Characterization and Behavior Analysis of a Thermoelectric Module Energy Harvesting System Exposed to Transient Sources

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***Abstract*—This study presents a characterization and analytical study on the behavioral analysis of a thermoelectric module (TEM) energy harvesting system. TEM was applied with transient sources to both of its sides with two different configurations, single TEM and multi-stage TEM, which were electrically connected in series and thermally in parallel. The output voltage of the TEM was harvested from the heat of the hotplate. Previous studies have focused on the steady-state analysis of a single TEM. In real applications, the temperature of both ends fluctuates with time. In this study, a MATLAB model of TEM was presented with the addition of a transient condition. A test rig was developed to configure the transient behavior of different TEM configurations. Both experimental and simulation data show that the multi-stage configuration of TEM could generate electricity with a maximum operating point at a test temperature of 50 °C to 100 °C. This maximum operating point was strongly influenced by the constancy of the thermal gradient of TEM. This finding is very useful in order to determine the best temperature range that TEM can work before it is applied to any medium to harvest energy. Multi stage TEM arrangement electrically in series and thermally in parallel has obtained the highest output voltage up to 0.115 V for six cascaded TEM compared to the other three tested circuit arrangements.**

***Index Terms*—Energy Harvesting System; Dynamic Transient Sources; Thermoelectric Module.**

I. INTRODUCTION

The conversion of waste heat into electricity has stimulated the fast growth of research in the area of heat energy. Thermoelectric module (TEM) is one of the preferred devices for thermal conversion because of its merits. For instance, it does not possess moving parts and does not produce waste, which is harmful to humans and the environment; therefore, this device has attracted considerable attention in the area of energy generation [1, 2]. TEM is a solid-state device that can be used either for the electrical conversion or the cooling process.

The practical configuration of TEM usually changes with different applications. Indeed, this device has become a preferred solution in areas such as automotive [3, 4], aerospace [5], thermal power plant [6], stove system [7, 8], edu-kitchen system [9], and recently, communication devices [10]. The thermal load changes of this application can create a thermal difference that can cause TEM to produce electricity. The device can create electricity when temperature differences exist between its two junctions. For instance, load changes may vary with time, and these changes create a dynamic characteristic. In this regard, a relevant description of the dynamic characteristics of TEM is important for its subsequent applications.

TEM can function as a thermoelectric generator (TEG) [11-13], which converts thermal gradient into electricity, and as a thermoelectric cooler (TEC) [1, 14, 15], which converts electrical potential into thermal difference for cooling purpose. Most studies have focused on the transient behavior of TECs because the mathematical analysis of transient behavior is much simpler than that of TEGs. Transient analysis of the TEM is a situation where one junction is exposed to a heat source that is not well established, while a junction again going through the process of natural cooling [16]. This means no heat sink is used throughout this analysis. In this transient state, the temperature profile and the electric current generated by the TEM, both of which will change with time. Compared with a steady source, transient source is more practical because it will investigate the exact nature of a TEM when it is in actual conditions. When no heat sink is used, the TEM will depend entirely on how it can release heat energy to heat in on the cold side. Some studies that dealt with this analogy also conducted steady-state analyses of TECs [14, 17] because of the effects of TEM thermo-electric coupled multi-physics. Thermal effects, such as the Seebeck, Joule, and Peltier effects, are important in the study of TEM thermal distribution. In addition, [1] examined two-stage TECs, which developed a 3-dimensional model of TEM.

The transient analysis of a single TEM [18, 19] has attracted considerable research attention. Focusing only on the behavior of a single TEM cannot facilitate the description of the power generation and thermal behavior of the overall TEM application. In particular, the output power produced by a single TEM is relatively very small. Huajun et al. [20] analyzed the series-parallel configuration of TEM. They found that the properties of TEM are identical to those of a series-parallel configuration. Nguyen and Pochiraju [16] stated that fully coupled and complete transient analyses of TEG are seldom conducted. They also analyzed a single TEM.

Multi-stage behavioral analysis is important because high-end TEM applications entail high power. We have developed an early MATLAB model for single and multi-stage TEM

[21]. In the current study, the transient behavior of a single and multi-stage configuration TEM is analytically and experimentally compared. This analysis considers both the power generation behavior and the thermal behavior of the two TEM configurations. Initially, TEM is modeled on the basis of its different configurations with the use of MATLAB. Then, the MATLAB model is analyzed for a steady-state condition to ensure that TEM characteristics meet the specifications given by the manufacturer. An experimental setup is designed for the two different configurations. Finally, the results from the test rig are compared with the simulation profile.

