

Enhancement of voltage generation for thermoelectric generator using parabolic pulsed heating

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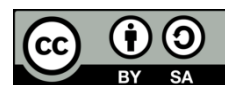
Steady heating

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ABSTRACT

This paper presents the results of investigations of the impact of parabolic pulsed heating on output voltage levels of a thermoelectric generator. The experiment was set up and tested under different test conditions. The output voltage levels were investigated. The experimental results showed that applying parabolic pulsed heating of 40, 60, 80 and 100 °C significantly maintained the output voltage levels of thermoelectric generator at about 80-95% which was different from steady heating case which was about 10-30% of maximum voltage level. Moreover, the parabolic pulse heating technique allows the heatsink to not be heated continuously and then the high temperature could be released out from a heat exchanger outside the heating period. This causes the next heating period to have a temperature difference between both sides of the device, and for that reason, could provide more power and efficiency.

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1. INTRODUCTION

Electricity can be directly produced form heat by thermoelectric generator (TEG) [1]. More than 70% of the global energy consumption is lost as waste heat the during conversion process. This wasted energy originates from numerous sources such as mining and smelting plants, factories, electricity generators, air-conditioning and lighting appliances, vehicles' engines, pipelines, brakes and exhausts, and even the human body [2], [3]. TEGs are made of 2 types of semiconducting materials, one is doped to be n-type and the other is doped to be p-type [4], [5]. One side of the TEG receives heating at the hot side (T_h : high temperature side), while the other side has lower temperature (T_c : cold temperature side). The electricity is generated by the different temperature (ΔT) between both sides of TEG [6]. The open circuit voltage generated by TEG (V) is determined by equation $V=n \Delta T$ where n is the number of connected thermocouples, α_{AB} is the Seebeck coefficients of the two joined materials A and B formingthe thermocouple ($\alpha_{AB}=\alpha_A-\alpha_B$) [7], [8]. However, the best conversion efficiency recorded for most structures and attractive material of TEGs is low relatively, about 7.3-11% [9]. Therefore, a number of studies have been conducted on TEG efficiency enhancement [10], [11] which can be classified into 3 common concepts. First, by using new or modified cell materials and structures [12] such as, figure of merit and thermocouples arrangement, rare earth materials, and innovative designs and devices [13] and TEG'type of structure [14], [15]. Vertical, planar and mixed. Second, providing high different temperature between both sides of the TEG such as cooling pads, heatsinks, multi-stage modules and other cooling systems.

However, using abundant rare earth materials allows for increased efficiency. But the cost of materials is more expensive as well and the maximum temperature difference of the TEG from both sides is still limited by the material, which means that the voltage generation is also limited.

Related research in [16], the TEG was applied with solar energy using a Fresnel lens. The distance between the lens and thermoelectric module was investigated. The TEG could produce 1.03 W with energy conversion efficiency of 1.81%. Lashin *et al.* [17] explained the TEG system was applied with an internal combustion engine through the exhaust gas channel. The research work provides an enhanced structural design with cooling fins, in order to maintain the temperature difference between the hot side and cold side of TEG. Zhu *et al.* [18] showed the TEG performance was investigated under highly concentrated light. The systems were designed for reducing temperature of photovoltaic cells. The photovoltaic cells were attached by TEG for reducing temperature of cell and the performance of TEG in case of partial illumination with different size of TEG and light intensity were analyzed. Results showed that the TEG (Length: 4 cm) delivered the maximum power when compared to the other TEG samples (length: 3 and 6.2 cm). Rahman *et al.* [19] reported the design and manufacture of a 3D flexible thermoelectric power generator using chemical vapor deposition (CVD) on a layer surface. The results showed that with an output voltage of a $4 \times 4 \text{ cm}^2$, the flexible TEG device was up to $\sim 1 \text{ mV}$, operating voltage at a temperature of $100 \text{ }^\circ\text{C}$. Yang *et al.* [20] describe a CMOS MEMS-based thermoelectric energy generator device used under natural cooling condition with a high output performance. The measured results showed an open-circuit voltage of as high as 1.6 V and an output power of $0.49 \text{ }\mu\text{W}$ when the temperature of the heat source was at $35 \text{ }^\circ\text{C}$, which makes it applicable to wearable TEG devices for converting body warmth. Balakrishnan *et al.* [21] illustrated an A3-D finite element model of a two-stage thermoelectric generator using low temperature bismuth-telluride thermoelectric material and Guterudite of medium temperature thermoelectric materials was used. The results showed the optimum structure of a two-stage thermoelectric device that can fully harvest electrical energy from the properties of thermoelectric materials. Ma *et al.* [22] reported TEG efficiency under steady-state and transient pulsed heating conditions. Square and triangular pulsed heat functions were compared for temporary studies. The results show that square pulsed heating provides the best efficiency compared to triangular pulsed heating and steady state heating.

