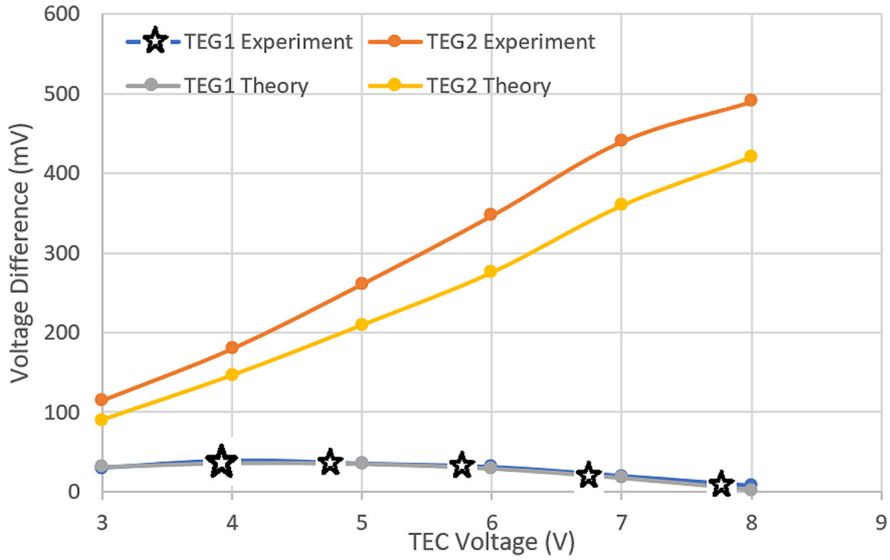

Figure 10. Power based on manufacturer's data (theoretical) compared to experimental results

RESULTS VALIDATION

To ensure the results achieved by the constructed experimental system, a comparison between the theoretical and experimental data was performed in Figure 10. Figure 10 shows the experimental results compared to TEGs theoretical results based on manufacturer data (TEG1-12611-08).

From the point of view of validating the results, it is obvious from our experimental case that the theoretical and experimental data were in good agreement.

CONCLUSION

This study constructed a TEC sandwiched between two TEGs with varying heat transfer conditions to simulate the heat transfer and thermoelectric behavior of both TEGs and the TEC system in order to externalize the influence of TEC on the performance of thermoelectric systems. The impact of the combined TEG-TEC on the performance parameters of the borehole system was comprehensively analyzed and compared in various cooling modes ranging from natural convection, forced convection, and water-cooling tests, including TEG output, conversion efficiency, TEC cooling capacity, that the system was operated with natural convection on both sides, and variable voltage TEC. Finally, a comparative analysis and numerical evaluation of the efficiency improvement of multiple cooling modes in the TEG and TEC systems was performed.

The following conclusions can be drawn. In terms of natural convection of heat transfer, it was obvious that as the TEC voltage increased, the temperature of the upper TEG's hot surface increased while the temperature of the lower TEG's cold surface decreased, with the lowest TEC temperature reaching 1.36 A.When utilizing a fan, i.e., forced airflow, the temperature profile for both UTEG and HTEC cooled surfaces falls with time, starting at around 70 °C for 7V and down to about 45 °C for 3V after about 60 minutes. The temperature declines by 10 °C in 60 minutes during the cold part of the LTEG, starting at 40 °C at 7V and ending at 30 °C at 3V. The temperatures and behavior of the system at various TEC voltages while the fan is on and the water is flowing were positive, with a temperature of 22 °C attained.

The power increases with increasing voltage and is reported for 3 and 8 V, 2.8 and 16.8 W, respectively. It is also observed that the current varies with TEC resistance and operating temperature.There is a perfect match between experiment and theory in all the presented paths, but unweighted is the derivation in the case of TEG2, which starts at voltage differences of 25mV for 3V TEC and ends at 70mV for 8V TEC.

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