II. MATHEMATICAL MODELING

TEM model TEP1-12656-0.6 from Thermonamic was used, and the specifications are shown in Table 1. The numerical modeling of TEM started with a single TEM. Subsequently, a single TEM was clustered into another block model for easy cascading in the multi-stage TEM analysis.

An important concern here is that the model must function beneath transient circumstance, in which the temperature of the cold side was left for natural cooling; most previous studies conducted their analysis in steady-state condition, which is practical for a simplified analysis [16]. Depending on the environmental condition, the TEM temperature varied with time in real situations.

Table 1
Specification of TEM (TEP1-12656-0.6)

Specifications	Values
Hot side temperature (°C)	300
Cold side temperature (°C)	30
Open circuit voltage (V)	8.4
Matched load resistance (Ω)	1.2
Matched load output voltage (V)	4.2
Matched load output current (A)	3.4
Matched load output power (W)	14.6
Heat flow across the module (W)	≈365
Heat flow density (W cm^{-2})	≈11.6
AC resistance measured at 27 °C and 1000 Hz (Ω)	0.5–0.7

For the heat model of TEM, the effects considered were thermal conduction and Joule, Peltier, Seebeck, and Thomson effects. For this design consideration, the Thomson effect was neglected because it produced such a small value from being a derivative of the Seebeck coeeficient over time [22]. TEM should possess the capability to produce high thermal conductivity by distributing the same amount of heat at both sides. The Fourier process indicated that thermal conductivity is expressed with heat transfer, Q_{tc}, as:

$$Q_{tc} = -\Delta T \kappa_{tc} \tag{1}$$

where κ_{tc} is the thermal conductivity, and ΔT is the difference between the high and low temperature sides. When electrical current, I, flows across a thermoelectric leg, it produces the Joule effect. This phenomenon was used to observe a different temperature applied to both TEM legs but with equivalent energy:

$$Q_{joule} = I^2 R \tag{2}$$

where R is the electrical resistance. The state of affairs when current flows through two dissimilar junctions is known as the Peltier effect, which is expressed as follows:

$$Q_{peltier} = \alpha \Delta T I \tag{3}$$

where α is the Seebeck coefficient of TEG. The condition in which a different temperature of two dissimilar junctions results in a potential difference is known as the Seebeck effect. The Seebeck coefficient is considered distinct and is expressed as follows:

$$\alpha = \frac{V}{\Delta T} \tag{4}$$

The energy balance equations used for steady-state analysis at the hot and cold junctions of TEM by the works done by [22] are expressed as:

$$Q_h = \alpha T_h I - \kappa_{tc} \Delta T - 0.5 I^2 R \tag{5}$$

$$Q_c = \alpha T_c I - \kappa_{tc} \Delta T + 0.5 I^2 R \tag{6}$$

Recurrent parameters were constantly used to specify TEM characteristics: T_h, temperature on the hot side; T_c, temperature on the cold side; W_m, power at the load resistance; R_L, internal resistance; R, ($R_L = R$); and V_m, load voltage. In detail, the electrical resistance and Seebeck coefficient are defined as:

$$R = R_L = \frac{{V_m}^2}{W_m} \tag{7}$$

and

$$\alpha = \frac{2V_m}{\Delta T} \tag{8}$$

The load resistance in Equation (7) is proportional to the internal resistance and can be changed with a variation in the value of m as follows:

$$R_L = mR \tag{9}$$

where m is the ratio between load resistance and internal resistance. From (4), I can be further defined as

$$I = \frac{\alpha \Delta T}{(1+m)R} \tag{10}$$

From Equation (10) and in accordance with Ohm's Law, the TEM voltage was obtained as

$$V = -R(I - \frac{2Wm}{Vm}) \tag{11}$$

At the beginning of the simulation modeling, steady-state analysis for a single TEM was conducted to verify the electrical parameters of the TEM model. The obtained model parameters from the steady-state analysis were α = 0.031 V/K, R = 1.2 Ω, κ_{tc}= 20.85 W/K, and $Z = 3.869 \times 10^{-5}$ K^{-1}(by applying (1) to (11).

TEM is modeled in accordance with the specifications given by the manufacturer in Table 1; TEM is assumed to obtain the matched load output power at the matched load output voltage and current. The implementation of the TEM model with MATLAB/SIMULINK is shown in Figure 1. TEM possess two inputs depending on the temperature profile applied to both the hot and cold side junctions.