However, most of the above-mentioned research applied steady state heating to the TEG. The other case depends on environmental factors which cause more complexity and hard controlling. In case of pulsed heating, it was found that it could significantly enhance TEG performance in a simulation [22], [23]. In addition, most works proposed only the maximum output and efficiency, while the maintain output value levels of the TEG have not been presented.

In this paper, a pulsed parabolic heating technique is presented for use with the most commonly used TEG structures. The experiments were tested under most testing temperatures T [24], [25] in range $0\text{-}100 \text{ }^\circ\text{C}$, the TEG output voltage level can be determined through both theoretical and experimental investigations. This paper is organized as follows: methodology and experimental test-rig in section 2, results and discussion in section 3, and conclusions in section 4.

2. METHOD

2.1. Experimental system

A schematic diagram of the TEG test is shown in Figure 1. The system can be divided into four parts; heat supply (IKA C-MAG HS7 Digital Hotplate) which can adjust different applied temperature, thermoelectric generator (TEG model type is SP1848-27145 and size is $4 \times 4 \times 0.34 \text{ cm}$ whose internal resistance is $2.5 \text{ }\Omega$), heat exchanger (dimension of $7 \times 9 \times 3.5 \times 0.1 \text{ cm}$ that was used to dispose heat with rate of $273 \text{ W/m}^\circ\text{C}$) and electrical resistance ($100 \text{ }\Omega$) and oscilloscope (GDS-2074A GW, INSTEK) which was used for the voltage measurement. The resolution of the measurement equipment was calculated $\sim 0.08 \text{ mV}$. To measure the temperature of hot and cold sides, type K thermocouples were used with an accuracy of $\pm 1.5 \text{ }^\circ\text{C}$ and the response time was 2.50 seconds.

2.2. Thermoelectric generator

TEG is a solid-state device which consists of a large number of p-type and n-type semiconductor junctions. One side of the TEG is heated and the other side has a lower temperature causing both sides to have different temperatures ($T_h - T_c$). As a result, heat stimulates free electrons to move. Therefore, the voltage according to the is as (1) [25]:

$$V_{out} = n(\alpha_A - \alpha_B)(T_h - T_c) \quad (1)$$

where V_{out} is output voltage of the TEG, n is the number of thermocouples, α_A and α_B are the Seebeck coefficient of p-type and n-type, respectively. T_h and T_c are the temperatures at the high temperature side and cold temperature side, respectively.

2.3. Experimental test scenarios

The experimental system described above for the ambient temperature in which the system was set up to be 25 °C. Three pulsed heating were applied to the TEG, including parabola pulse and steady state heat. Experiments performed over a continuous period time (1,000 seconds). The output voltage levels of the TEG were investigated. Elements used for the aforementioned experiment test set-ups is shown in Figure 2.

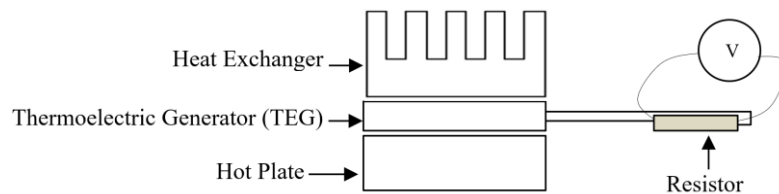


Figure 1. Diagram of TEG module testing concept in this research

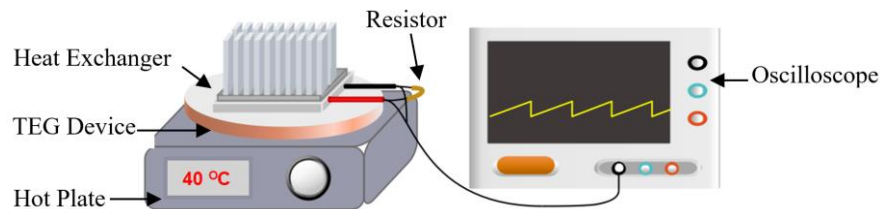


Figure 2. shows elements used for the aforementioned experiment test set-ups

3. RESULTS AND DISCUSSION

In this section, the results are explained and discussed and as follows: the output voltage levels of three pulsed heating conditions are compared the different temperature of both ends of TEG in different heating conditions and the normalized values of average output voltage levels.

