

Thermoelectric generator experimental performance testing for wireless sensor network application in smart buildings

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Abstract. In order to make a conventional building more efficient or smarter, systems feedbacks are essential. Such feedbacks can include real-time or logged data from various systems, such as temperature, humidity, lighting and CO₂ levels. This is only possible by the use of a network of sensors which report to the building management system. Conventional sensors are limited due to wiring and infrastructure requirements. Wireless Sensor Networks (WSN) however, eliminates the wiring limitations but still in certain cases require periodical battery changes and maintenance. A suitable solution for WSN limitations is to use different types of ambient energy harvesters to power battery-less sensors or alternatively to charge existing batteries so as to reduce their changing requirements. Such systems are already in place using various energy harvesting techniques. Thermoelectric Generators (TEG) are one of them where the temperature gradient is used to generate electricity which is conditioned and used for WSN powering applications. Researchers in this field often face difficulty in estimating the TEG output at the low-temperature difference as manufacturers' datasheets and performance data are not following the same standards and in most cases cover the high-temperature difference (more than 200C°). This is sufficient for industrial applications but not for WSN systems in the built environment where the temperature difference is much smaller (1-20C° is covered in this study). This paper presents a TEG experimental test setup using a temperature controlled hotplate in order to provide accurate TEG performance data at the low-temperature difference range.

1 Introduction

Energy used within buildings and building services accounts for about 80% of the total energy use in the United Arab Emirates with 73% residential consumers [1, 2], with the introduction of green buildings regulation and policies, the local authorities' plan for

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energy rating in buildings. To reduce energy use in general, effective building energy management systems are essential. For the precise control feedback from the different energy systems and buildings areas, WSN is used. Wireless communications and the internet is the main topic for research in a variety of applications, in relation building energy systems and the use of WSN, wireless sensor nodes are distributed around the building and continuously measures, log, and transfer data to a central location. Powering these sensor nodes is still a challenge and ambient energy harvesting is a promising solution for such applications. Thermoelectric generators (TEG) is one of the energy harvesting technologies that can be used. Their operation is based on the concept of thermoelectricity, which is the direct conversion of temperature difference to electricity via a temperature gradient (Seebeck effect). Thermoelectric (TE) devices were originally made of two different metals and later with the introduction of semiconductors variety of doped materials were used to make TE modules. A module normally consists of multiple TE elements connected electrically in series and thermally in parallel in such a way to maximize the generated voltage. One side of the module is to be the hot side where heat is applied, while the other side is called the cold side where heat gets dissipated or rejected, Figure 1 below shows a schematic of a TEG module. [3,4]

The generated voltage from a TEG is directly proportional to the temperature difference between both sides of the module and the Seebeck coefficient of the material used is shown in Equation 1.

$$E_{emf} = S \Delta T \quad (1)$$

Where E_{emf} represents the generated electromotive force, S is the Seebeck coefficient which is material dependent, and ΔT is the temperature gradient difference. [6]

Commercial sensor nodes which use TEG as a power source are available commercially but mostly for high-temperature difference applications such as boilers and industrial processes. Examples of commercial sensor nodes are shown in Figure 2 below. When it comes to buildings applications the temperature difference available is much lower. If boilers, hot water, and space heating systems which are not the main energy consumers in the UAE are excluded, the available temperature difference can be as low as 20C° or even lower in certain cases. The selection of suitable TEG for such task requires performance data within this range of temperature difference which is not currently available. [7, 8]

