Experimental Characterization of a Thermoelectric Generator System

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***Abstract*—This research paper presents a detailed investigation of the performance of a thermoelectric generator (TEG) system. The TEG system is composed of multiple thermoelectric legs connected in series, a heat source, and an electric load. The experimental setup is designed to simulate real-world operating conditions and allow for the measurement of the TEG's power output as a function of the temperature difference between the hot and cold sides, and the load conditions. The performance evaluation of the TEG system is conducted using a commercial thermoelectric generator module (TEM) and several measurement instruments such as power analyzers, thermocouples, and electronic devices. The results of the study are used to plot the TEG's operating curves, which show the power output as a function of the temperature difference and the TEM current including the identification of the maximum power point (MPP). The operating curves allow for the evaluation of the TEG's behavior and thermal characteristics under different conditions. Additionally, this result provides valuable insights into the performance of TEGs and contribute to the advancement of this technology.**

***Index Terms*—TEG, experimental setup, TEM, operating curves**

I. Introduction

Thermoelectric generators (TEGs) have gained attention in recent years as a promising technology for converting waste heat into electricity). TEGs are based on the Seebeck effect, which states that a voltage is generated when two dissimilar materials are maintained at different temperatures [1]. This effect can be harnessed by connecting multiple thermoelectric modules (TEMs) in series to form a TEG. TEGs have the potential to be used in a wide range of applications, including automobiles, industrial processes, and even health applications [2]. However, the performance of TEGs is highly dependent on the TEMs used, the temperature difference between the hot and cold sides, and the load conditions [3]. To fully understand the capabilities and limitations of TEGs, it is necessary to conduct performance evaluations in a controlled laboratory environment.

In this research paper, the performance of a TEG system is evaluated in a laboratory environment using a commercially available TEM [4]. The TEG system is composed of multiple TEMs connected in series, a heat source, and a load. The heat source and load conditions are varied to investigate the effects on the TEG's performance.

Characterizing a thermoelectric module (TEM) is an essential step in understanding its performance and potential applications. One of the main parameters used to characterize a TEM is its electrical resistivity, which is a measure of the resistance of the material to the electric current flow [5]. A higher electrical resistivity results in a lower power output from the TEM. Another important parameter is thermal conductivity, which is a measure of the ability of the material to transfer heat. A TEM with high thermal conductivity will have a lower temperature difference between the hot and cold sides, which in turn will result in a lower power output.

The Seebeck coefficient, also known as the thermoelectric power, is a measure of the voltage generated per unit temperature difference between the two sides of the TEM. A higher Seebeck coefficient results in a higher power output from the TEM. Characterizing a TEM can help in understanding the potential performance of the module and the optimal operating conditions for a specific application. It can also be helpful in the selection of TEMs for a particular application, for example, higher electrical conductivity and lower thermal conductivity TEMs may be preferred for high-temperature applications.

One way to evaluate the behavior of TEMs is using a testing setup known as the "two-thermocouple method" [6]. This method involves attaching thermocouples to both the hot and cold sides of the TEM and measuring the voltage and temperature difference between them. By measuring the voltage and temperature difference, it is possible to calculate the Seebeck coefficient, electrical resistivity, and thermal conductivity of the TEM. Another way to evaluate TEMs is by using a testing setup known as the "three-point method" [7]. This method involves attaching thermocouples to the hot side, cold side, and the center of the TEM, measuring the voltage and temperature difference between them. By measuring the voltage and temperature difference, it is possible to calculate the thermal conductivity and Seebeck coefficient of the TEM. In addition to these testing methods, it is also important to measure the power output of the TEM under different loading conditions [8].

The experimental setup must be designed to minimize errors and uncertainties in the measurements, to obtain accurate and reliable results. Once the operating curves have been obtained, the TEM's performance can be evaluated under different conditions. Additionally, by comparing the operating curves at different temperatures, it is possible to investigate the effects of temperature on the TEM's performance.