3.1. The output voltage levels of two type heating conditions are compared

Experimental results from the test described above for ambient temperature of the system was set up to be 25 °C under different heating conditions were applied including parabolic pulsed heating and steady state heating showed that parabola pulsed heating provided better performance for the TEG compared with steady state heating in long time period.

Figures 3 to 6 show the measured output voltage levels for each particular testing temperature T level of 40 °C, 60 °C, 80 °C, and 100 °C. As shown in Figure 3(a), Figure 4(a), Figure 5(a) and Figure 6(b), steady heating applied to TEG could provide highest output voltage level (0.4-1.9 V) which was almost the same as when parabolic pulse heating was applied to TEG but for long time period testing, could provide different output voltage levels. Figure 3(b), Figure 4(b), Figure 5(b) and Figure 6(b), parabolic pulse heating maintain output voltage level but steady heating provided an output voltage level (0-0.4 V) for all testing T level.

The obtained results showed that applying steady heating to TEG could provide high output voltage levels of TEG initially but for longer periods, out voltage levels of TEG decreased near to zero for all tested T levels. This was different from the case of applied parabolic pulse heating that could maintain output voltage levels. This is because there is time to release heat out from heat exchanger at the cold side of the TEG.

3.2. The different temperature of both ends of TEG in different heating conditions

Figures 7 to 10 show that the maximum hot side and cold side surface temperature of the TEG attains a value of differentiated heating temperatures where generated heating from hot plate for particular

applied heating temperature for both side of TEG were compared between steady state heating is shown in Figure 7(a), Figure 8(a), Figure 9(a) and Figure 10(a) and parabolic heating is shown in Figure 7(b), Figure 8(b), Figure 9(b) and Figure 10(b).

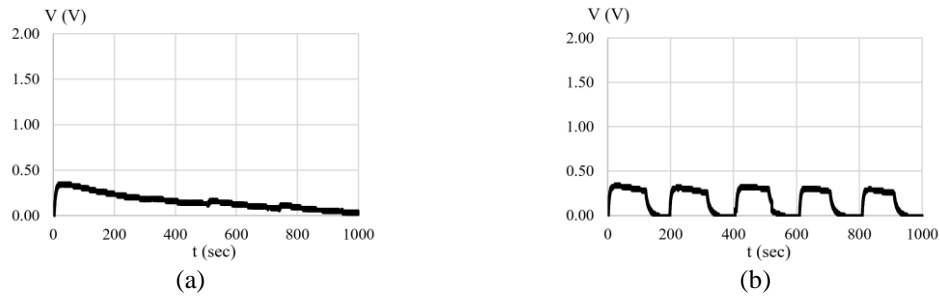


Figure 3. Voltage level output of TEG under different heating condition at 40 °C (a) steady heating and (b) parabolic heating

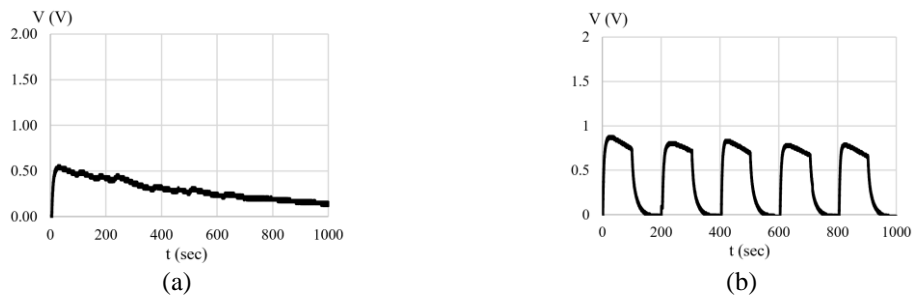


Figure 4. Voltage level output of TEG under different heating condition at 60 °C (a) steady heating and (b) parabolic heating