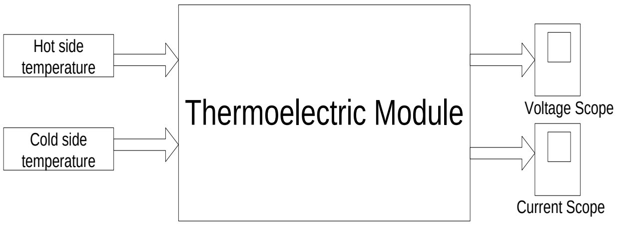

Figure 1: TEM block model as applied in MATLAB

III. Experimental Analysis

An experiment was conducted to validate the model and determine the effect of the transient input parameter on the thermal behavior of TEM. The experimental setup in Figure 2 was tested under different temperature gradients by variation of the hotplate temperature from 50 °C to 250 °C. The selected TEM can work at a temperature as high as 330 °C with a continuous heating source, so the selected hotplate temperature is appropriate for the behavioral analysis of TEM. The selected TEM was covered with a graphite sheet on both of its sides to provide low contact thermal resistance. Thermal grease, commonly used to equally distribute heat on all hot side surfaces, is therefore not needed in this design experiment. TEM was placed on top of the heat source (Stuart CB160). The temperature of the hot and cold sides was measured by a thermocouple with a tip diameter of 1.5 mm. Next, the temperature values were recorded with TC-O8 PicoLog data logger from Pico Technology.

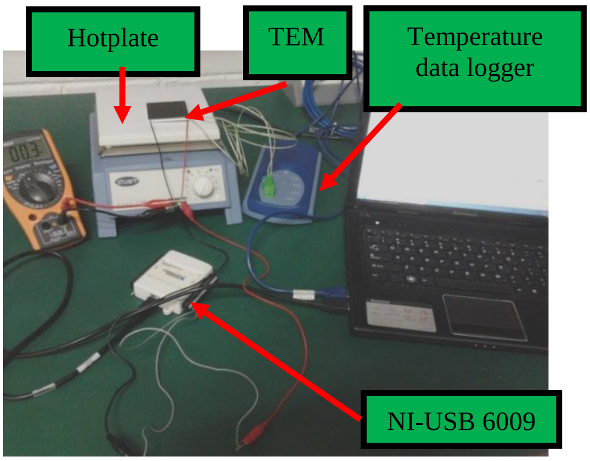

Figure 2: Experiment setup

The setup experiment was run for 700 seconds, and sample data were taken every second. Although the hotplate was set to a certain value (e.g., 50 °C), the temperature of the hot side as measured by the thermocouple could not achieve the set value. This phenomenon is attributed to the heat dissipation of TEM through its cold junction. This dissipation reduced the applied temperature to the hot junction. The temperature of the hot side was also varied throughout the duration of the experiment. Both sides of TEM were then analyzed as the transient response because both temperature values were fixed and varied with time, as well as dependent on the conditions of the surroundings.

The output voltage of TEM was recorded with NI-USB 6009 data acquisition card from the National Instrument. The card was connected to MATLAB environment. The recorded voltage was then displayed in the time domain. The experiment was conducted to determine the behavior of the multi-stage configuration of TEM compared with that of the single one. Four sets of experiments were conducted in this analysis. The purpose of Case 1 was to get the best TEM array that can generate the highest output voltage before it was combined with SS in GTFS. Cases 2, 3 and 4 were carried out to determine whether the temperature range TEM is able to operate properly for the three different configurations; single TEM, three cascaded TEM and six cascaded TEM.

IV. Characterization of the Best TEM Arrangement

TEM can be used in two circumstances, either to increase the output voltage or output current. TEM arrangement must be guided by both of these objectives, which play an important role for an application. TEM can be arranged electrically in series to increase output voltage, and in parallel to increase the output current. Some previous studies have discussed these configurations, such as Liang et al. (2011) has made an analysis of the TEM, which are connected electrically in parallel. Wang et al. (2013) set both configurations as the basis of the study and Ma and Yu (2014) studied the multistage TEM with two cascaded TEM connected electrically in series.

However, it should be seen that in the study of TEM, there are two main factors, which are interrelated; output power and thermal effect, where the output power is affected by the output voltage and current. In this study, the analysis was carried out for four different configurations; electrically in series and thermally in parallel (E1), electrically in series and thermally in series (E2); thermally in series and electrically in parallel (T1) and thermally in parallel and electrically in parallel (T2), in which these arrangements are shown in Figure 3. TEM is composed of a sequence TEMs and are numbered from 1 to n, Tip and Tic is the temperature at the hot and cold side of each module TEM i-th ($1 \leq i \leq n$).

