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Original Research Article

Effect of Temperature on Thermoelectric Generator (TEG) Voltage Output through Characterization for Mobile Phone Charging Application

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ABSTRACT

The lack of uninterrupted power supply has caused a quagmire in the telecommunication sector in rural areas in Nigeria. This work focused on evaluating the effect of temperature on thermoelectric generators (TEG) to generate voltage by characterization of the TEG to charge mobile phone with a view to determining the best temperature for high-quality voltage performance for a certain load. This work used two thermoelectric modules connected in series while maintaining the interface at different temperatures in the range of 28.7 to 128.7 °C to produce the desired voltage at 10 °C intervals. The cooling start temperature was pegged at 132.1 °C and dipped at 124.6 ºC. It was observed from the result that the optimal temperature for the heating trial experiment was 88.7 ºC and the optimal cooling temperature was between 132.1 and 132.6 ºC which resulted in a charging voltage of 6.19 to 7.26 V. This indicates that below the given temperature and voltage for both heating and cooling profile, the phone will not charge due to poor current and voltage levels. This suggests that maximum power point tracking is recommended in order to adjust the temperature to achieve the appropriate voltage. The TEG1-241-1.4-1.2, however, is unable to withstand temperatures higher than 200 °C.

1. INTRODUCTION

The situation of the power supply in Nigeria has been very epileptic for the past decades, thus there is need to look for alternate sources of energy. The case of operating mobile phones in rural, sub-urban areas and some parts of urban areas has caused a quagmire to the telecommunication industry (Obidike, 2011).

With the advent of the invention of thermoelectric generator, there is need to evaluate the performance of the thermoelectric generator power system through characterization by exploiting the temperature differentials by characterization to determine the optimal temperature difference that will produce the desired voltage and power output depending on the system load specification.

Chen et al. (2023) stated that the output characteristics in terms of the voltage, current and power of the thermo-electric generator system will change with the temperature difference between the hot ends, which is the same scenario, in the experiment of this main paper. Chen et al. (2023) conducted a study and stated in the paper that, the thermoelectric generator of the hot end varies with time during a period of 350 seconds. In this study the change rate was approximately 60 º C/seconds in a specific region of his work, where the most significant drop was observed. However, this was a gap as it is not the same case in this main paper as there was a small steady change in temperature within as small amount of time in second's unit which makes this main study preferable. Park et al. (2014) conducted a study which was a proposed system that tracked the varying maximum power point with a simple and cheap temperature sensor based circuit without instantaneous power management or TEG disconnection. The gap in this work did not declare the optimal temperature in the summary at which the maximum power was obtained, which is an essential factor in the TEG system. Mohamed et al. (2021) conducted a study, on the effects of fuel cell vehicle waste heat temperatures and causing speeds on the outputs of a thermoelectric generator energy recovery module. This study used the thermoelectric energy module to recover low grade waste heat from a 2 kW fuel cell vehicle and improved its energy utilization. The module deployed the integration of a TEG cell with a heat pipe and a finned heat sink. The temperature of the cold region in this reviewed study was around 472 °C and produced a power output of 3 W. This indicates the poor efficiency of the entire system. This gap in performance was addressed and produced a greater power with low grade temperature range ensuring the durability of the TEG system. Ando Junior et al. (2018) conducted a work on the "characterization of a thermoelectric generator (TEG) system for waste heat recovery. The reviewed paper presented the development and characterization of a thermoelectric generator (TEG) system for waste heat recovery to low temperature in industrial processes. The open circuit voltage that was obtained was 0.4306 V. This voltage is not enough to charge a phone, however, the power output of 29 W is very high and will cause over voltage in the phone. This is not recommended for the phone technology as the voltage and power margins are low and extreme respectively. This main paper addressed such gap. Wang et al. (2020) conducted an experiment on a heat pipe thermoelectric generator for industrial high temperature waste heat recovery. The target temperature was about 630 °C which created the gap of power loss and poor efficiency including danger of TEG device failure over a period of time. This main paper was able to manage the temperature to produce enough power. The goal of this work was to solve the problem of mismatch between energy supply and energy demand. However, it did not address the gap of in-efficiency and TEG device safety at handling such high temperatures. This main paper addressed the gap and produced significant voltage with low temperature operating conditions and was still able to power the phone. Aranguren et al. (2017) conducted a study on thermoelectric generators for waste heat harvesting using a computational and experimental approach. A prototype divided into two levels along the chimney which used the waste heat from a combustion system was built. The experimentation was used to determine the parameters (including temperature) that influence the generation of power from the TEG system and to validate a generic computational model able to predict the the thermoelectric power generation profile of any application, where waste heat was harvested. This work did not evaluate the power for the TEG system in the summary but just stated that the prediction for the TEG system to produce power has an accuracy of ±12%. Ni et al. (2023) conducted a study on the performance analysis of compact thermoelectric generation device for harvesting waste heat. This work established the fact that temperature is important for evaluating the performance of the TEG device. It deployed two heat collectors and three coolers. It could be observed that the average difference on both sides of each layer of the thermoelectric modules ranges from 316 and 321 °C. It should be noted that the gap in this work had some challenges due to its high system operating temperature which can reduce the performance of the entire system. This main paper addressed such gap by using low temperature conditions to achieve the same purpose of effective power generation to charge the phone. This also helped to curb energy loses plagued by high temperature system operation.