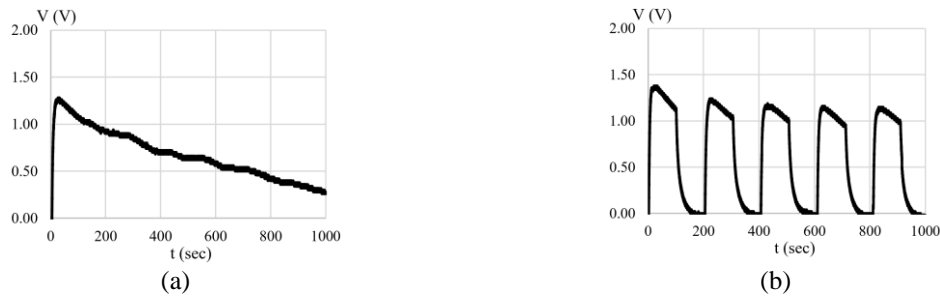


Figure 5. Show voltage level output of TEG under different heating condition at 80 °C (a) steady heating and (b) parabolic heating

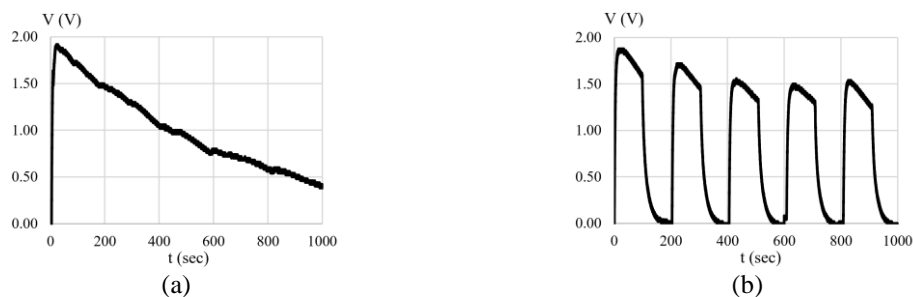


Figure 6. Voltage level output of TEG under different heating condition at 100 °C (a) steady heating and (b) parabolic heating

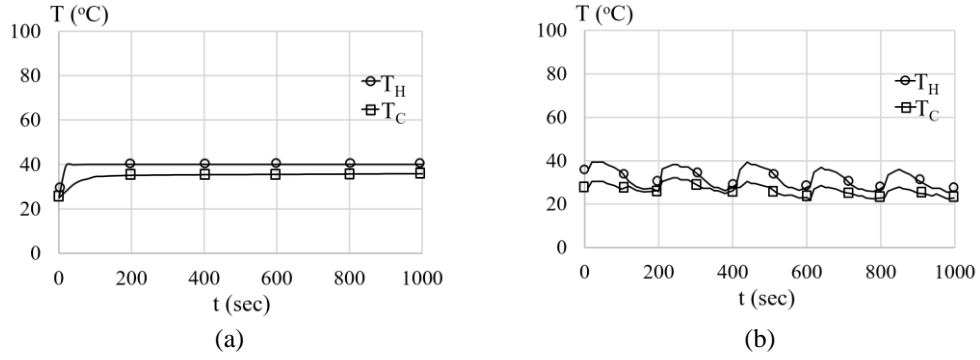


Figure 7. Different heating condition curves at 40 °C (a) steady heating and (b) parabolic heating

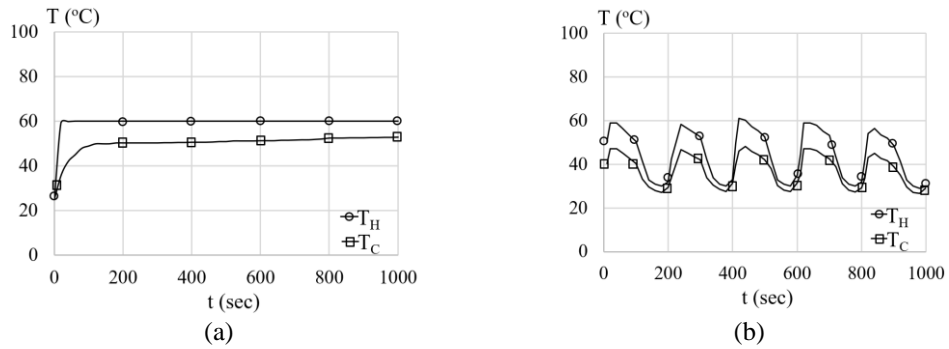


Figure 8. Different heating condition curves at 60 °C (a) steady heating and (b) parabolic heating

