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Study on Performance of Thermoelectric Generator in Living Room Usage

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ABSTRACT

The rapid development of the present era gives us awareness of harvesting wasted energy using an alternative method besides choosing burning fuels as a primary energy resource. The effort in developing a renewable harvester method has resulted from most of the technologies that are able to be sustained compared to unrenewable resources. The thermoelectric generator (TEG) is one of the technologies that converts heat energy into electrical energy and are continuously studied to ensure our future generation can benefit from it. This device has many advantages compared to the other available energy harvester, which does not need any mechanical component to operate with a small and compact size. With the increasing energy consumption in buildings and houses, finding a way to capture heat energy located in the place was considered. In this study, an analytical procedure was performed by using simulation modelling of MATLAB/Simulink software with the derivation of the equation on TE to find the most feasible way to harvest this heat energy in the living room area by first selecting the TE modules that is available in the market. The TE module showed that the average generation power and the average voltage were 0.03 W and 0.35 V, respectively. It was shown that 16 modules could provide enough power for the internet of things (IoT) devices like those used in sensors and controllers. To conclude, the desirable option to install a TEG block is at the ceiling bottom surface as the ceiling receives more heat than the wall for the tropical climate in Malaysia.

1. Introduction

In a modern global age, harvesting wasted energy is a focus point for researchers to develop methods with climate-related issues. In the past decade, fossil fuels have been essential ingredients to fulfilling our daily needs by producing electricity. Commonly, fossil fuels are used to generate energy through the burning process. Apart from non-renewable resource problems, there is a negative impact that brings out the origin of producing greenhouse gases. This burning process has caused a more significant issue in our environment, which leads to global warming. For this reason, harvesting wasted energy can be an alternative method with most technologies developed to have a sustainability characteristic to capture the energy, thus bringing a better solution to the environment [13]. The wasted energy can be appeared in many forms (such as light, vibration and kinetic energy). Besides, heat energy can also be classified into wasted energy. Most processes that create energy will encounter heat loss making nearly 60 % of energy have been released from the process and get

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wasted to the environment, also called waste heat [12]. Especially in industries that generate waste heat throughout the industrial process which is not put in practical use and is disposed or discharged into the environment [10]. Waste heat sources mainly include the transfer of heat loss from industrial products, home appliance equipment and through natural processes by conduction, convection and radiation. Therefore, harvesting wasted heat is a crucial alternative to reducing greenhouse gas emissions and reducing the energy demand of using fossil fuel as the primary source.

In order to capture this energy a device which consists of a solid-state device called thermoelectric (TE) generators (TEG) was introduced. The foundation of this device was discovered around the 19th century where the Seebeck effect was established. TE used to capture this heat energy and transform into electricity when there is a form of temperature difference [12]. Furthermore, the TEG device contains a TE material that has two different compounds which are connected in parallel form and the circuit connected in series makes the electron produced from the temperature gradient want to pass through two different sides that consists of hot and cold sides to produce electricity. Thus, the advantage is that they are very simple without moving parts, hence require low maintenance and can be used as heat sources. However, there was a downside of this device which the efficiency produced was very low [12]. Thus, many researchers nowadays are developing new methods in order to improve the potentiality of this device capable of assisting to reduce energy consumption for the future user.

The increment on energy consumption may be a worldwide issue, where future buildings are moving towards passive houses that require essentially less energy and numerous researchers attempt their best to discover a method to guarantee continuous supply of energy source. Hence, if there is a method that can produce electrical energy effortlessly at a cheaper cost, it will be one thing that everyone desires to make it happen into reality. A passive house, with a successful plan of utilizing solar radiation, superior cover and better air tightness by enhanced building envelope can decrease energy consumption more than 50 % compared to existing buildings [7]. For better insulation, it can be determined within the heat flux from the outdoor environment that was rejected from the exterior wall surface, the exterior surface temperature of the wall will grow naturally; thus, there will be a temperature gradient between the exterior and interior surface wall [4].

Although improving the insulation and air tightness were continued to develop, the essential reason of the building envelope is to secure the resident from cruel outdoor climate. The other way to optimize the load reduction effect is by harvesting the temperature difference which has continuously existed in current buildings, also translated as unused or waste heat [13]. This may result in a great solution to supply power sources for small devices in houses or buildings. This is where the research about TE generators comes in, when there is wasted heat present such in the building, it can be collected and transformed into electric power. From the previous studies, the sum of heating and cooling load reduction depends on the climate of the locale where the demonstrated building is located [4]. This research focuses on the living room space of the terrace house, which has a tropical climate.

2. Literature Review

With time, technologies are rapidly developed along with fast information at our fingertips. Along with people mostly nowadays live in urban residential areas, they are more attracted to smart building concept. This is where development of Internet of Things (IoT) are getting focus point by researchers. IoT is made up of all connected sensors and data that are been stored [6]. As buildings contributes 40 % of global power consumption, a control system can regulate, track and enhance buildings power consumption which these system do not intrude data for uses and on energy use [6].

Figure 1 shows basic uses of IoT in smart building concept such as smart home security, CCTV, sensors and connected appliances [2,3,6]. To be applied with renewable energy as a power source, commonly not more than 5 V of electric voltage with a required minimum power usage in each system are needed. IoT devices consume 12–16 mW, according to the research provided by Ferentinos *et al.*, [8].

