Temperature Gradient Measuring System Development Using Wireless Sensor Networks For Detection Of Ambient Air And Soil

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Abstract:* This paper proposes a concept utilizing a thermoelectric generator (TEG) device to convert thermal energy different between ambient air and soil into electrical power. In this study, soil temperature profile with three various depths has been studied to find the optimum depth for maximum temperature differences between ambient air and the soil. The study area coverage is at the lake nearby Universiti Kebangsaan Malaysia (UKM), Bangi Malaysia. After the temperature data collected, the efficiency of TEG with different configurations was tested in the lab. Then, energy storage devices and buck-booster are used to further enhance the capabilities of TEG. All the models are then integrated and tested to power up electronics load according to the temperature profile collected. The results have proposed the depth of soil 20 cm will provide an optimal average temperature different of 3.34 ^{0}C. Based on the temperature gradient data, combination of four TEG TEP-12656 in a series connection with DC booster circuitDC1587 will produce an optimum voltage output about 3 V. This output voltage is enough to fully charges small storage system such as super capacitors 10 F in 6.58 minutes. Arduino Uno was used as a load and it was successfully powered up for a short duration of time before energy fully depleted.

***Keywords:* Thermal energy, energy harvesting, thermoelectric, temperature of soil, wireless sensor network.**

1. INTRODUCTION

The usage of wireless sensors networks (WSNs) has been increasing over the years due to its potential to be applied in various fields such as medical [1]-[2], automation [3]-[6] and agricultural [7]-[8]. However, the usage of WSNs is challenged particularly in remote areas due to its limited energy and lifespan [9]-[10]. The main aspect that affects the WSNs application is the energy source as the available energy influences the performance and lifespan of the system [11]. The usage of battery to supply a large network is not practical as it costs a lot especially in replacing battery and maintenance fees. Besides, battery has a finite capacity [12]-[13].

Researchers has been coming up with alternative solutions to improve the lifespan of WSNs by reducing the overhead connections and duty cycle. A few algorithms have proven to improve the lifespan of the sensors in WSNs. However, energy harvesting remains one of the best alternatives. Energy harvesting, in facts, able to provide a reliable and in-situ energy source by converting ambient to electrical power [14]. In contrast, energy harvesting also enables the deployment of new sensors system particularly in areas where wired infrastructures are not practical to be built [15]. A few different techniques for energy harvesting has been studied, for example, solar [16]-[17], wind [18]–[20], heat [21]–[24] and vibration [25]–[27]. This leads to the need to change from primary battery to secondary battery, and using the energy harvesting to charge and recharge the secondary battery [28]–[30].

One of the technologies that has been studied is the usage of energy from temperature difference between two objects. The ambient air becomes warm in daylight due to the solar radiation and becomes cold at night. This periodic changes in temperature of air will transfer to any objects in contact. The object's temperature variation is then dampened by the thermal inertia, therefore creating a temperature difference between ambient air and the object [14]. Solid-state thermoelectric that utilizes Seebeck effect is considered to be efficient and reliable as it does not have any moving parts [31].

A complete system of thermoelectric energy harvesting constitutes of an interface between the ambient air and soil, a TEG and an electronic load. The output of the energy harvesting system is based on the energy source as well as the harvesting component. By using TEG to enable self-powering WSNs, it can reduce the maintenance work and cost, indirectly reducing the environmental pollution caused by the side chemicals products from battery production.

The connection of multiple TEGs will be electrically in series, as have been suggested by Azdiana et al. [32]. This is because parallel connections of TEG will have lower voltage and higher currents, leading to I2R or Joule heat losses. After all, the maximum power output for either series or parallel connections are almost similar [33]. In fact, research by Pullwit et. al. shown that the losses due to mismatch conditions is lowered in series connection [11].

One such application for thermal energy harvesting is using the temperature difference between ambient air and soil [34]. TEG can harvest the solar heat radiation and the usage of heat sink in soil allows energy harvesting throughout day and night. The solar radiation accumulates a significant amount of heat in the soil, and taking soil thermal inertia into account, it could be a potential energy sources to power up WSNs. The sensors and devices could be powered up by secondary battery, operating at nominal voltage for a short amount of time, a few times a day.