The main objective of this study was to obtain the best TEM configuration which are able to obtain the highest output voltage. This configuration was the basis configuration for the analysis. Figure 4 shows the distinction of output voltage for these configuration. Referring to the figure, E1 managed to produce the highest output. For both T1 and T2 thermal configuration, the voltage generated by the TEM decreased, when the number of cascaded TEM increased. This clearly shows in order to increase the TEM output voltage, the most important aspect is that it should be arranged thermally in parallel. Then, it determines whether the arrangement should be connected electrically in series to increase the voltage or in parallel to increase the current.

Because the main purpose of this study was to increase the output voltage, the next analysis used the E1 configuration. For E1 configuration, there was also a linear relationship for the number of the cascaded TEM and the open voltage output. Since the number of cascaded TEM also effects E2 configuration, the voltage increases with the square of the number of cascaded TEM.

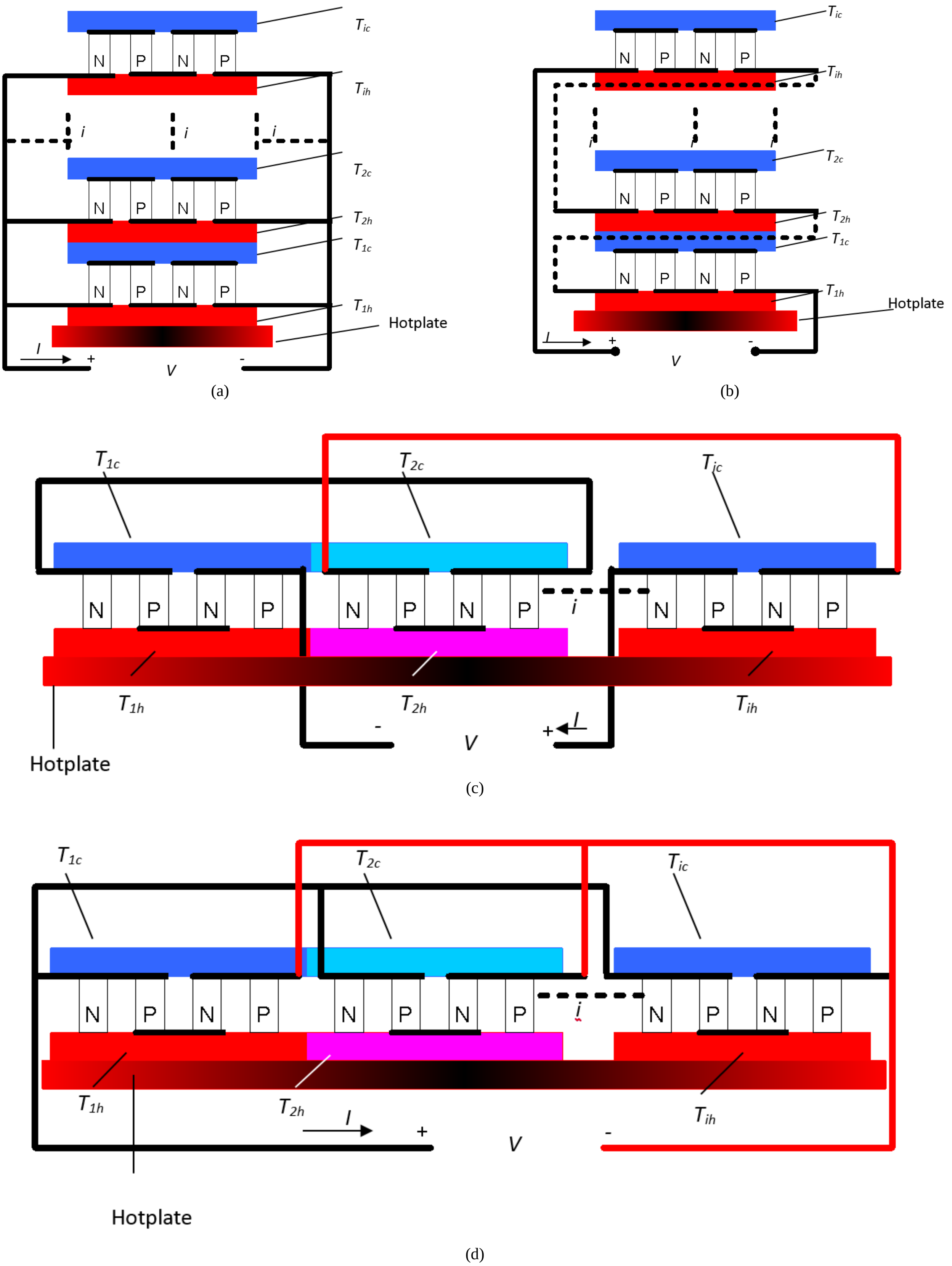

Figure 3: TEM configurations: (a) E1; (b) T2; (c) E2; (d) T1

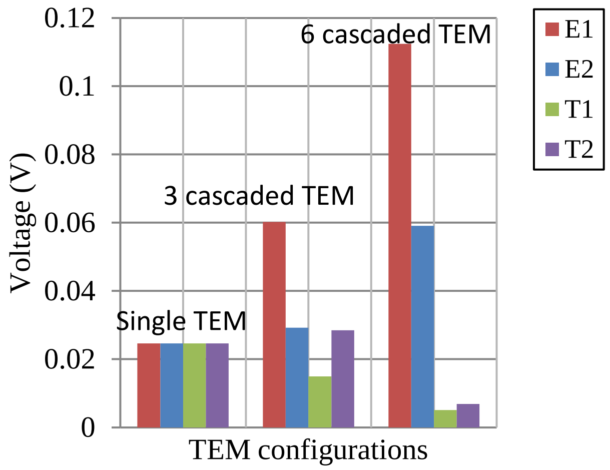

Figure 4: TEM output voltage for different configuration

V. Power Generation Behavior

TEM converts the thermal energy into electricity when a thermal gradient exists between its two junctions. Analyzing the capability of TEM to generate voltage in different configurations is essential. For this analysis, the same three configurations discussed earlier were used.

A. *Single TEM*

For the single TEM, the test temperature of the hotplate varied from 50 °C to 250 °C. Figure 5 shows the TEM power plot over 700 s. This data were plotted using the measured value of voltage and current throughout the sampling time. The TEM power increased with the test temperature because of the increase in thermal gradient between the two TEM junctions, which were adjusted with the increment in the output voltages. The details are shown in Table 2.