Fig. 1. Application of IoT (sensors) in buildings [6]

2.1 Methods of Harvesting Energy

Renewable power harvesters may be used to effectively control network devices or fuel the energy storage devices such as batteries to minimize the use of wire and constantly charging these devices without any need of replacing it [1]. As the use of IoT devices has grown in a number of fields and the interest to improve efficiency to minimise energy usage, renewable energy production is considered a source of energy [2]. There are many current researches about these harvesting technologies. IoT devices are driven by environmental sources of energy including solar radiation, mechanical vibration, flow of liquid, electromagnetic wave and sound systems [3]. Table 1 describe the list of available renewable power harvesters available and the power density, thus to highlight TE is used in high temperature gradient in applications such as in power plant industry, car exhaust and aerospace exploration [9].

Table 1
A list of available renewable power harvester technologies [2,3]

Renewable power harvester	Power density
Solar energy-outdoor	15 mW/cm³ (sunny day) ~ 0.15mW/cm³ (cloudy day)
Solar energy-indoor	10~100 μW/cm³
Vibration (piezoelectric) at 105Hz	330μW/cm³
Vibration (electrostatic) at 10Hz	0.021 μW/cm³
Vibration (electromagnetic) at 52Hz	184 μW/cm³
Fluid flow at 5 m/s	16.2 μW/cm³
Sound noise at 100 dB	960 mW/cm³
Magnetic field energy at 60 Hz	130 μW/cm³
TE at 5°C temperature different	40 μW/cm³

2.2 TE Generator (TEG)
2.2.1 Basis of TEG

TEG are energy conversion devices which can convert thermal energy to electricity without any need of moving parts like turbines. TEG works by exploiting a temperature gradient between two sides of the generator. When two dissimilar materials are heated on one end and simultaneously cooled the other end, this will make electrons want to flow from the hot end to the cooler end. The phenomenon where a temperature difference can create a voltage is known as Seebeck effect [11]. The dissimilar semiconductor material consisting of thermopiles was designed for traditional TEG shows in Figure 2. Every thermopile consists of several thermocouples which have many N-type and P-type blocks connected in series and squeeze between a thermally conductive hot plate and cold plate. Since the semiconductor material has a positive and negative charge, the arrangement will allow electrons to flow from through the plate making thermally induced electric current to power a circuit [9]. But there is a downside when TEG produces power, where the efficiency will lose during the process. Thus, the advantages of TEG include longer lifetime compared to other power systems, no pollution created during operation and most importantly has no operational expenses.

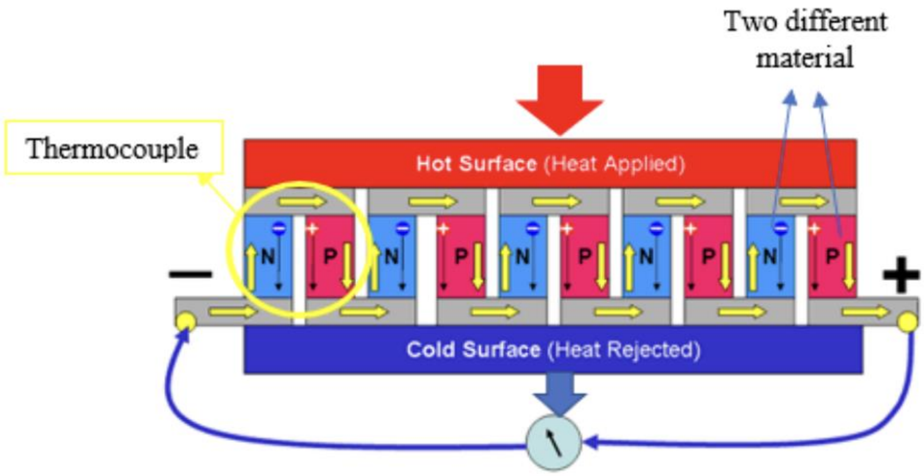

Fig. 2. Traditional TEG consists of N-type and P-type material [9]

Usually, to maximise the output power of the TEG, a larger number of TE elements are connected electrically in series and thermally in parallel [14]. In order to form the basis of the TE device, standard TEG modules usually use tellurium (Te), bismuth (Bi), antimony (Sb) or selenium (Se) [5,14]. Selecting different types of material will produce different output power depending on the application that is needed. Since the TEG output power is not strictly proportional to the difference in temperature [5] thus, it is important to consider selecting material with a difference range of temperature suitable for the application. The most widely used of TE material are bismuth telluride (Bi2Te3) and antimony telluride (Sb2Te3) due to being highly effective at room temperature [14].

2.2.2 TEG implementation in building condition

TEG would perform successfully at high temperature difference in the context of energy harvesting, which is capable for industrial application. Besides that, low temperature difference applications are common inside the building environment. The usual conditions of temperature gradient in a building environment are heat produced from IoT equipment such as smart lamp, sensors, smart tv and etc as shown in Figure 1. Other than that, solar radiation produced by the sun will produce sufficient heat in the exterior and interior wall producing temperature gradient [4]. A study from Inayat *et al*. [19] showed the development and installation in nano-scale embedded TEG for electricity generation of a proof of concept in exterior window glass. Throughout this study, approximately 32 W/m² of power generated of the proposed glass had the temperature gradient in range of 25°C. This experiment could be applied in tropical weather in Malaysia but may produce slightly lower power generation.