The system design for thermoelectric energy harvesting devices are quite straightforward. A heat sink is buried in the soil and a ceramic plate is placed on top of TEG. During daytime, the ambient air is warmed up and will heating the ceramic plate. While the heat pipe will transfer the heat to the buried heat sink and be dispersed. This system shows an advantage during night time, as it is still able to generate energy due to inverted temperature profile. Ambient becomes cool and soil becomes warm. Research by Yildiz & Coogler has shown that the microscale TEG is capable of generating 15µW/cm3 from temperature difference of 10 ℃ [35].

According to Aliyah & Zamri, the nature as a whole are affected by different factors such as microclimate, built environment, topography, the plants and buildings. Therefore, all these factors contribute to different temperature of ambient air [36]. Research by Muhammad et al at Gombak, Malaysia has shown that the deeper the depth of soil, the more constant the temperature as compared to ambient air [37].

Therefore, this paper will introduce a study regarding temperature profile at UKM, Bangi, with a shallower depth will have to be conducted. This paper study the performance of TEG and test the reliability of the thermal energy harvesting system using temperature difference between ambient air and soil. At the end, a feasibility study whether an electronic device such as microcontroller Arduino Uno could be supplied by this approach.

2. METHODOLOGY

The methodology divided into three parts which are data temperature gradient measuring, TEG configuration lab measurement based on temperature profile data and model integration.

A. Data Temperature Monitoring

Arduino Uno and waterproof-temperature sensor DS18B20 are used to collect the temperature of the surface and in the soil of three various depth at 10 cm, 20 cm and 30 cm. The site that has been studied is at the lake nearby Faculty of Engineering and Built Environment (FKAB), Universiti Kebangsaan Malaysia, Bangi. Since WiFi utilities is not available in this area, thus data collected is not able to store in cloud. Therefore, Ethernet Shield V2.0 has been used to utilize the micro SD card slot to store the data collected.

The data collected is then analyzed in computer and graph is plotted to analyze the relationship. This temperature collecting model is built inside a box to prevent the electronics component from water damage. The setup is as in Figure 1. Two situation that needs to be considered when using the box is that, the box needs to withstand rain, and stagnant water after the rain, or the level of lake water rises up after dusk. The box is sealed using plastic bags and hot glue gun; the box is placed on top of a chair.

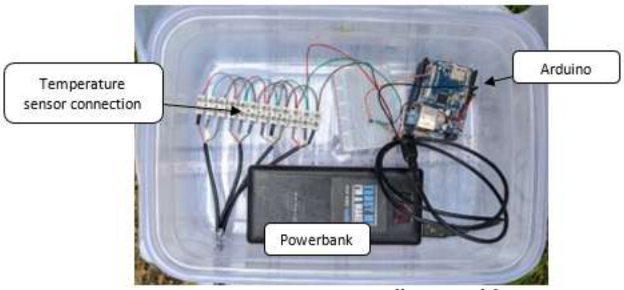

Figure 1: Temperature collector model

The connection of Arduino Uno and DS18B20 is based on Figure 2, where the resistor works as pull-up resistor. Since this temperature collector model is deployed nearby the lake where there is not any power outlet available, two powerbanks are used alternately for keeping the model staying functional for a week. A fully charged 20000mAh powerbank can power up the model for 2 days straight.

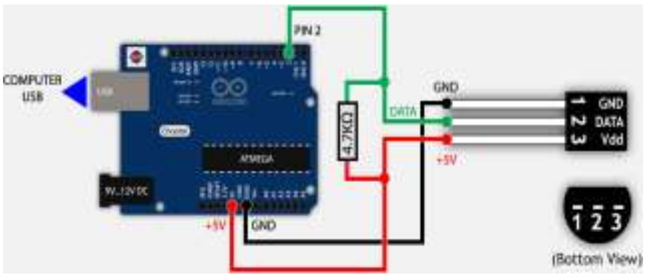

Figure 2: Schematic connection

The timestamp for the model is set beforehand using laptop before deployed. The timestamp is obtained from https://www.epochconverter.com/, and the unit has to be converted as the count starts from 1st Jan 1970. Epoch is used as the reference point from where the time is counted. The timestamp process would have been easier if RTC DS3231 module had been used.