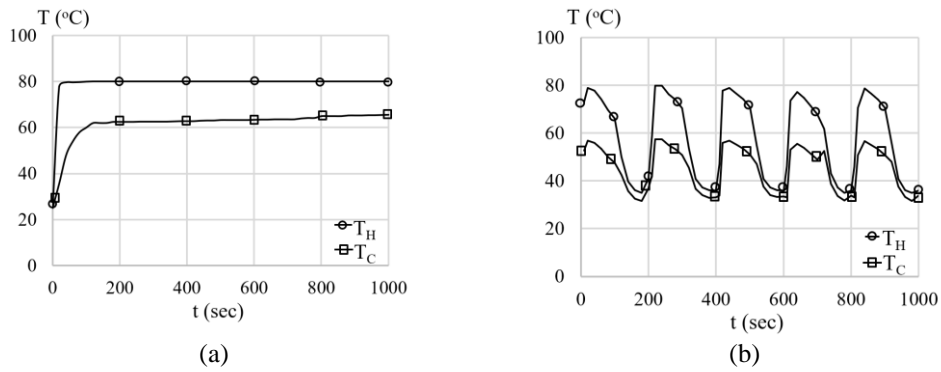


Figure 9. Different heating condition curves at 80 °C (a) steady heating and (b) parabolic heating

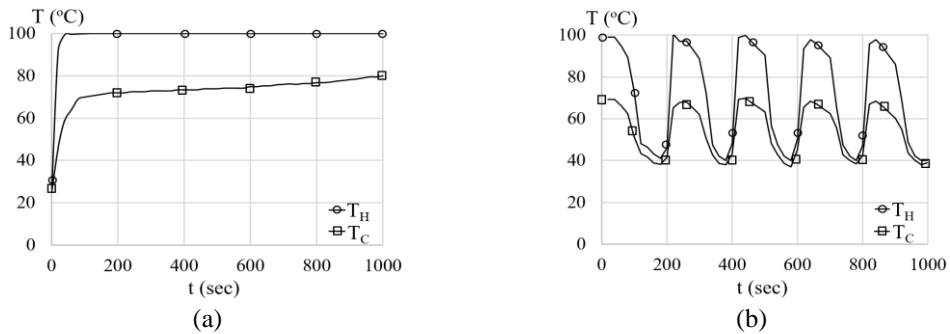


Figure 10. Different heating condition curves at 100 °C (a) steady heating and (b) parabolic heating

3.3. The normalized values of average output voltage levels

The experiment results show in Figures 1 to 6 that application of particular testing heat T of 40-60 °C could provide output voltage level (0.4-1.9 V) in both types of heating conditions for all particular T testing level. But for a longer time period, the different heating condition could provide significantly different output voltage levels. The above explanation is clearly shown by Figures 11 to 14; where applying the differentiated heating temperatures. With steadily applied heating, the voltage drop was about 90%, 75%, 70% and 70% at temperatures (T) of 40, 60, 80 and 100 °C respectively. Parabolic pulse heating could maintain output voltage level for all T levels.

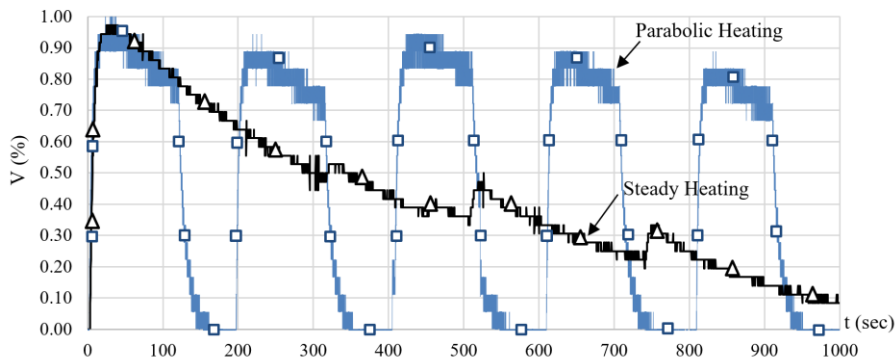


Figure 11. Normalized voltage value between steady and parabolic heating at particular testing temperature 40 °C