Another study by Byon and Jeong [4] studied designing an energy harvesting block consisting of TEG attached to phase change material. The phase change material then connected to the TEG design's cold side. The phase changing material will act as a heat sink for TEG, producing a temperature difference across the process while the wall produces heat from solar radiation process. The experiment was conducted in South Korea, which has four different weather conditions consisting of summer, autumn, spring and winter compared to Malaysia's tropical region. This study found that the average power output for single TE module (TEM) is 0.03 W and annual power was 2.1 kWh/m².

Omer *et al*., [13] produced a Smart TE Waste Heat Generator which defines power and cost parameters installed in the power plant industry as in higher temperature applications that can be found in buildings e.g. the power plant industry. By harvesting the hot pipe water produced by the power plant industry, a natural temperature gradient can be obtained by using hot and cold pipes that can produce more than 100°C temperature gradient. Thus, the power output found in this study was 7.2 W for the power plant application. In more common applications such as residential houses, a water heating system can be used in harvesting heat. The study from Al Musleh *et al*., [2] was done using the method of Maximum Power Point Tracking (MPPT) as the experimental process. The result produced 18 mW of load power at 10°C temperature difference. From this literature review, it showed that many applications in the building environment could be made in the study. But to increase the TEG efficiency to supply electricity to more significant devices, continuous research needs to be done for the TEG to operate in their desired condition.

3. Methodology

This research went through a process which selecting TEM and collecting the datasheet parameter from manufacture consists of temperature differences, ΔT across two surface temperature between hot and cold side of TEG, match load current, I_m and match load voltage, V_m. This output parameter usually provided by the TEM manufacture, thus from the equation of thermal and electrical formula can be derived and develop through MATLAB/Simulink simulation, to prove either the parameter values obtained similarly with the datasheet from manufacture. By comparing this TEM, the next step can be done by inserting temperature values on the living room condition using MATLAB/Simulink modelling. Hence, we can analyse the TEG performance of the output power to operate with temperature different conditions and predict the possible quantity of TEG used in buildings or houses targeted in the living room area.

3.1 TE Module Selection

In general, there are plenty of TEM available on the present market. TEM have various sizes and different output values depending on the application corresponding with the temperature that TEG wants to operate. In this research, the TEM used was TEG1-24111-6.0 manufactured by TECTEG MFR with the dimension of 56 mm x 56 mm showed in Figure 3. The specification of the TEM containing 126 of thermocouples and different compounds used hybrid of bismuth telluride (BiTe) and lead telluride (PbTe) as their semiconductor material which this TEM was reliable for electricity generation purpose. To define their products, TEG manufactures have provided the following parameters of matched load output voltage (V_m), matched load output current (I_m), matched load output power (W_m), hot-side temperature (T_H), coldside temperature (T_C) and maximum efficiency (η_{max}) that are listed in Table 2.