B. TEG Measurement

The purpose of TEG measurement is to find the output voltage based on the previous data experiment. The collection of temperature data of the difference between surface and soil depth will be use as a reference. While different methods of connecting multiple TEG affects the output of TEG. It can either be connected in series series or parallel, electrically or thermally. In this setup, the TEGs are connected electrically in series, and stacked up to study the effect of on the outcome. Data collected are then plotted onto graph for analysis to determine which configuration is the most suitable for this research. Besides, there many different types of TEG as well, of various sizes and materials, and it affects the output significantly.

Five variation of tests has been conducted using a total of three TEG with the model TEP1-12656-0.6 measuring 56mm x 56mm, to evaluate its performances. The tests are carried out as follow: (1) single TEG, (2) two TEG series, (3) three TEG series, (4) two TEG parallel and (5) three TEG parallel. Figure 3 shows the connection of TEG. The test is repeated using TEG model SP-1848, measuring 40mm x 40mm.

Figure 3: Different TEG connections: (1) single TEG, (2) two TEG series, (3) three TEG series, (4) two TEG parallel and (5) three TEG parallel

The setup to test TEG is shown in Figure 4. TEG is placed onto the hot plate where thermocouple data logger TC-08 is used to monitor the temperature on both sides of TEG. Heat sink is then placed on top of TEG to improve the cooling effect and ease the heat flow.

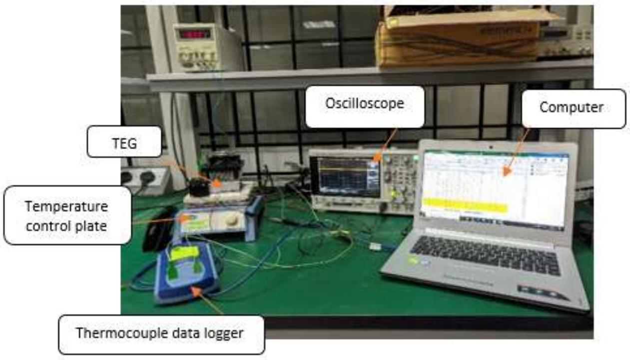

Figure 4: Actual test setup for TEG testing

In order to manage and stabilize the voltage output supplied to electronics load, a demonstration circuit DC1587 by Linear Technology is used. This board has a component LTC3105, a high efficiency step-up DC/DC, single polarity converter that can operate from input starting from 250mV, specially designed for low power application. The output of this board is stored in a super capacitor, which is then connected to another DC1587 board. The first DC board is used to step up the voltage, and second DC board is for regulating the voltage output.

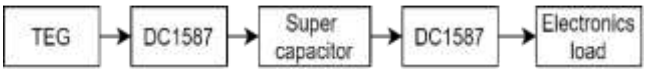

Figure 5: Connection layout

The demonstration circuit board DC1587 has been tested to evaluate its performance as well, by supplying DC voltage. The stepped-up voltage from DC board is used to charge super capacitor, and the time taken has been recorded. Two super capacitors of 10 F 2.5V each are connected in series to increase its voltage capacity to 5V.

C. Model Integrationeasurement

After each component has been tested and evaluated, the components are then integrated to a fully functional system. Aluminum is used as the plate and heat pipe for its good thermal conductivity property and a widely available material. A heat insulator is used to wrap around the heat pipe, to prevent unnecessary heat loss and to prevent unwanted heat from the soil to disturb it, indirectly improving the efficiency of heat transferring to heat sink. In addition, thermal paste is used to fill in the gaps between the components to maximize surface area in contact.

The top plate will absorb the heat energy, passed it to TEG and then dissipated to soil via heatsink. At the same time, there exists a temperature difference across TEG, hence generating voltage. Figure 6 shows the process flowchart.