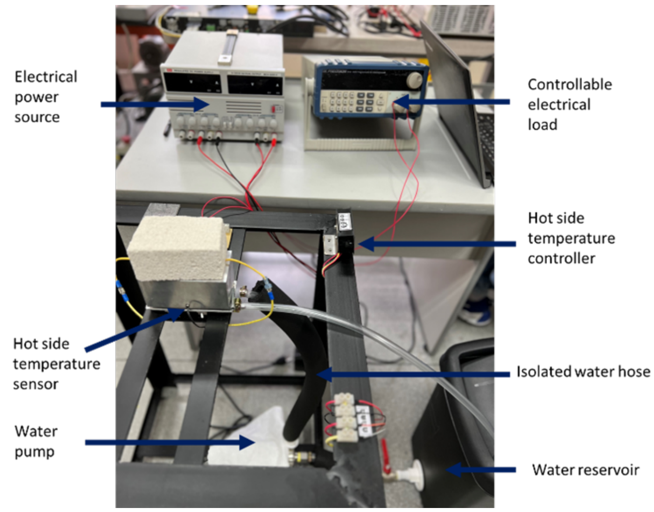
The experimental assessment of TEG systems can help in the design and optimization of TEGs for various applications. This work presents a comprehensive experimental setup for evaluating the power output of a TEM under controlled conditions. The establishment of this methodology is important for characterizing TEMs and understanding the performance of thermoelectric generators.The characterization of TEMs and the knowledge of their operative curves are crucial for the design and optimization of TEGs, reaching the maximum power point (MPP) and increasing their efficiency. This paper will provide valuable insights into the performance of TEGs and will contribute to the advancement of this technology.

This research paper presents a detailed experimental study on the performance evaluation of a commercial TEM: Section II provides a description of the experimental setup, including the heat source, load, and temperature measurement devices and the measurement protocol for obtaining the operating characteristics of the TEM. Section III presents the characteristic power curves of the TEM, which show the power output as a function of temperature difference and load, and a detailed analysis of the curves. Finally, Section IV summarizes the main findings and highlights the importance of the work and suggests possible future work.

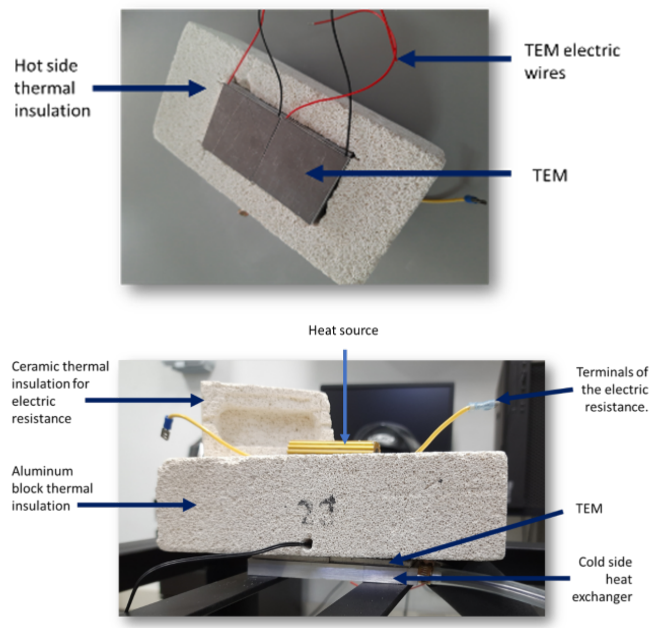
II. EXPERIMENTAL SETUP FOR TEM CHARACTERIZATION

The experimental setup for evaluating the performance of a thermoelectric module is presented in Figure 1. The setup is composed of two main parts: the power generation system and the instrumentation.