Liu etal. (2015) conducted the study on the performance of a waste heat recovery thermoelectric generator system for automotive application. It used energy harvesting system, which extracts heat from an automobile exhaust pipe and turns the heat into electricity using TEG system. It could be observed that the operating temperature of the engine of exhaust does not agree with the temperature difference of 258 ° C experimented in this study, making the work unrealistic for the purpose of use in modern vehicles which operate at lower temperature values. This main paper worked with the scope of the ambient temperature limit of an automobile with little energy losses. However, the TEG system in this main work, could still operate at high peak temperatures not more than 200 °C. Montecucco et al. (2014) carried out a research on the effect of temperature mismatch on thermoelectric generator, which was electrically connected in series and parallel. They stated that the application of thermo-electric generator to recover useful energy from waste heat, has increased rapidly in recent years with applications ranging from micro-watts to kilowatts.

It is in existing literature, that thermoelectric generators (TEG) systems preferably homogeneous ones in nature, can be connected in series, parallel and series-parallel to provide required voltage and current. In majority of the TEG systems, the individual thermoelectric modules are subject to temperature mismatch due to operating conditions.

Temperature mismatch can occur in TEG systems when optimal temperature is deviated to an erratic temperature level causing the drop in the power output of the system. In addition, when different TEG systems are connected having different distributed temperatures. they cause power losses as a result of internal resistance of each of the individual TEG systems (Montecucco et al. 2014). The solution is to provide the need for maximum power point tracking system to ensure the optimal temperature is always within its little error deviation to ensure consistent power output, voltage and current.

According to Andrea et al. (2014), it was observed that the variability of the electro-thermal performance and mechanical clamping pressure of individual TEG modules can also cause a significant mismatch. In the experimental findings of this reviewed work, the literature confirmed the variable temperature distributions are commonly found in present thermoelectric generators making them unpredictable. The experimental findings of this work observed there was a power loss due to temperature mismatch. This reviewed work also noted that the magnitude of the voltage, also depends on the materials in use and different materials may be optimized for performance at different temperatures.

The aim of this main work is to evaluate the effect of temperature on thermoelectric generator through characterization and apply it in mobile phone technology. The specific objectives are to characterize the heating temperature profile as it rises and to characterize the effect of the temperature associated with the voltage output when it falls or cools. The justification of this work indicates that by evaluating the effect of temperature on the thermoelectric generator, it assists researchers in understanding how the voltage and power output will perform when connecting it to a load for optimization. The significance of the study could impact positively the telecommunication world especially in rural areas and sub-urban areas in Nigeria where power availability and sustainability of electricity power supply is non- existent.