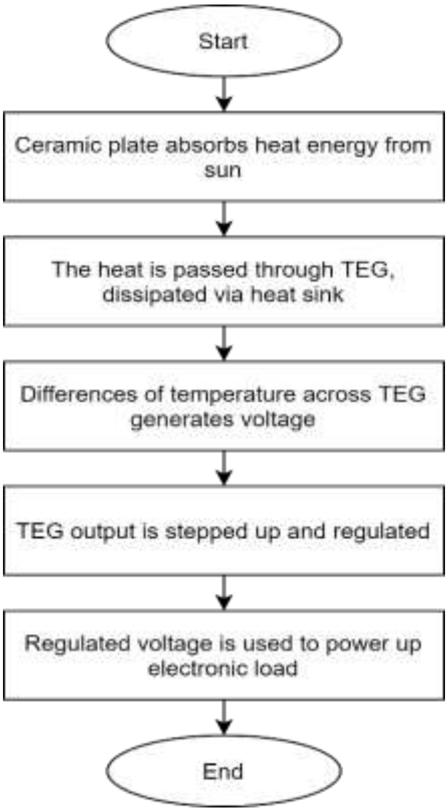

Figure 6: Process flowchart

3. RESULTS AND DISCUSSION

A. Data Temperature Monitoring

The temperature different between surface and in soil by the lake of FKAB, UKM Bangi has been studied for 5 days. There are three various depths at 10 cm, 20 cm and 30 cm. From the graph plotted in Figure 7, it can be clearly seen that the deeper the depth of soil, the temperature becomes more stable. Therefore, it gives a bigger difference of temperature with surface temperature by reference. In fact, the depth of 10 cm shows a similar temperature profile pattern as the surface of soil.

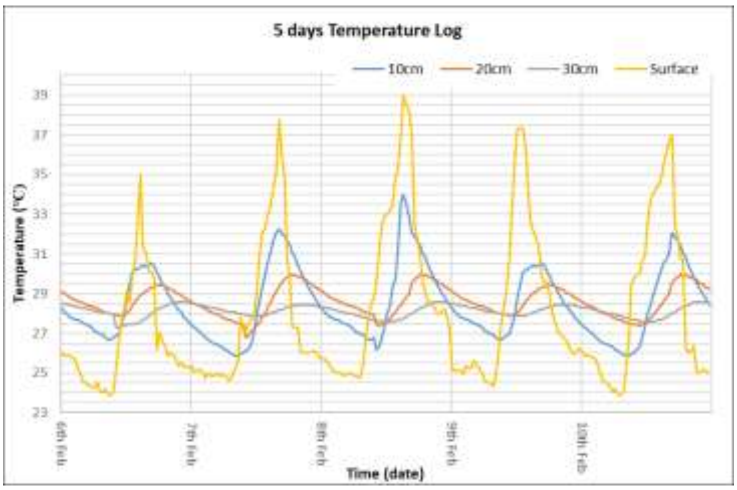

Figure 7: Temperature of Soil in various depth

Table 1 summarize the data extracted from graph in Figure 7. The highest temperature recorded on the surface is 39 ^{0}C and its lowest is 23.87 ^{0}C. It is clearly shown that with depth of 30 cm able to give maximum differences with reference to the surface of soil around 11.25 ^{0}C. While average temperature different is about 3.34 ^{0}C. Figure 8 shows the absolute temperature difference.

Table 1: Comparison differences in Temperature

	10 cm	**20 cm**	**30 cm**	**Surfaces**
Highest temp (^{0}C)	34.00	29.94	28.56	39.00
Lowest temp (^{0}C)	25.87	26.75	27.31	23.87
ΔT when surfaces peak (^{0}C)	7.32	10.38	11.25	
ΔT when surfaces at its lowest (^{0}C)	2.63	3.81	3.94	
Average temperature difference (^{0}C)	2.51	3.34	3.31	