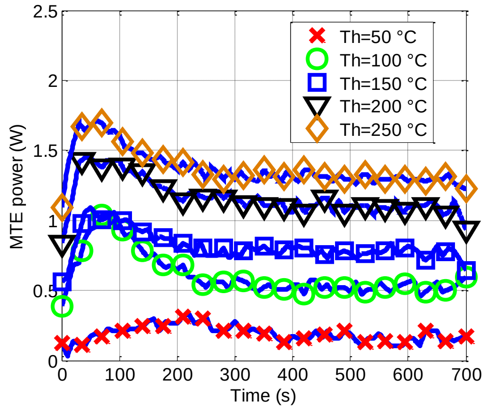

Figure 5: Plotted TEM power at different test temperatures for a single TEM

Table 2
Test Temperature of the Measurement and Output Voltage of a Single TEM When It is not Connected to Electrical Load

Hotplate temperature (°C)	Th (°C)	Tc (°C)	ΔT (°C)	Experimental Voltage (V)
50	45.25	36.89	8.36	0.0246
100	84.52	59.79	24.73	0.0861
150	128.86	88.96	39.9	0.1167
200	177.05	119.72	57.33	0.1689
250	228.58	153.18	75.4	0.1996

The test conducted considers open loop configuration. In addition, the calculated power was obtained from the simulation file because the TEM model could predict the internal resistance of TEM with the increase in test temperature. Data from Table 3 show that the output current decreased when the output voltage increased. From the calculated power in Table 3, the value of the internal resistance of TEM could be obtained. The same pattern from the previous analysis could be observed, in which the internal resistance increased with the test temperature. This result was again attributed to the increase in the thermal gradient of the two junctions of TEM. Furthermore, when the temperature of the hot side increased at the same increment at each increase point, the percentage of increment of the obtained power decreased. For example, the percentage of the increment in power was 222% from 50 °C to 100 °C, but it became 33.5% from 100 °C to 150 °C, 42.8% from 150 °C to 200 °C, and 17.4% 200 °C to 250 °C. In short, the increment decreased as the temperature of the hot side increased. This result indicates that TEM possesses a certain saturation point in which its performance is affected. For the next analysis of multi-stage TEM, the test temperature was therefore set to 150 °C.