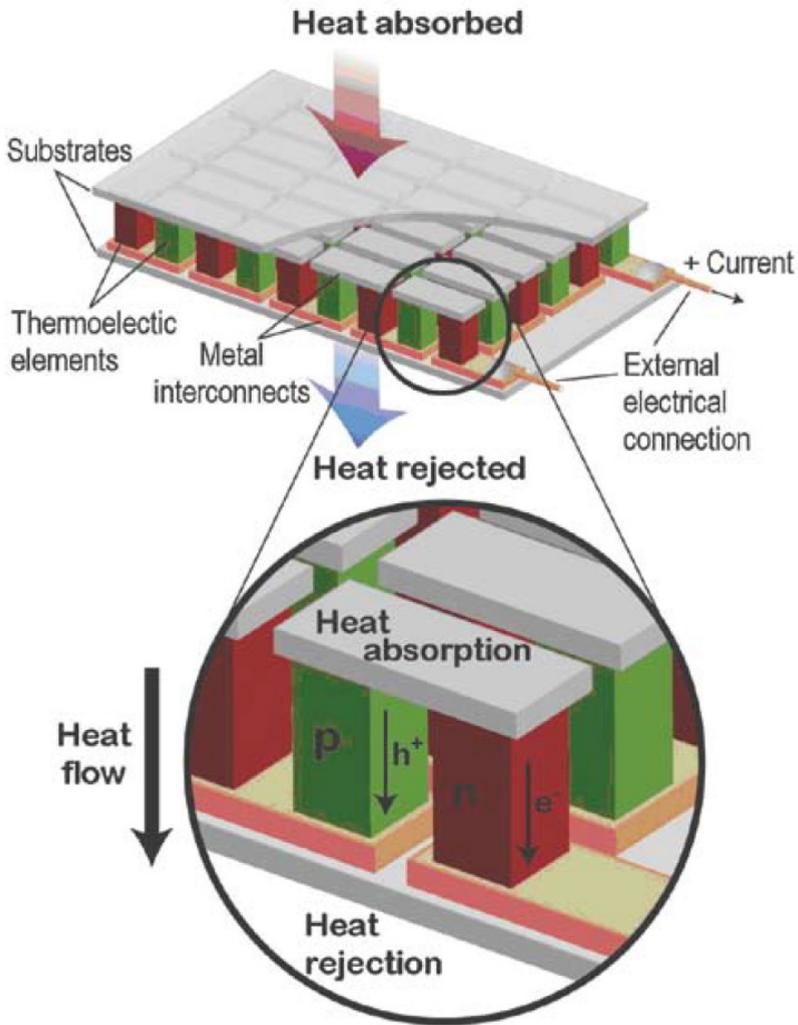
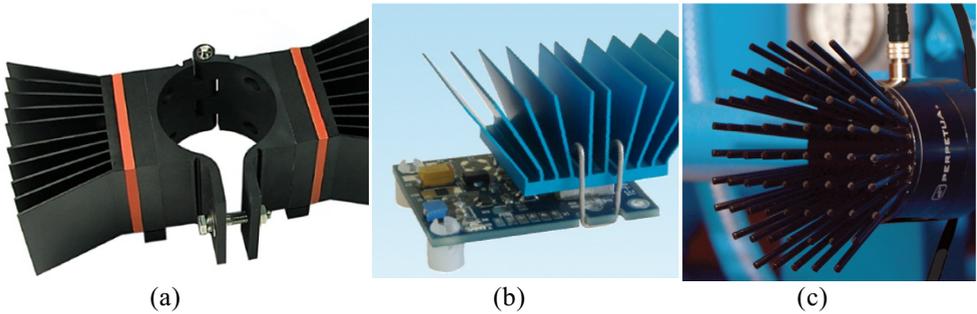


Fig. 1. Schematic of a TEG, TE elements of different types connected together to form a module. [5]



2 Experimental setup

The experimental setup consisted of a high precision feedback controlled hot plate where the TEG being tested is placed on top with the hot side of the TEG facing the hot plate. K-Type thermocouples were used on both sides of the TEG to measure the actual temperature from each side. Aluminum heat sink with copper core was used to cool down the cold side of the TEG by forced convection using an electric axial fan. Thermal paste with a thermal conductivity of 0.925 W/m-k was used between all the different layers to ensure proper heat transfer, finally, the setup was fastened to the hot plate to maximize the accuracy of the results, Figure 3 below shows a schematic of the setup.