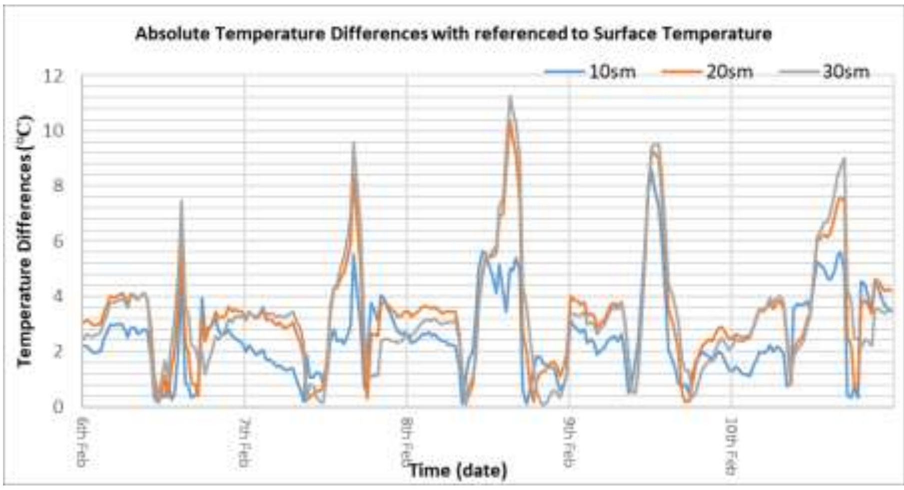

Figure 8: Temperature differences with Referenced to surface temperature

Based on the result, the deeper the depth of soil, the more constant the temperature it is. During the peak temperature, 30 cm gives the highest temperature difference. However, as comparison to average temperature difference throughout five days period, 20 cm shows a better reading. However, the data size collected is not enough to represent the average temperature profile in Malaysia. Besides, it was a sunny week during the process of collecting temperature; there has not been much rain.

B. TEG Measurement

The data collected based on five variations of test on the performance of TEG has been analyzed and plotted onto graph. Graph in Figure 9 showing the voltage generated by series connection of TEG TEP-12656 model. It can be clearly seen that as the number of TEG in series connections increases, the voltage generated increases linearly too. This shows the scaling properties of TEG. From the graph it shows in 10 ^{0}C it will produce output voltage around 1.4 V.

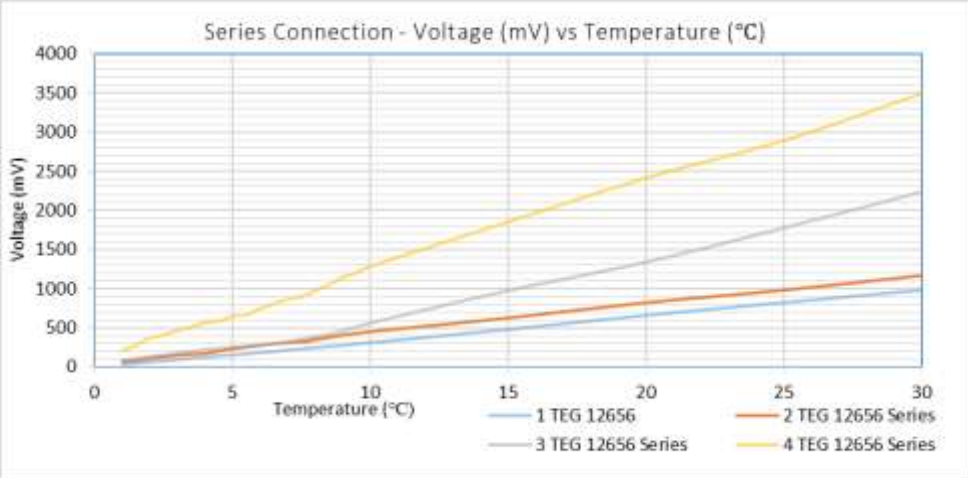

Figure 9: Series Connection Performances Evaluation TEP-12656

Referring to Figure 10, the result obtained from parallel connection of TEG TEP-12656 are showing the opposite result. This is due to as TEG are stacked up, the heat dissipation become less effective. The differences in temperature between two sides of a single TEG becomes lesser, leading to lower output.