The power generation system is composed of the TEM manufactured by Thermal Electronics Corp. [4], a heat source, a heat sink, and a load. The TEM is the main component of the power generation system, and it converts heat energy into electrical energy. The heat source, which is a hot plate or a heater, is used to provide the heat energy to the TEM; it includes an electrical resistance with a value of 100 used to heat the hot side of the TEM. The load is a programmable electronic load used to consume the electrical energy generated by the TEM. The hot side temperature is controlled by an on-off temperature controller that regulates the power supplied to the electrical resistor. The cold side of the TEM is maintained at a constant temperature by using a large reservoir of water (tank) that is continuously pumped by a pump. The tank of water provides a large thermal mass that allows the cold side of the TEM to maintain a constant temperature, which is important for accurate measurement of the TEM's performance.



(a) Instrumentation



(b) Power generation system

Fig. 1: Components of the experimental setup to evaluate TEG power generation at different temperature boundaries.

One of the key aspects of the experimental setup is the use of a controlled heat source and a load to simulate real-world operating conditions. This allows for the measurement of the TEM's power output as a function of the temperature difference between the hot and cold sides and the load conditions. To obtain the operating characteristics of the TEM, a series of measurements are taken at different temperature differences and load conditions. These measurements are then used to plot the TEM's operating curves, which show the power output as a function of the temperature difference and the load. The operating curves are important because they allow for the identification of the maximum power point (MPP), which is the point on the curve where the TEM produces the maximum power output. The on-off temperature controller allows for precise control of the hot side temperature, while the large reservoir of water ensures that the cold side temperature remains constant. This combination of temperature control and measurement allows for accurate characterization of the TEM's performance and the determination of its operating characteristics.

The instrumentation part is composed of devices used to measure the performance of the TEM. These include an oscilloscope, a multimeter, and thermocouples. Auxiliary control electronics are also used in the experimental setup to control the temperature of the heat source and to automate the measurement process.

The experimental procedure for evaluating the performance of a thermoelectric module using an oscilloscope involved the following steps:

- The temperature gradient across the TEM was set to a specific value by adjusting the temperature of the heat source using the on-off temperature controller and maintaining the cold side temperature constant using the large reservoir of water.
- The load was programmed with a current profile consisting of step changes in current, with each step being $50mA$.
- The oscilloscope was used to record the voltage and current generated by the TEM for a period.
- The instant power consumption was computed by multiplying the voltage and current values and recorded and saved for further analysis.
- The above steps were repeated for different temperature gradients and load conditions.
- The data obtained from the oscilloscope was analyzed to determine the TEM's operating characteristics, such as the maximum power point (MPP) for each temperature difference.
- The oscilloscope was used to dynamically observe the behavior of the voltage, current, and power consumption, allowing the detection of any unwanted behavior that can occur in the TEM, such as ripple, voltage sag, etc.

Figure 2 depicts the oscilloscope screen during a single experimental test, where the green trace corresponds to the current supplied by the thermoelectric module (TEM). In contrast, the yellow and red traces represent the measured voltage and calculated power output, respectively. The overall power output profile exhibits a parabolic shape, suggesting that the maximum power point is attained at a specific current and voltage value. Notably, a noticeable inverse relationship is observed between the current and voltage, as an increase in the module's current leads to a corresponding decrease in the voltage.

III. EXPERIMENTAL RESULTS FOR TEM CHARACTERIZATION

In this research, a digital filter process is applied to a current signal to remove unwanted noise and improve signal quality. The filter used is a Butterworth filter, a type of low-pass filter that is characterized by a flat frequency response in the passband and a roll-off that is -3dB per octave in the stopband. The filter order is specified as 3, and the cutoff frequency is specified as 0.05 Hz. These values are used to calculate the filter coefficients 'b' and 'a'.