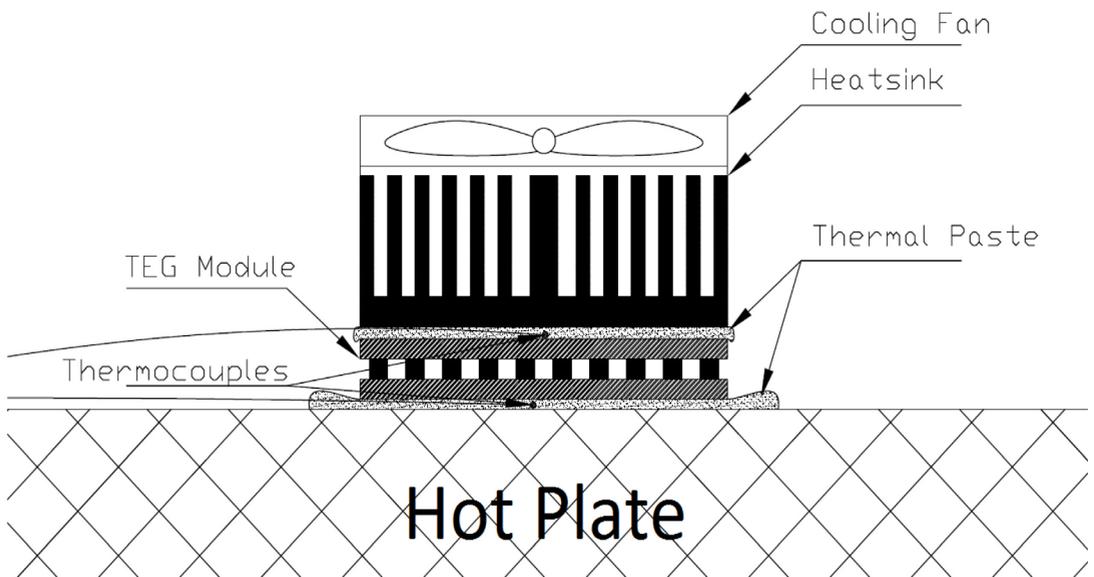


Fig. 3. Schematic illustration of the testing setup.

A TG12-4 TEG module was acquired for this test, which is a Marlow Industries Inc. product, designed as a universal TEG, rated at 4 watts at a temperature difference of 180C° . [12] Manufacturer's data sheet provides performance data with 50C° as cold side temperature and a minimum of 70C° as hot side temperature. It is common practice for manufacturers and suppliers of TEG to provide performance data at high-temperature difference which normally covers the optimum operation condition for the TEG to generate the rated power. In practice, however, different applications have a variety of working temperature ranges, and often users and researchers face the issue of not having performance data at the low-temperature difference. This is the main motivation for the construction of this setup and conduction of these experimental measurements. Figure 4 shows the module used and its positioning on the hot plate. [12]

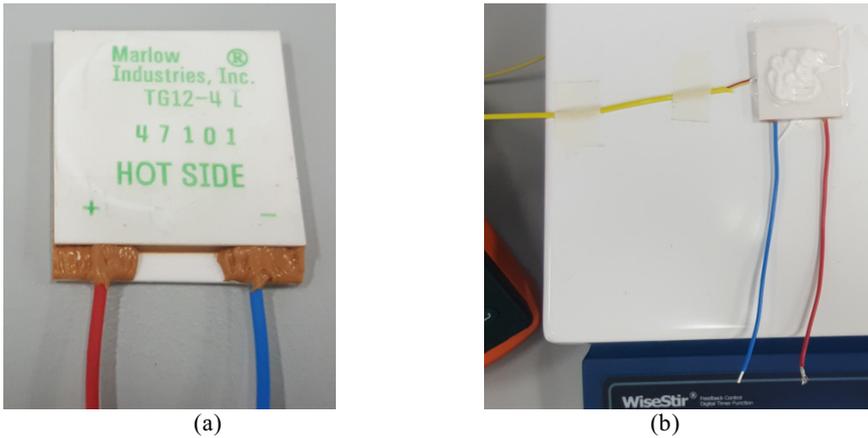


Fig. 4. (a) TEG module obtained for testing (b) TEG module installed on the hotplate with the hot side thermocouple.

The K-Type thermocouple was placed between the TEG and the hot plate to measure the hot side temperature, thermal paste was used to ensure thermal conductivity from the plate to the TEG and the thermocouple. Figure 5 shows an example performance data for the device from the manufacturer’s datasheet.