Table 3
Test temperature of the measurement and the simulated output together with the current, resistance, and power when a single TEM is not connected to any electrical load

Hotplate temperature (°C)	Simulated Voltage (V)	Current (A)	Resistance (Ω)	Power (W)
50	0.0275	6.93	0.004	0.1905
100	0.0892	6.88	0.013	0.6137
150	0.1196	6.85	0.017	0.8193
200	0.1718	6.81	0.025	1.1700
250	0.2026	6.78	0.030	1.3736

The variation in open circuit voltage at different test temperatures was then analyzed in terms of how the voltage is affected by the temperature gradient. The graph in Figure 6 shows that the open circuit voltage proportionally increases with the temperature gradient. Linear basic fitting was applied to the plotted open circuit voltage. The analysis shows that the new relationship between the open circuit voltage and the temperature gradient was obtained as:

$$V_{open\_circuit} = \left(0.0026 \times \Delta T\right) + 0.013\Big|_{k=6} \qquad (12)$$

where k indicates the number of cascaded TEM. The equation shows that the open circuit voltage of the test temperature can be predicted for further analysis.

B. *Multistage TEM*

The single TEM was extended into a multi-stage configuration, and the power generation behavior of this arrangement is further explained. For the multi-stage TEM, two design experiments were considered: first, cascading three TEMs in series, and second, cascading six TEMs in series. This number was being chosen to see the effect of three cascaded TEM whether the power generated was proportional with the increasing number of cascaded TEM. However, the test temperature was limited to 150 °C because the analysis of a single TEM shows that TEM can effectively work up to this given temperature.

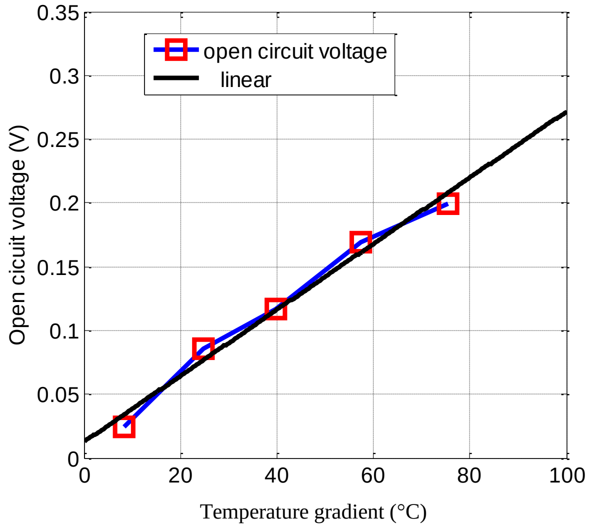

Figure 6: Open circuit voltage as a function of the temperature gradient

The TEM power of multi-stage TEM increased when the number of cascade TEM increased, and thus when the supplied temperature increased (Figure 7). The plotted graph shows that when the number of cascaded TEMs is doubled, the TEM power is approximately doubled as well. This result indicates that multi-stage TEM is necessary to produce high power. Although TEM can produce high power with an increase in temperature, this power becomes saturated at a certain temperature. This discrepancy is caused by the limit in temperature set by the manufacturer and the difficulty of TEM to dissipate heat at a high temperature.

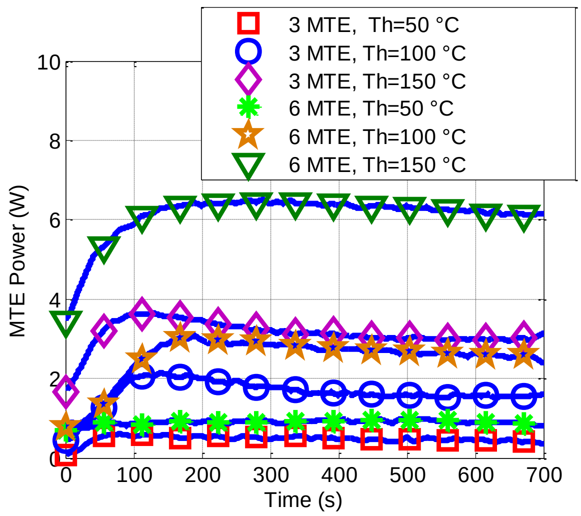

Figure 7: Plotted TEM power at different test temperatures for multi-stage TEM

For multi-stage configuration, the behavior of the open circuit voltage is exactly the same as that of single TEM. The additional advantage of this configuration is that the number of cascaded TEMs acts as a multiplier for the open circuit voltage of a single TEM. The open circuit voltage has about the same value as that of the voltage of a single TEM based on the number of cascaded TEMs. This clarification can be understood by comparison of the data in Table 2 with those in Table 4 and 6.