2. MATERIALS AND METHODS

2.1. Design, Coupling, Calibration and Characterization of the TEG Power System

The main experiment was conducted through design, coupling, calibration and characterization as shown in Figure 1. This work was extracted from the main experiment. However, a holistic view of the main experiment will be explained for clarity. This work used a method called the TEG Characterization test rig method. The details of the experimented was elaborated. The experiment was a transient output which is associated with time. The thermoelectric modules were placed on an aluminum slab, for protecting it from the electric hot plate and a heat sink was put in place for thermal conduction. The protective cables were used just to protect the TEG wires from burning. The electric plate was used to simulate how the charcoal heat profile will work. The output of the wire was then fed to a power system which was designed from scratch using a circuit board. The function of the circuit power system was to serve as a voltage regulator. The output of the thermoelectric device after the electric hot plate was been switched on, was fed into the

IN4007 diode due to the fact that the voltage signal was inverted. The negative terminal of the TEG has to be fed to the positive terminal of the circuit input and the positive terminal of the TEG will be fed to the negative terminal of the TEG. This is where the IN4007 diode comes in to regularize the circuit to ensure a DC voltage is produced. One of the circuit components is the LM317 Integrated circuit was connected to two capacitors which the first is 10 μF 25 V capacitor and the second capacitor of 220 μF 25V, with the former fed into the central mid-point and the later connected to the right side just before the IN4007 Diode. The duty of these capacitors is to remove the ripples from the DC signals for more smoothened DC signal. A resistor is connected to the left leg of the LM 317 Device and the second leg is connected to the central pin where the 10 μ*F* meets.

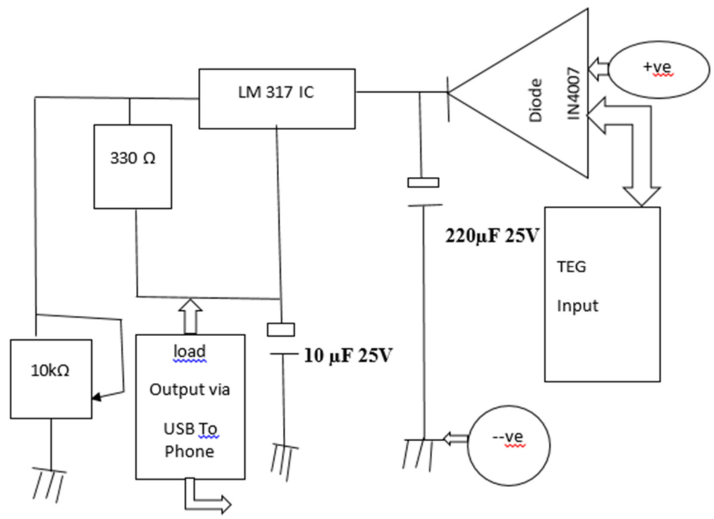

Figure 1: Schematic diagram of design, coupling, calibration and characterization of thermoelectric generator power system

The 330 Ω is a bias resistor for the LM317 device. The bias resistor contributes to the improved performance of the LM317. It also helps to reduce the number of components. The variable resistor, 10 kΩ, is a variable resistor for regulating the desired optimal voltage range and current by adjustment. Figure 1 shows the thermoelectric generator power system circuit. It should be noted that the thermoelectric generator and voltage regulator charger circuit was combined to form a power system. The output was then connected to a multi-meter that can measure current and voltage. The USB port was connected to the circuit using a USB wire to the phone which successfully charged an android phone at a particular voltage. This work also discovered the designated voltage (6.19 V) below which the power system will not charge. The open circuit voltage of the phone was synchronized to cut-off with the diode green light at 3.5 V.

2.2. TEG Characterization Heating and Cooling Test Rig Method

Following the TEG Characterization test rig method above in figure 1 from the TEG main experiment, two TEG modules were placed on the electric hot plate in which 4-5 trials were conducted. The second aspect of this main work focused on two trials for the heating and cooling experience with a method named the TEG characterization heating and cooling test rig method. For the heating test, the electric hot plate was applied to the TEG system and given ample time to heat up from 28.7 ºC about 128.7 ºC with interval of 10°C and then began cooling when the hot plate was unplugged to cool the TEG System. The heating process lasted for 4-5 minutes before producing desired voltage. The cooling test process got initialized. The initial peak temperature was pegged at 132.1 ºC and cooled steadily with little temperature difference to 124.6 ºC. The cooling process lasted for 10-15 minutes.

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3. RESULTS AND DISCUSSION

Figure 2 and Figure 3 shows a maximum voltage of 8.89 V for heating and cooling profile experiment. The heating profile result was generated. Equation 1 is a linear relationship showing an increase in temperature of the two TEG connected in series as the voltage generated from the TEG power system increased.

$$Y = 0.0959x - 2.5045 \quad (1)$$

Where x is the temperature and Y is the voltage

The regression value generated from the plot of the Microsoft excel software was 0.9708 which showed there was negligible error or insignificant deviation.in the result output. The maximum voltage at 108.7 ºC gave a voltage output of 8.89 V, validating the result of the open-circuit voltage in the main experiment.