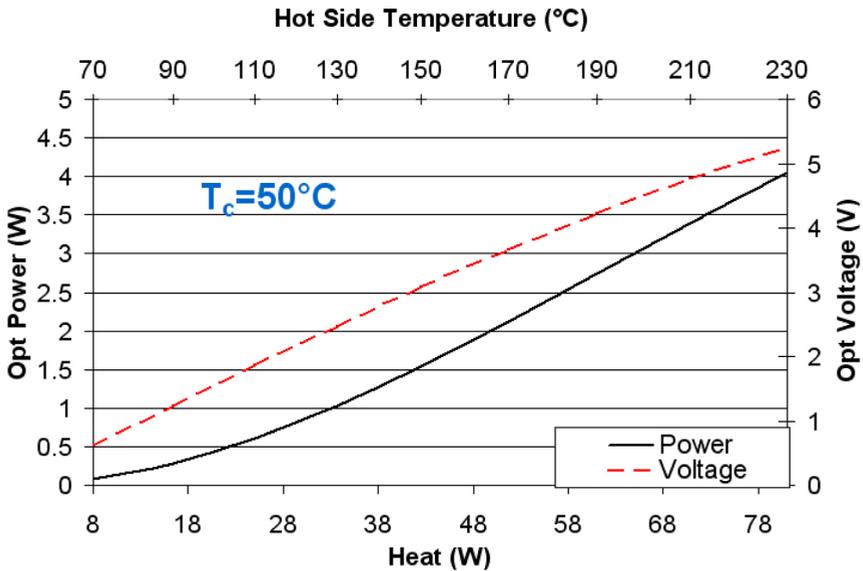


Fig. 5. Performance data from Manufacturer’s data sheet [12].

The second thermocouple was placed on top of the TEG and attached to the cold side of it, thermal paste was used to ensure thermal conductivity. The heat sink was then placed on top with the copper core centered over the TEG. To maximize the cooling effect of the heat sink, an axial electric cooling fan was used which is powered by an independent power source of 12V DC. The fan speed was maintained at the same level

during the experiment, Figure 6 next shows the heat sink used and then the heat sink with the fan attached to it.

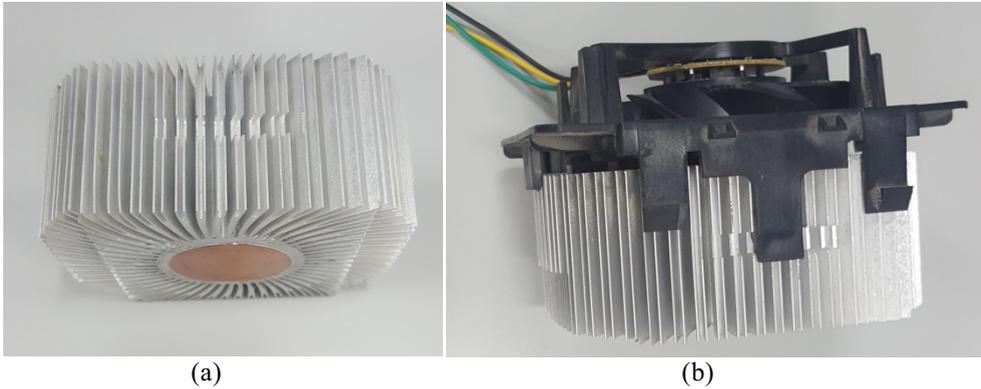


Fig. 6. (a) Heat sink used (b) Heat sink with the electric axial fan attached.

The complete setup was then secured to the hot plate as any movement will affect the accuracy of the measurement. Both thermocouples were attached to dual channel temperature data logger, and the TEG output to a digital multimeter set to measure open circuit voltage, or short circuit current, Figure 7 below shows the complete setup of the experiment where the hot plate with the TEG and heat sink in the middle, temperature data logger on the left, and digital multimeter on the right. The hot plate temperature was then varied from 40C° down to 0C° with 2.5C° steps, allowing enough time between changes for the TEG temperature to reach steady state and the generated electricity to stay at a fixed level. The values were recorded, and a next setting was applied. It was noted that the TEG hot side temperature was a couple degrees Celsius lower than the hotplate temperature but this has no effect on the experiment results as thermocouples were installed directly to the hot and cold sides of the TEG.