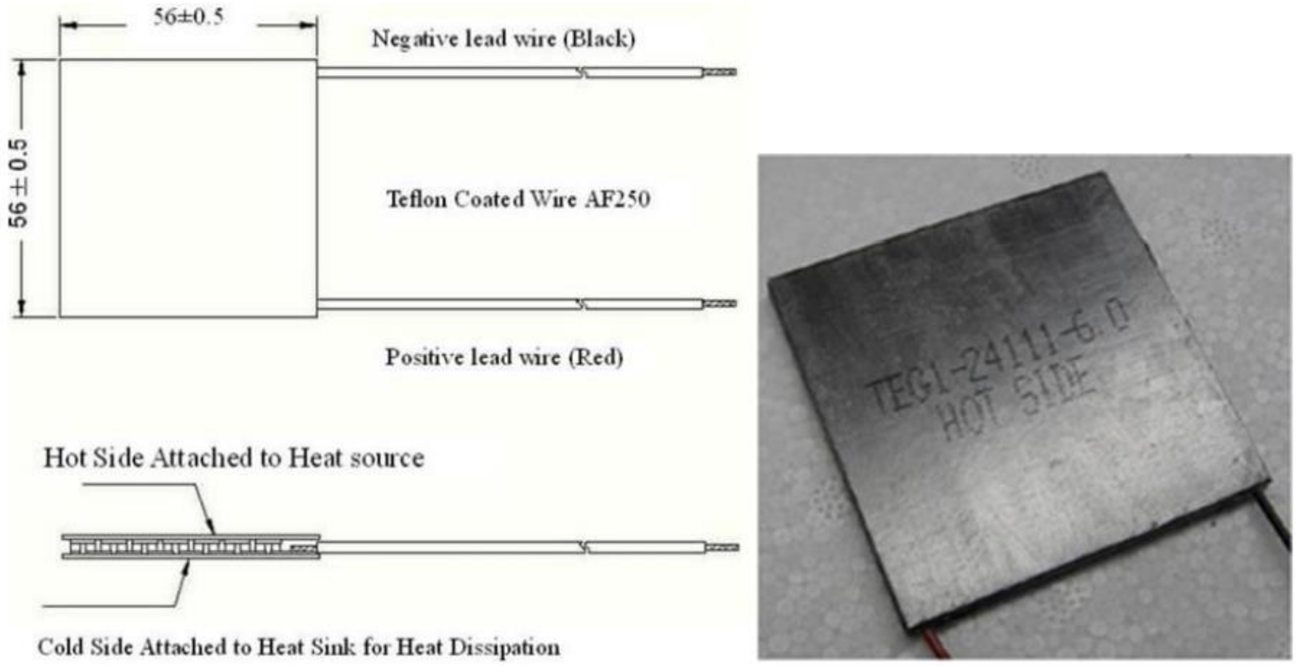

Fig. 3. Dimension of TEM TEG1-24111-6.0

Table 2
Specification of Seebeck module for TEG1-24111-6.0

Seebeck module	TEG1-24111-6.0
V_m	8.8 V
I_m	2.0 A
W_m	17.6 W
T_H	300°C
T_C	30°C
η_{max}	5.8 %

3.2 Calculation of TEM Parameter

TEM devices commonly are grouped into TEG and TE coolers (TEC). TEG functions to convert thermal energy into electrical energy throughout the temperature difference and is called Seebeck effect, while TEC function in the opposite principle whereby converting electrical energy into temperature difference and is called the Peltier effect.

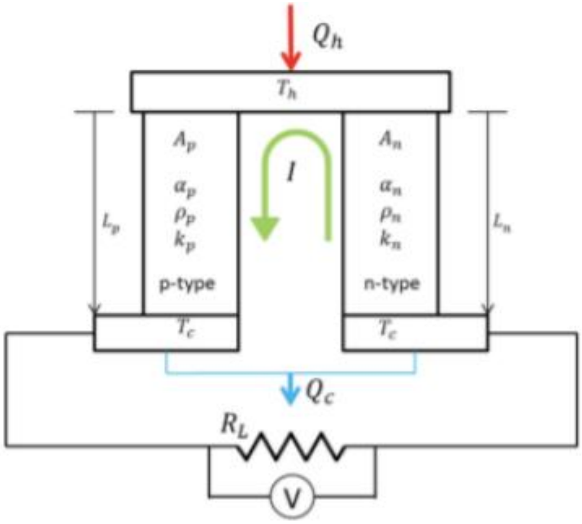

Fig. 4. TEG connected to a load

If a TEM is operating as a generator, a temperature difference must exist between the surfaces. This process (Figure 5) allows for energy transfer between two surfaces when load that is connected to the end of a TEM generates power once current passes through the load.

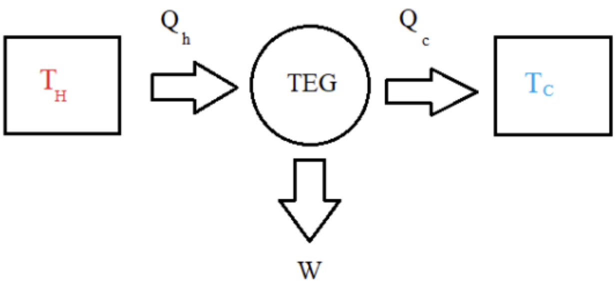

Fig. 5. Energy flow for a TEG

When there are two different surfaces which are the thermal power, it will be absorbed from the cold surface, Q_h (W) and thermal power removed from the hot surface, Q_c (W). This equation can be obtained as,

$$Q_h = SIT_H - 0.5I^2R + K(T_H - T_C) \tag{1}$$

$$Q_c = SIT_C + 0.5I^2R - K(T_H - T_C) \tag{2}$$

$$W = SI(T_H - T_C) - I^2R_L \tag{3}$$

$$V = S(T_H - T_C) - IR_L \tag{4}$$

$$I = \frac{S(T_H - T_C)}{R_L - r} \tag{5}$$

where S is the Seebeck coefficient for TEM (V/K), I is the current output of the module (A), R_L is the total resistance (Ohms), r is the internal resistance in the TEM circuit (Ohms), TC is the temperature at cold surface (K), T_H is the temperature at hot surface (K), and K is the thermal heat transfer coefficient of the module (W/K). Furthermore, electromotive force (EMF) generated by the existing Seebeck voltage, E (V), where ΔT is the temperature difference between two surfaces ($T_H - T_C$) can be defined as,

$$E = S\Delta T \tag{6}$$

If the internal resistance, r (Ohms) need to be observed, because an electron passes through the cell in TEM converting some of electrical into heat energy. Then, the relation of internal resistance can be defined as,

$$r = \frac{(E - V_m)}{I} \tag{7}$$

But in this case, to obtain the maximum power transfer where a condition of internal resistance must be equal to total resistance where the initial equation is expressed as $R = mr$, where m is the resistance ratio between the load and internal resistance. Thus, the resistance ratio is $m = 1$. Therefore, the matched load current output, I_m can be defined as,

$$I_m = \frac{S\Delta T}{2R} \tag{8}$$

Then, the matched load power value, W_m and the maximum efficiency, η_{max} can be defined as,

$$W_m = \frac{S^2(\Delta T)^2}{4R} \tag{9}$$

$$\eta_{max} = \left(1 - \frac{T_C}{T_H}\right) \frac{\sqrt{1 + ZT_{avg}} - 1}{\sqrt{1 + ZT_{avg}} - \frac{T_C}{T_H}} \tag{10}$$