Table 5 shows that when the temperature of the hot side increases with the same amount at each increase point, the percentage of obtained power increase. At 50 °C to 100 °C, the percentage was 244%, but from 100 °C to 150 °C, the percentage was 90.37%. This finding means that multi-stage TEM best demonstrates the increment in power at the range of 100 °C to 150 °C.

The same analysis was made on the six cascaded TEMs. The increment of open circuit voltage compared with that of three cascaded TEMs indicates the recurrence of a certain pattern of TEM behavior, as shown in Table 6.

Table 4
Test Temperature of the Measurement and Output Voltage of the Three Cascaded TEMs When They are not Connected to Any Electrical Load

Hotplate temperature (°C)	Th (°C)	Tc (°C)	ΔT (°C)	Experimental Voltage (V)
50	37.47	33.03	4.44	0.0602
100	69.16	54.26	14.90	0.2295
150	106.49	79.72	26.77	0.4494

Table 5
Test Temperature of the Measurement and the Simulated Output, Together with the Current, Resistance, and Power When Three Cascaded TEMs Are Not Connected to Any Electrical Load

Hotplate temperature (°C)	Simulated Voltage (V)	Current (A)	Resistance (Ω)	Power (W)
50	0.0690	6.93	0.01	0.4786
100	0.2393	6.88	0.03	1.6473
150	0.4596	6.82	0.07	3.1360

Table 6
Test Temperature of the Measurement and Output Voltage of the Six Cascaded TEMs When They are not Connected to Any Electrical Load

Hotplate temperature (°C)	Th (°C)	Tc (°C)	ΔT (°C)	Experimental Voltage (V)
50	34.20	26.52	7.68	0.1124
100	60.58	35.67	24.91	0.3497
150	91.19	50.58	40.61	0.8772

In the three cascaded TEMs, the percentage of obtained power increases when the temperature of the hot side increase at the same amount at each increase point. Table 7 shows that from 50 °C to 100 °C, the percentage was 182.77%, but from 100 °C to 150 °C, the percentage was 140.91%. This value shows that increasing the number of cascaded TEMs increases the obtained power for the increase point of 100 °C to 150 °C. This finding agrees with the earlier prediction that multi-stage TEM possesses a better operating point than single TEM.

Table 7
Test Temperature of the Measurement and Simulated Output Together with the Current, Resistance, and Power when Six Cascaded TEMs are not Connected to Any Electrical Load

Hotplate temperature (°C)	Simulated Voltage (V)	Current (A)	Resistance (Ω)	Power (W)
50	0.1297	6.93	0.02	0.8991
100	0.3685	6.90	0.05	2.5424
150	0.8972	6.83	0.13	6.1249

VI. THERMAL BEHAVIOR

The heat dissipation of a hotplate could not be precisely measured because the equipment encountered contact and radiation losses [16, 23]. A thermocouple could be used to accurately measure the heating rate of a hotplate. The temperature profile was recorded with a high-precision data logger, which listed the value depending on the experiment run time.

The power generation behavior of TEM shows that it operates well at the temperature of 0 °C to 150 °C. Therefore, the experimental setup for the thermal behavior investigation of TEM was conducted only in this operating temperature for all configurations of TEM. The temperature profile in Figure 6 shows the actual temperature of the hot and cold side junctions of TEM in the case of a single TEM. The recorded temperature profile on the hot side indicates that when the hotplate is set to 50 °C, the temperature of the hot side does have the same target temperature. It initially increases and maintains at a temperature that is close to the target value depending on three factors: thermocouple placement, TEM heat distribution, and the surrounding environment.

When the experiment was extended to multi-stage configuration, the temperature profile shows the same result, with the temperature of the hot side increasing to the target temperature value. The temperature of the cold side was observed to follow the increase in temperature of the hot side. Figure 8 shows that the temperature gradient for all TEM configurations ranged from 4 °C to 8 °C, which represents the same criterion affected by the recorded temperature profile. The analysis started to record at the early stage as soon as all the devise were connected together, but the hotplate transient temperature may be vary due to the hotplate unstable condition.

Table 8 summarizes the temperature gradient increment in percentage for different TEM configurations. The trends of TEM indicate that for all three configurations, the temperature gradient increment in percentage was at its highest rate when the hotplate setting increased from 50 °C to 100 °C. Subsequently, the value rapidly decreased when the temperature setting increased to a high value for a single TEM configuration. This result shows that TEM is capable of operating at its maximum rate for this temperature setting.