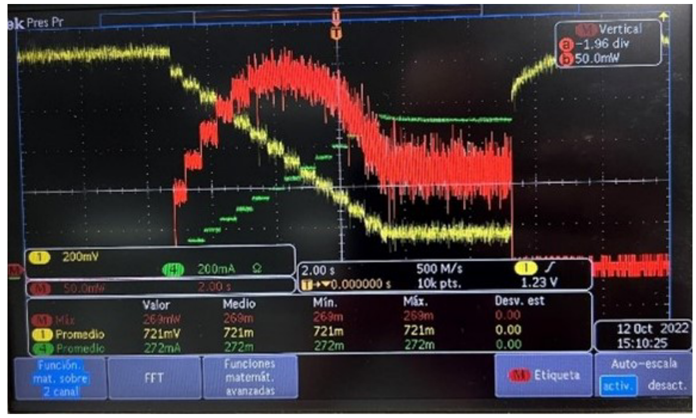


Fig. 2: Experimental measurement of Voltage, Current, and Power Output of a TEM in the oscilloscope.

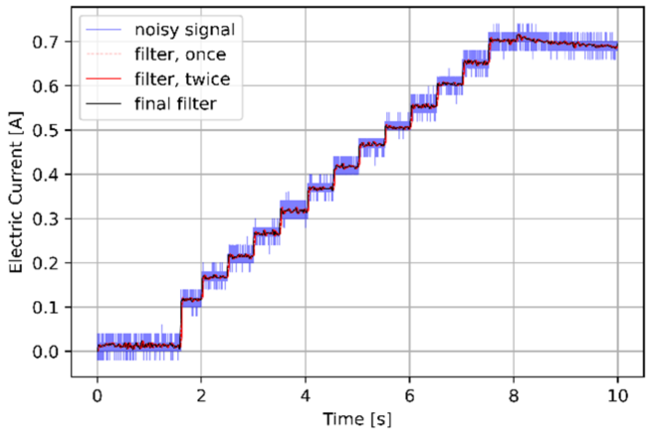
Next, the filter is applied to the current signal.

Figure 3 shows the filtered current signal and its corresponding power output over time. The red and black lines in indicate the filtered signals, while the blue lines indicate the raw signals. The filtered signals are smoother and less noisy than the raw signals. The y-axis on the left side of the plot shows the current in amperes, while the y-axis on the right side of the plot shows the power output in watts. The x-axis represents time in seconds. Overall, the figure demonstrates the effectiveness of the filtering process in reducing noise and improving the accuracy of the data.

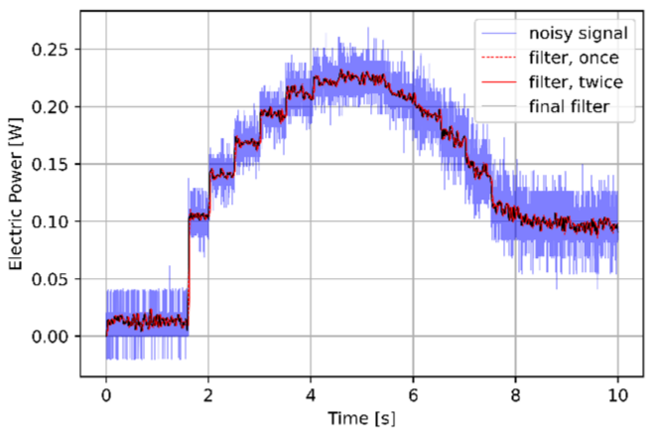
After applying the digital filter process to the current signal, the filtered signals for each temperature gradient can be further analyzed by fitting them to a polynomial curve. The method of fitting a polynomial curve to the filtered signal is carried out by utilizing the least-squares polynomial fit algorithm. In order to select the most appropriate polynomial model for the filtered signal, various polynomial models, such as quadratic or cubic equations, were compared based on their goodness of fit, which can be evaluated using the coefficient of determination (R^2). Figure 3 shows the polynomial curve that best represents the filtered signal and can be used as a model of the actual thermoelectric module (TEM) behavior under different temperature gradients, with a constant cold side of $24.3°C$. Table 1 shows the coefficients of the polynomial $y = ax^2 + bx + c$ and the corresponding R^2 values for each different temperature curves.