Fig. 7. The complete setup of the experiment showing the hot plate with the TEG and heat sink in the middle, temperature data logger at the left, and the digital multimeter at the right.

3 Experiment results

The temperature of the hot plate was varied from 40C° down to 0C° on 2.5C° steps. On each step, the open circuit voltage and the short circuit current were measured using a digital multimeter. Enough time was allowed between measurements for the TEG output values to reach steady state. The test was carried in a room with the following conditions; room temperature 20.3 C°, relative humidity of 56%, and an atmospheric pressure of 1010 mbar. The temperature of the cold side of the TEG was slightly rising due to the increase in hot side temperature, but values were nearby the room temperature due to the heat sink and the cooling fan. The hot side temperature was increasing based on the changes on the hot plate set temperature, with a slight difference. Both sides temperatures are presented in the graph shown in Figure 8. The temperature difference ranged from 1C° to 20C° which covers a good range of temperature difference available in buildings for WSN applications and energy harvesting.

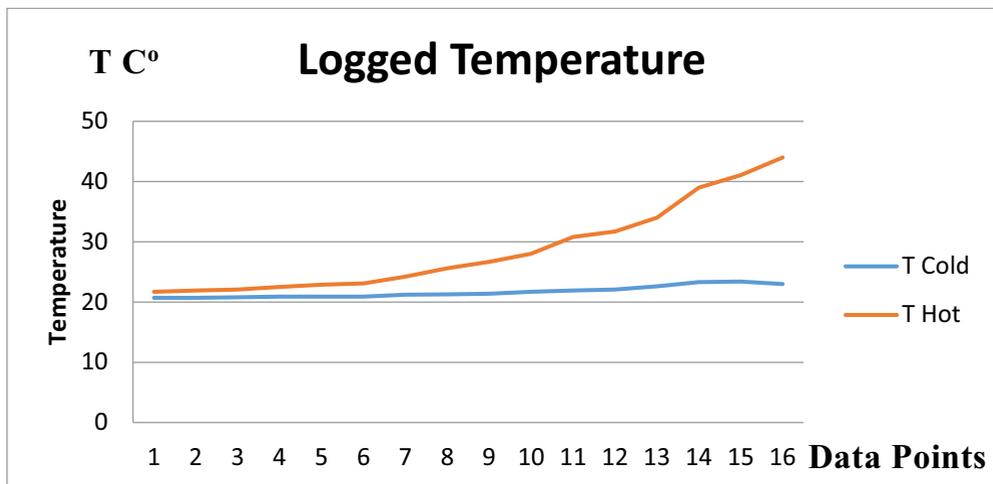


Fig. 8. Graph showing the logged temperature data from both sides of the TEG.

The multimeter was permanently attached to the TEG for continuous measurement of the open circuit voltage. The voltage values were recorded every time both sides of TEG temperature values reached a steady state. After every voltage reading, the short circuit current was recorded at the same temperature difference. Using Equation 1 of the Seebeck effect the Seebeck coefficient was calculated to be 41mV/C° for this specific TEG. Open circuit voltage was observed to be directly proportional to the temperature difference, it was closely following the increase in the TEG hot side temperature as shown in Figure 9.