The temperature profile was expanded with the three listed key factors. In terms of TEM performance, which is summarized in the stretch of the increase in temperature gradient in percentage, TEM worked well when the temperature of the hotplate increases from 50 °C to 100 °C for either single TEM or multi-stage TEM. This thermal behavior is important prior to the setting up of the hot side of the TEM because such a behavior considerably affects performance.

Table 8
Summary of the Temperature Gradient Increment in Percentage Based on Different TEM Configurations

TEM configuration	Hotplate setting (°C)	Temperature gradient increment in percentage (%)
Single TEM	50–100	195.81
	100–150	61.34
	150–200	43.68
	200–250	31.52
Three TEMs in series	50–100	235.6
	100–150	79.66
Six TEMs in series	50–100	224.35
	100–150	63.03

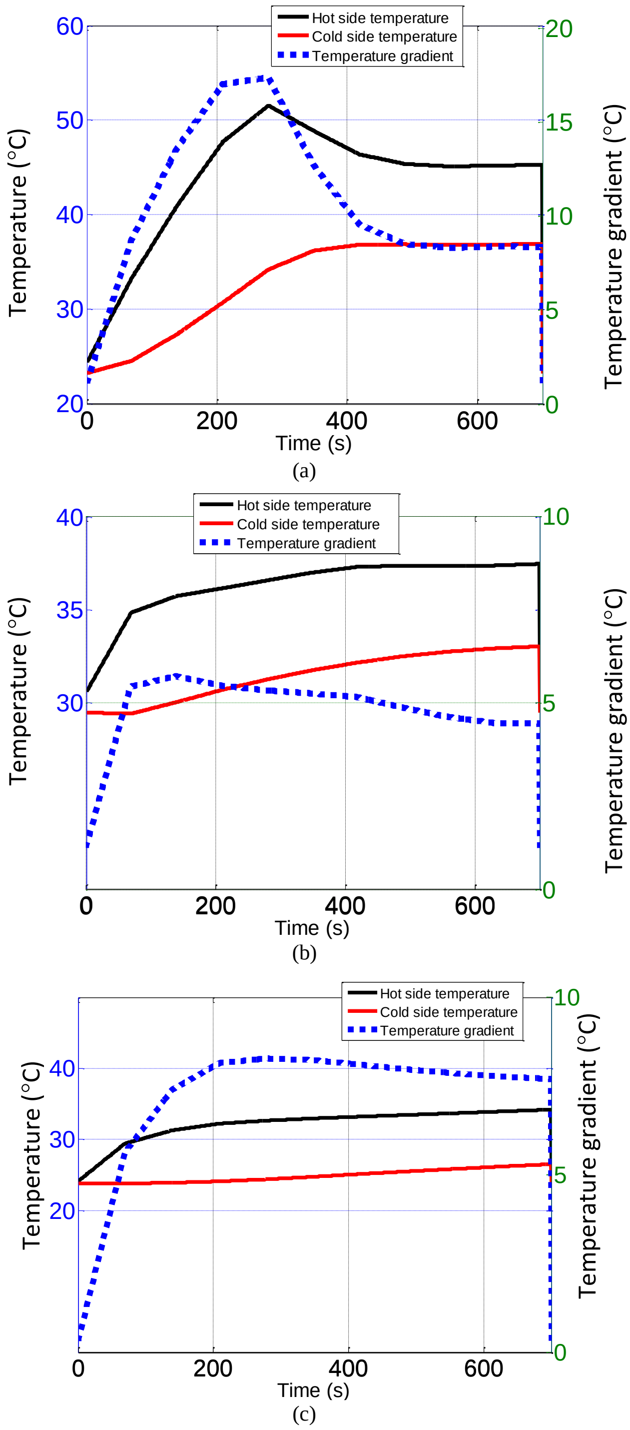

Figure 8: Temperature profile when the hotplate is set to 50 °C for different configurations of TEM: (a) single TEM, (b) three TEMs in series, (c) six TEMs in series

VII. CONCLUSION

This study addressed several configurations of TEM to characterize its behavior. The characteristics of thermal and power generation were numerically and experimentally investigated. The analysis was conducted for transient condition, so the cold side temperature of TEM was left for natural cooling, whereas the hot side temperature depended on the normal heat dissipation of the hotplate. The experimental results show that the open circuit voltage of TEM can be increased by electrical cascading of TEM in series and thermal cascading in parallel. This aspect of the behavior analysis is important before any maximum power point tracking method is applied to the chosen TEM configuration. This finding is useful as a guide to set the operating temperature to be applied to TEM. Comparison of the simulation and experimental results indicates that they agree well. The results also show that the open circuit voltage proportionally increases with the temperature gradient.

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