Figure 3 shows the cooling profile temperatures and cooling voltage profile result data after heating of the two TEG connected in series. The graph plot shows a polynomial relationship in 2nd order equation given as:

$$Y = -0.7534x^2 + 9.9613x + 99.5 \quad (2)$$

This work showed a second order polynomial equation relation between the cooling temperatures and voltage result value. Equation 2 has a regression value of 0.9796 which indicates negligible or no error in the experiment. The decrease in temperature showed a decrease in the voltage. The temperature peaked at 132 ºC and cooled to 124.6 º C in which the experiment was stopped at 3.5 V. It took almost 10 to 15 minutes to cool to that point. The operating cut off voltage was obtained between 6.19 and 7.26 V, below which after 6.19 V, the phone will stop charging. The open circuit voltage was obtained at 3.5 V below which the LED green diode switches off. This 3.5 V LED diode was designated that way to synchronize with the operating open circuit voltage of the phone, to avoid damage or under-voltage charging.

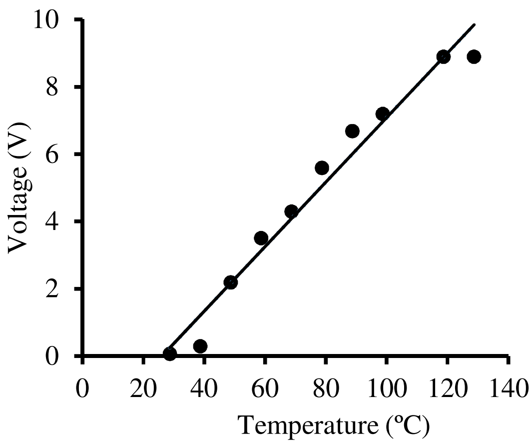

Figure 2: Plot of voltage against temperature for heating profile of two TEGs series connection using electric hot plate as heat source

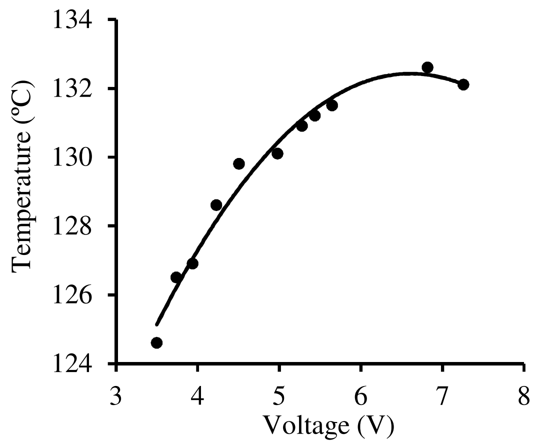

Figure 3: Plot of temperature against voltage cooling profile for two series TEG connection using electric hot plate as heat source

4. CONCLUSION

This work has been able to address the aim and objectives to indicate the characterization of the thermoelectric generator in terms of the effect of temperature on the voltage output. There are gaps in the reviewed works mentioned above and their experiment did not follow such patterns as it was stated. Some had rapid changing temperatures within few seconds, indicating the unpredictability and uncertainty of thermoelectric generators in the reviewed works. This makes this main work more preferable over other reviewed work due to its fast transient charging process and lower cost of materials for the research experiment. It can be observed, that the threshold voltage for charging the mobile phone is around 6.19 V which had an optimal temperature of 88.9 ºC. From the result it took 10-15 minutes for the TEG series connection to cool from 131.2 º C to 124.6 º C and the load open circuit voltage was 3.5 V below which, it will cut-off. This indicated that in situations of emergency, when the source of heat has been used up in this context of a clean charcoal, the mobile phone can still perform for about 5-10 minutes after cooling or disconnection from the heating source. Finally, the cooling profile indicated that between 132.1 ºC and 132.6 ºC the phone produced a charging voltage between 6.19 V and 7.26 V, below which the phone did not charge indicating the need to maintain the temperature level between the mentioned temperature ranges using maximum power point tracking mechanism.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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