In order to get a better performance of TEM, a condition need to be considered where Seebeck coefficient S must be high combining with the low electrical resistance R and thermal conductivity K. Thus, from the maximum thermal efficiency can be rearranged to find the Figure of Merit (FOM) defined as,

$$Z = \frac{1}{T_{avg}} \left[\left(\frac{1 + \frac{\eta_{max}}{\eta_c} \frac{T_C}{T_H}}{1 - \frac{\eta_{max}}{\eta_c}} \right)^2 - 1 \right] \tag{11}$$

where the average temperature, T_{avg} = 1 2 (T_H +) and the Carnot efficiency, η_C = (1 − T_C T_H). To set the preferable highly maximum output, with matched load power has an equal value between load resistance and internal resistance. The maximum value of current in short-circuit when the voltage, V = 0, then the maximum short-circuits current (I_{SC}) can be obtained. Other than that, to find the maximum voltage value at open-circuit, V_{OC}. The current flow through the circuit needs to be considered as I = 0. These values then can be collected to find an accurate data and determine the usable electric power that been generated.

$$I_{SC} = \frac{S\Delta T}{R} \tag{12}$$

$$V_{OC} = S(T_H - T_C) \tag{13}$$

Usually, TEM manufacture has provide parameters of the datasheet consisting of temperature hot side, T_H and temperature cold side, T_C , the matched load power, W_m , voltage, V_m output values and η_{max} , the maximum thermal efficiency. The use of experimental data given for TEG modules can be found for finding effective material parameter. The effective parameters of modules are specified as,

$$K = \frac{S^2}{RZ} \tag{14}$$

$$R = \frac{V_m^2}{W_m} \tag{15}$$

$$S = \frac{2V_m}{\Delta T} \tag{16}$$

The values achieved using an ideal TE equation usually differ from experimentally identified data. This equation does not include the temperature changes within semiconductor material. Losses from Thomson effect and thermal resistance are also not considered. Besides, an alternative method of simulation for the above formulae was developed by using MATLAB/Simulink for theoretical examination in TEG system.

3.3 MATLAB and Simulink Method

The TEG system aims to achieve maximum performance characteristics. The thermal and electrical calculation of TEG system characteristics has been described in the previous section where it was confirmed that the output changes depending on the geometric properties, semiconductors properties and temperature. In this research, a model was built using MATLAB/Simulink software to construct the most suitable TEG modules framework according to experimental parameters. The base parameters include the resistivity of semiconductor, Seebeck coefficient and thermal conductivity in a single TEM are shown in Figure 6 of the derivation equation for each parameter using command on the MATLAB libraries. Thus, this study's parameter values can be obtained with this simulation method. To get as close to the actual application, the design of the system block in Simulink libraries using these parameters is critical.

```
%% SIMULINK MODEL
%Th %Hot side temperature (Celsius)
Th = 300;
% Hot Side temperature (Kelvin)
Th = Th + 273.15;

%Tc %Cold Side Temperature (Celsius)
Tc = 30;
%Cold Side Temperature (Kelvin)
Tc = Tc + 273.15;

%delta_T %Temperature difference between the hot side and cold sid
delta_T = Th - Tc;

%Vm %matched voltage
Vm = 8.8;

%Wm %Matched Power
Wm = 17.6;

%R %internal Resistance
%RL %Load Resistance (matched to internal resistance where R=RL)
RL = (Vm^2)/Wm;
R = RL;

%Seebeck Coefficient
S = 2*Vm/delta_T;
% = (2*Vm)/u(1)

%Optimal Load Resistance
mewopt = (delta_T+max_eff*Tc)/(delta_T-max_eff*Th);
%       =  (u(1)+max_eff*(u(3)))/(u(1)-0.05847*(u(2)))

%Figure of Merit
Z = (mewopt^2-1)/(1/(Th+Tc));
% = (u(1)^2-1)/(0.5*(u(2)+u(3)))

%Thermal Conductivity
K = (S*delta_T)/R*Z;
% = (u(1)^2)/(u(2)*u(3))

%if RL = mR where m is the ratio between the internal and load
m = 1;

%I %Electric current
Ie = (S*delta_T)/((1+m)*R);
%  = (u(1)*u(3))/((1+m)*R)

%Im %Matched Load Current
Im = (S*delta_T)/(2*R);
%  = (u(1)*u(3))/(2*R)


%Isc %Short Circuit Current @V1 = 0     %Isc = 2*Im=(2*Wm)/Vm;
Isc = (2*Wm)/Vm;
Isc_1 = 2*Im;

%V %Output Voltage
V = -R*(Ie-Isc);
% = -u(2)*(u(1)-(2*Wm)/Vm)
```

Fig. 6. MATLAB coding for TEM analytical base parameter

The output parameter of TEG depends on the parameter properties is listed in Table 3. Thus, from the parameter properties, the output power on simulation data using MATLAB/Simulink modelling method for TEM can be compared with a datasheet provided by the manufacturer showed in Figure 7 whereby simulation data obtained on the upper graph and lower graph is the datasheet from the manufacturer. The similarity values achieved from this primary result proved that the method equation can be used for the targeted application with the output value of power, voltage and current are 17.59 W, 17.60 V and 3.99 A respectively.