TABLE I: Polynomial coefficients fitted from experimental and filtered data.

	a	b	c	R^2
T_H=60℃	-1.2459	1.0118	-0.0004	0.997
T_H=70℃	-1.1596	0.8698	0.0003	0.989
T_H=80℃	-1.1861	0.7737	-0.0001	0.978
T_H=90℃	-1.2159	0.6819	-0.0002	0.996
T_H=100℃	-1.0748	0.5259	3.00E-06	0.984
T_H=110℃	-1.1398	0.4204	7.00E-05	0.992



(a)



(b)

Fig. 3: Improved Accuracy of Current and Power Output Measurements with Signal Filtering: a) current profile, b) power output.

The R^2 values range from 0.978 to 0.997, indicating a high degree of correlation between the temperature and the data being measured. In general, the data suggests that as the temperature increases, the R^2 values also tend to increase, indicating that the correlation between the temperature predicted by the polynomial approximation and the measured data becomes stronger. However, there is some variability in the data, with the R^2 value for $90°C$ being significantly higher than the surrounding values.

These models can be used to predict the TEM's performance under different conditions and can also be used to optimize the TEM's performance. The polynomial curve can be used to determine MPP of the TEM, which is the temperature gradient at which the TEM generates the maximum power. The polynomial curve can also be used to calculate the TEM's performance, which is the relationship between the power generated by the TEM and the electric current delivered at a fixed temperature and specific load.

IV. Conclusions

The results of this research paper provide valuable insights into the behavior and thermal characteristics of a thermoelectric generator (TEG) system. The experimental setup designed and utilized in

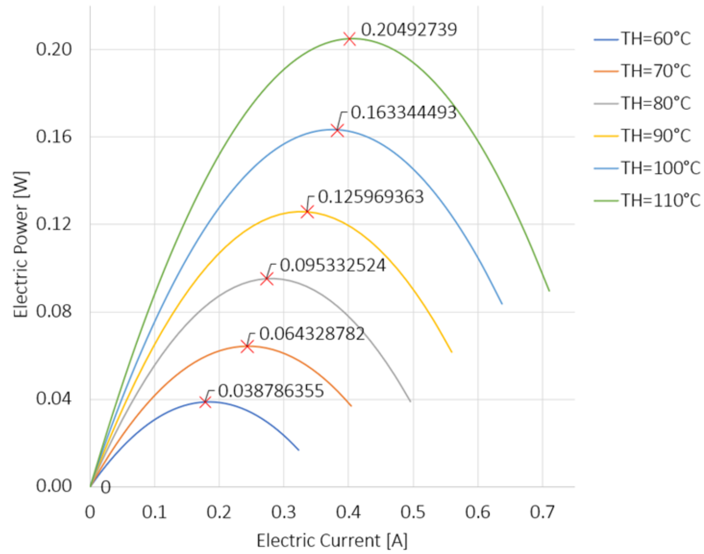


Fig. 4: Polynomial curves for filtered current vs. power at different temperature gradients for different temperatures between the hot and cold sides. Cold side temperature 24.3℃.

this study provides an accurate simulation of real-world operating conditions and allows for the measurement of the TEG's power output under different load conditions and temperature differences. The operating curves obtained through the study show the TEG's behavior and thermal characteristics, including the maximum power point (MPP), under varying conditions. This study contributes to the advancement of TEG technology by providing a comprehensive analysis of the TEG system's behavior and thermal characteristics. Furthermore, the experimental setup designed and utilized in this study provides a valuable tool for evaluating the power generation of TEGs under known boundary conditions. As future work, the evaluation of the pressure over the hot and cold side of the TEG and the effect of transient thermal conditions over the power generation could be investigated. These additional studies would provide a more comprehensive understanding of the behavior and performance of TEG systems and contribute to the advancement and optimization of this technology.

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