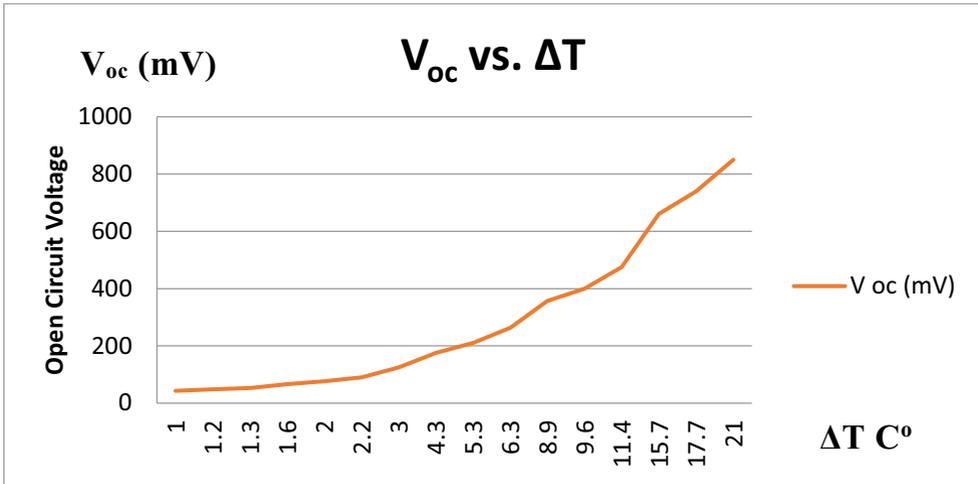


Fig. 9. Graph showing open circuit voltage vs. temperature difference.

Short circuit current followed the temperature increase with similar behavior to the open circuit voltage as shown in Figure 10, this indicates that the generated power of the TEG is increasing in a comparable scheme.

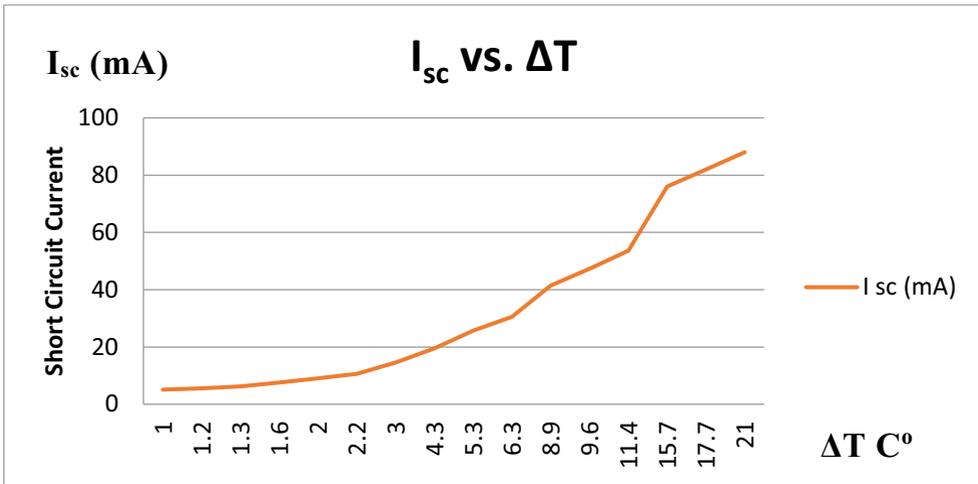


Fig. 10. Graph showing short circuit current vs. temperature difference.

4 Results discussion

Generated electricity from the TEG due to the temperature difference showed a directly proportional to the increase in the hot side temperature, which is matching the behavior described in the performance data provided by the manufacturer. The experimental test results showed the electrical output capabilities of the subject TEG at the very-low-temperature difference as low as 1 C°, such performance data is not covered in the product datasheet, this is exactly what designers and researchers in the field of ultra-low-temperature difference are looking for.

The Seebeck coefficient was calculated using Equation 1 by substituting the measured values of the open circuit voltage at each data point, results were varying within a narrow range from 39.6 mV/C° to 41.8 mV/C° with the average at 41 mV/C° including the extremely low-temperature point.

Furthermore, taking in consideration that the subject TEG module is a general purpose TEG, which means considering the operation condition at the design stage of the TEG module could maximize the module performance at such low-temperature difference.

5 Conclusion

The experiment showed that testing of TEG using this method is possible, while further testing and validation is required. The use of an air-cooled heat sink makes it rather complicated to accurately calculate the heat flux through the TEG in order to estimate efficiency values. A suitable solution for this is to use heat exchanger instead in which a refrigerant flow at a certain flow rate and temperature. Measuring the inlet and outlet temperature of the refrigerant together with the flow rate will provide more accurate figures on heat dissipation from the cold side of the TEG. The presented setup is suitable for performance measurement of TEG. In order to measure efficiency, a heat flux meter needs to be installed on either side of the TEG, or use the heat exchanger method mentioned earlier.

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