Table 3
Semiconductor parameter of TEG1-24111-6.0

Parameters	Values
Area	56 mm x 56 mm
Temperature hot side , T_H	300 °C
Temperature cold side, T_C	30 °C
Seebeck coefficient, S	0.065 V/K
Thermal conductivity, K	0.86 W/K
FOM, Z	0.0011 $1/K^{-1}$

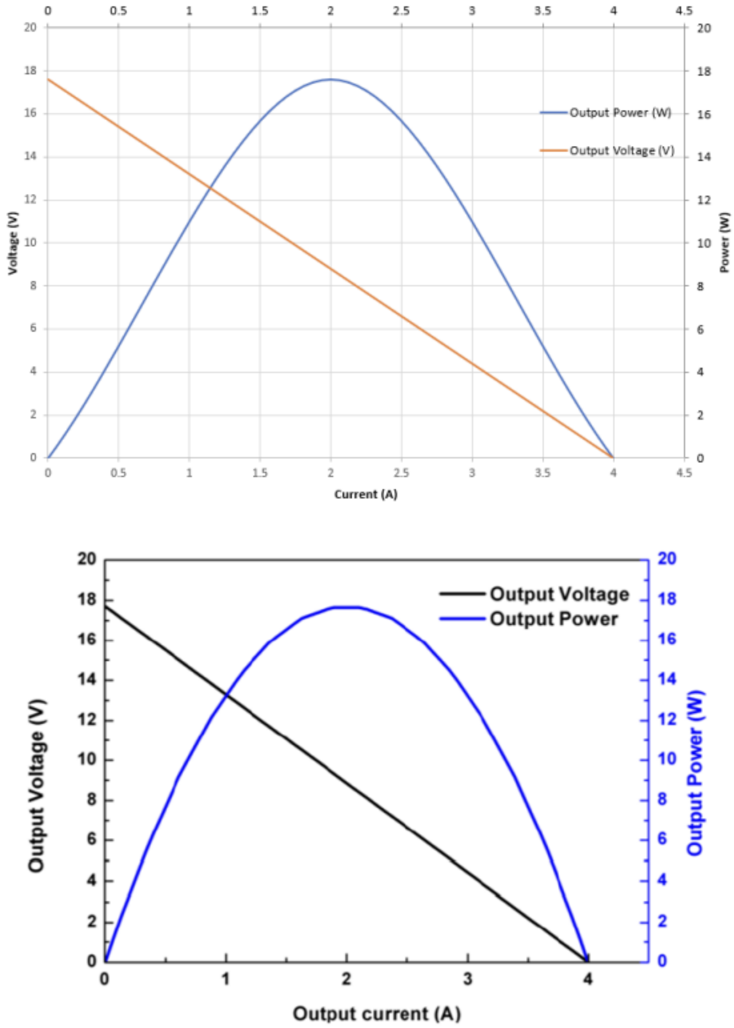

Fig. 7. I-V and I-W output characteristics of simulation data compare with manufacture data

Figure 8 (a) shows the main block of masked implementation of Seebeck Module or TEG Module where the temperature at hot and cold side, T_H, T_C value of the module is entered to determine the effective parameters in the TEG system. The purposed model of this masked icon was to make it easier to use and understand by importing a TEG icon image file. Thus, the value of current and voltage output can be evaluated using the module's current output. Figure 8 (b) shows the detail of the TEG module's subsystem implementation. The equation for each parameter expressed by the previous section is entered in the ‘function’ block as shown above. A numerical calculation is run to see whether the TEG Module is successful or not. The module's result was determined as a function of temperature difference, current and voltage values listed in Table 4.

Table 4
Comparison between simulation and datasheet

TEG1-24111-6.0 Simulation Data	TEG1-24111-6.0 Datasheet
R= 4.4 Ω	R_L = 4.4 Ω
I = 3.99 A	I = 4.0 A
V= 17. 60 V	V= 17.7 V
W= 17.59 W	W= 17.6 W
η_{max}= 5.847%	η_{max}= 5.8 %