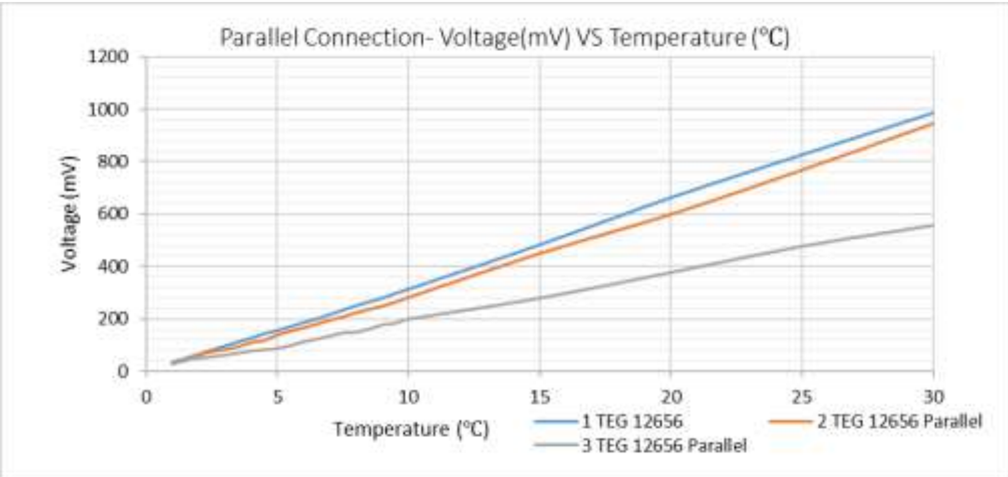

Figure 10: Parallel Connection Performances Evaluation TEP-12656

Another interesting finding is that the voltage generated by the TEG during heating up and cooling down processes are different by a sight margin. However, it still exhibits a linear relationship between temperature and voltage generated. From Figure 11, voltage generated during heating up is slightly more than during cooling down. One possible explanation is that the test is carried out using hotplate. During heating, heat can be supplied accordingly and quickly. However, during cooling, it requires time.

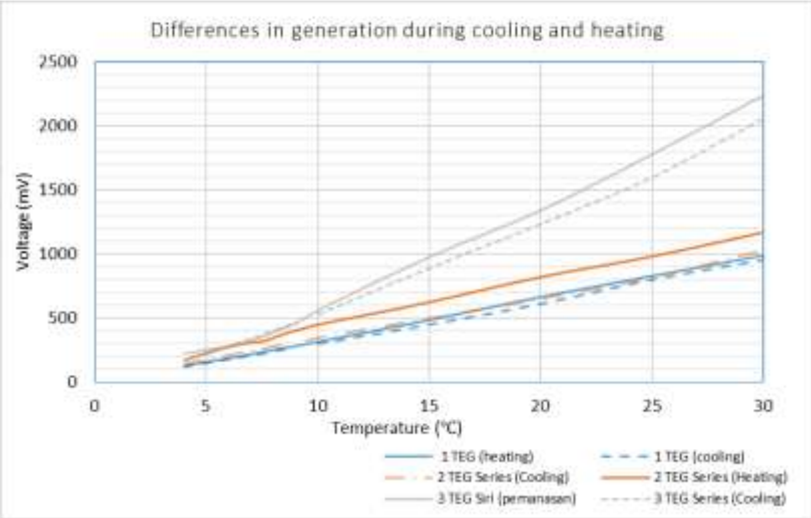

Figure 11: Performance Comparison between Heating and Cooling

The second type of TEG that has been tested is TEG model SP-1848, and the result is compared with TEP-12656 in Figure 12. It exhibits a similar characteristic as the previous model TEP-12656, series connection increases the total output whereas parallel connection reduces the total output. However, one observation that can be made is that differences in TEG size affects the output as well. The bigger the TEG, the greater exposure of its sides to respective heat and ambient air, hence, generates higher output. As a result, TEP-12656 with series connections will be used as it will generate higher output.