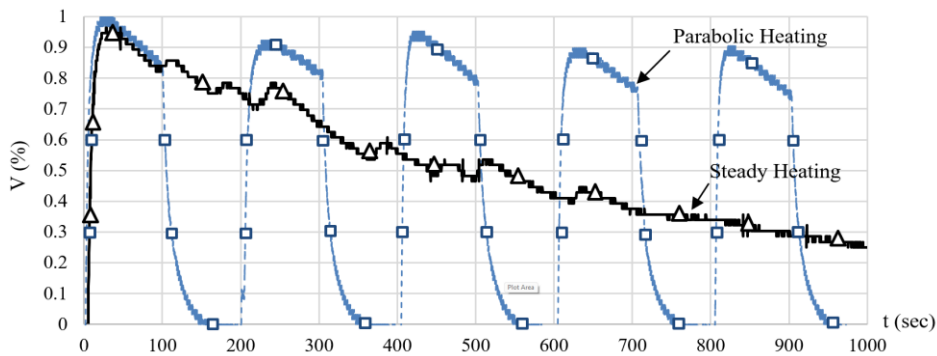


Figure 12. Normalized voltage value between steady and parabolic heating at particular testing temperature 60 °C

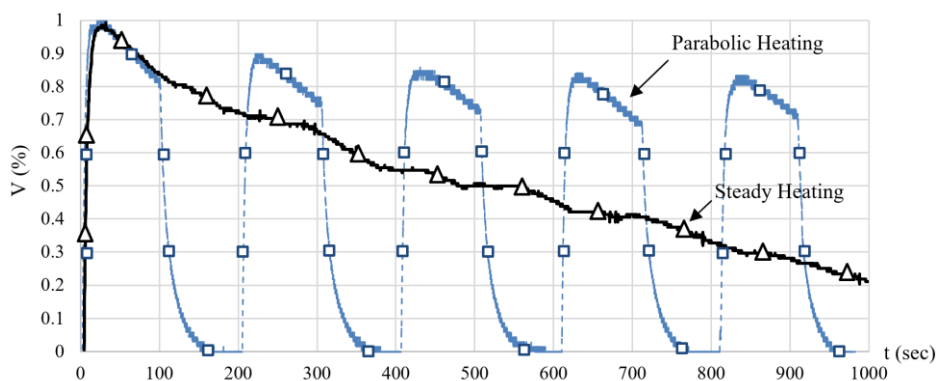


Figure 13. Normalized voltage value between steady and parabolic heating at particular testing temperature 80 °C

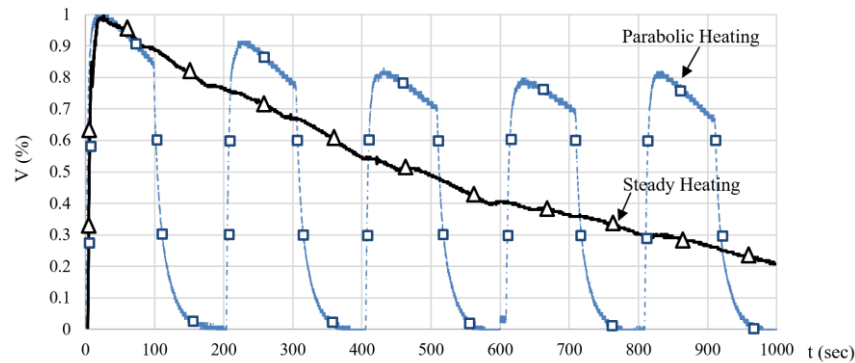


Figure 14. Normalized voltage value between steady and parabolic heating at particular testing temperature 100 °C

4. CONCLUSION

This paper proposed an alternative technique used to increase voltage generated from TEG using parabolic pulsed heating. Parabolic pulsed heating and steady heating functions were applied to TEG. The experimental results from the different heating conditions were compared. Results showed that parabolic pulsed heating enhanced the performance of the TEG significantly. This technique has many advantages of a heating technique that allows the TEG cold side; T_c to gradually cool out before the next heat treatment is applied to hot side of TEG; T_h . The results showed that the proposed technique was able to maintain the output voltage level for all T test temperatures.

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