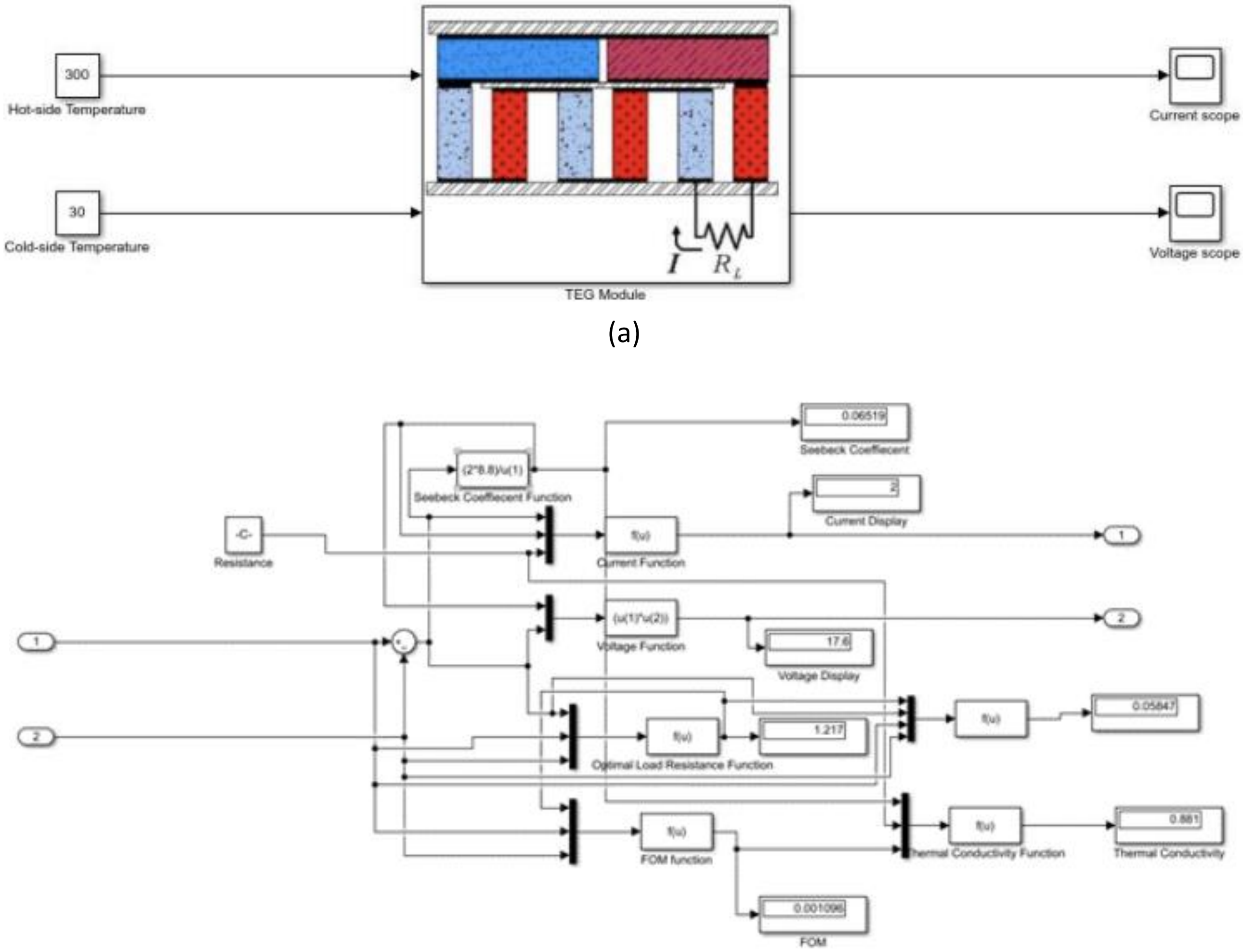

Fig. 8. TEG module block diagram (a) Masked implementation and (b) Subsystem implementation

3.4 Location and Climate Data Collection
3.4.1 Outdoor and indoor temperature

The purpose of harvesting heat from the building was not to substitute for current renewable energy system with high efficiency, such as photovoltaic. But with the capability of TEG, it is able to harvest energy from temperatures below 100°C [4]. By using TEG, it is able to utilize unused low temperature exists in surface temperature on the building. Tuck *et al.*, [16] conducted a field measurement in a two-storey corner terrace house model located in Taman Melati, Kuala Lumpur, Malaysia and held from 15 February 2018 until 11 March 2018. Located in an equatorial area, Kuala Lumpur has a tropical rainforest climate throughout the year. Figure 9 shows the mean monthly outdoor air temperature obtained from a weather station located in Universiti Teknologi Malaysia, about 5 km away from the house under survey from January 2018 to December 2018. This data was supported by Tenaga *et al.*, [15] annual report of Malaysian Meteorological Department which shows similar with the mean outdoor temperature of 28°C. For this research, the cold side temperature was fixed at 26°C as the lowest temperature.

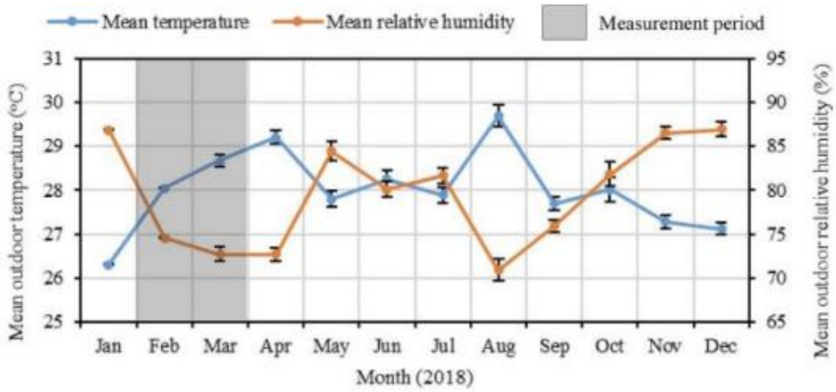

Fig. 9. Annual mean outdoor temperature and mean humidity obtained from weather station in Universiti Teknologi Malaysia [16]

According to Tuck *et al.*, [16]. Indoor temperature of house models studied ranged between 27-37°C. This is also supported by other researchers including [18] for the average apartments in Malaysia, where the mean indoor temperature ranged between 22-31°C. In the meantime, for average urban houses in Malaysia studied by Zakaria [17] ranged between 29-30°C. These results were similar and consistent, considered to be valid for this study.