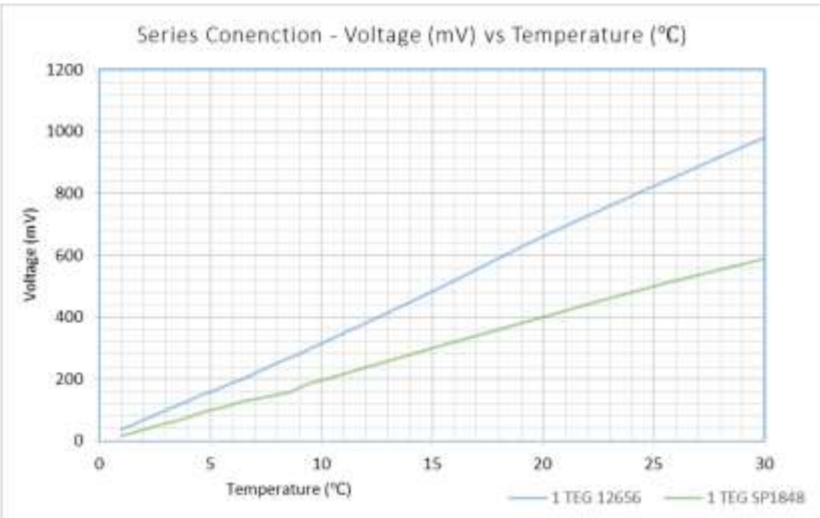

Figure 12: Comparison TEG 12656 and TEG SP1848

To improve the efficiency of the TEG output, demonstration circuit DC1587 has been used and its performances are tested in the lab. It needs at least 250 mV for it to operate. Two super capacitors rating 10 F 2.5 V each are connected in series and time taken to fully charge it are recorded in Figure 13. 1 V and 0.55 V are used because average temperature during daytime and nighttime is about 8 ^{0}C and 3.5 ^{0}C where TEG generates 1 V and 0.55 V respectively. This is based on the depth of 30 cm in the soil. From the result obtained, assuming the temperature stays constant during the daytime, it needs about 6.58 minutes on average to fully charge it to 5 V. As for night time, it needs 27.19 minutes to fully charge it.

One of the minor problems faced is that when using DC generator to charge the supercapacitor, the value fluctuates a bit within range of ±0.2 V, therefore it might affect the actual time needed to fully charge.

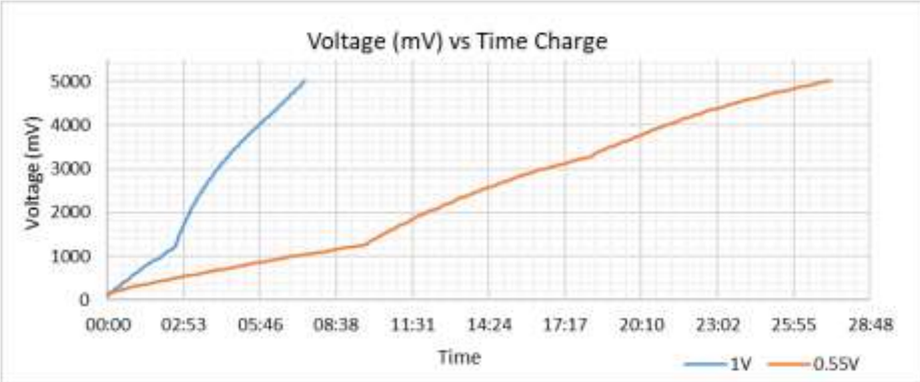

Figure 13: Time taken to fully charge Super capacitor

A prototype model has been built as in Figure 14. There are a few weaknesses in this model. First, the aluminum is prone to rustiness when exposed to air and water over a long period of time. Besides, the electronics loads that are connected to the TEG circuit must be waterproof [34].

Figure 14: Model Prototype

4. CONCLUSION

A thermal energy harvesting system based on temperature of ambient air and soil is built. The study area coverage is at the lake nearby Universiti Kebangsaan Malaysia (UKM), Bangi Malaysia. There are three different depths was study with a depth of 20cm will give maximum reading average temperature reading of 3.34 ℃. Then, characteristics of TEG has been studied based on temperature gradient data different between surface and soil depth. There are a combination of number TEG connection with series and parallel. From this depth, combination of four TEG TEP-12656 model can generate sufficient voltage 1.4 V at average temperature 10 ℃. Due to its low efficiency, DC booster circuit DC1587 has been used to increase its output level. From the experiments an optimum voltage output 3 V will be able to fully charges in 6.58 minutes. However, it is still not efficient enough to be a stand-alone power supply to power up Arduino Uno for a short period of time. The advantage of this system is that it can harvest energy regardless of day or night as there will be temperature difference when the temperature profile switched. There are a few suggestions to further improve this system. Firstly, load matching influences a lot on the output of TEG. Maximum efficiency of TEG can be attained when total resistance of load is equal to internal resistance of TEG. Second, since the energy harvesting of thermal using TEG is very low, probably it can be integrated with different type of energy harvesting especially solar energy harvesting. A lot of studies have been made in solar-thermal hybrid energy harvesting. Lastly, the wiring and components should be waterproofed.

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