3.4.2 Specification of house model

The living room area of the terrace house model is highlighted through this method. Figure 10 shows the illustration of the floor plan of the investigated house with the side plan of where the house located. Table 5 shows the specification description of the two-storey corner terrace house specific to the living room area. There were two most preferable location for TEG to be placed on the wall or ceiling surface where the heat source produces the most. The TEG will generate more electricity if they receive more heat from the sun [4].

Fig. 10. The illustration of model two-storey terrace house (a) Ground floor plan and (b) Side view [16]

Table 5
Specification of the house model [16]

Description	Value
Site location	Kuala Lumpur, Malaysia
Building type	Two-storey corner terrace house
Floor are (m^2) – living room	15.2
U-values (W/m^2K)- living room	Window – 5.7
	Ceiling – 1.40
	Roof – 0.70
	Floor – 0.20
	Wall – 2.15
Ceiling	4-mm thick cement board
Wall material	114-mm thick brick wall with 18-mm thick cement plaster on both sides

3.4.3 Surface wall temperature

The result obtained significant values of surface temperature on the wall of the two-storey corner terrace house. Figure 11 shows the different temperature between the indoor temperature of the model house with the surface temperature of exterior and interior wall through 14 days of experiment. The data collected with 1 hour delay between maximum temperature on exterior and interior wall surface. The maximum temperature was collected at 1.30 - 2.30 p.m where the peak value exterior temperature wall surface was 39°C, while the interior surface temperature of the wall was 35°C [16].

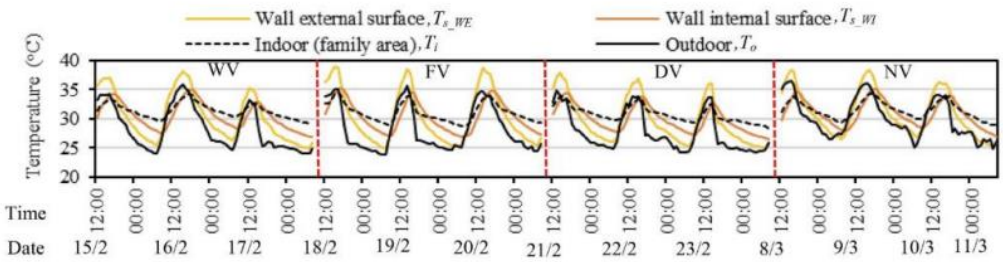

Fig. 11. The difference between surface temperature of exterior and interior wall with indoor temperature [16]

3.4.4 Surface ceiling temperature

The Figure 12 shows the different temperatures between the model house's roof surface and ceiling surface through 14 days of the experiment. The top surface of the ceiling was heated by thermal radiation from the attic air at the bottom section of the roof, with a mean maximum surface temperature of 42°C, 3°C lower than the air temperature in the attic. The temperature was dropped to 40°C once the heat reached the bottom surface of the ceiling, followed by an interior air temperature of roughly 34°C at 1.5 m above the family area's floor level [16]. The bottom ceiling surface was chosen in this research to simulate the best condition of the TEG system to be cold at the cold side of the TEM.

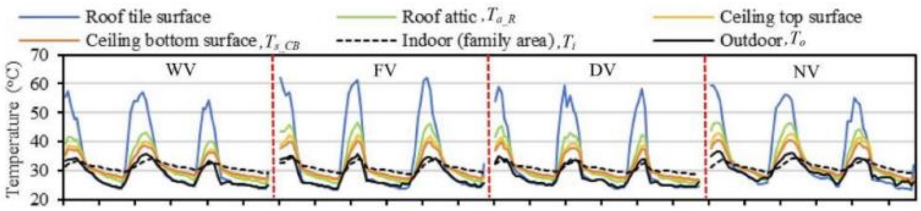

Fig. 12. The difference between surface temperature of exterior and interior wall with indoor temperature [16]

4. Results and Discussion

This section covers the predicted outcome values of TEM in two different conditions and suitable to be placed in the living room. This include conditions at external wall and ceiling bottom surfaces. The Simulink software was used to model a subsystem block for the TEG model in the targeted area. This study had collected climate data from previous researches. The measurement was conducted in a two-storey corner terrace house located in Taman Melati, Kuala Lumpur, for 14 days from 15 February until 11 March 2018. The two different condition temperatures were taken and applied on the hot-side temperature in this experiment which was at the external wall and ceiling bottom surfaces showed in Table 6. The cold-side temperature was fixed at 26°C.

Table 6
Temperature of two different condition

Date	External wall surface Temperature °C	Ceiling bottom surface Temperature °C
15 Feb	37	38
16 Feb	38	39
17 Feb	35	36
18 Feb	39	40
19 Feb	38	40
20 Feb	38	40
21 Feb	37	40
22 Feb	36	40
23 Feb	35.5	38
24 Feb	38	38
8 Mar	38	40
9 Mar	35.5	40
10 Mar	36	40
11 Mar	37	39

4.1 Simulink Simulation Result

By using Simulink simulation, the data were recorded between the measurement temperature. Figures 13 and 14 shows the voltage and current output produce with respected to hot side temperature between 35-40°C. The graph for the output voltage shows gradually increase when temperature start at 36°C until it reaches 40°C. For the output current shows a constant value from 35°C until 37°C and gradually increased when it reaches 38°C.

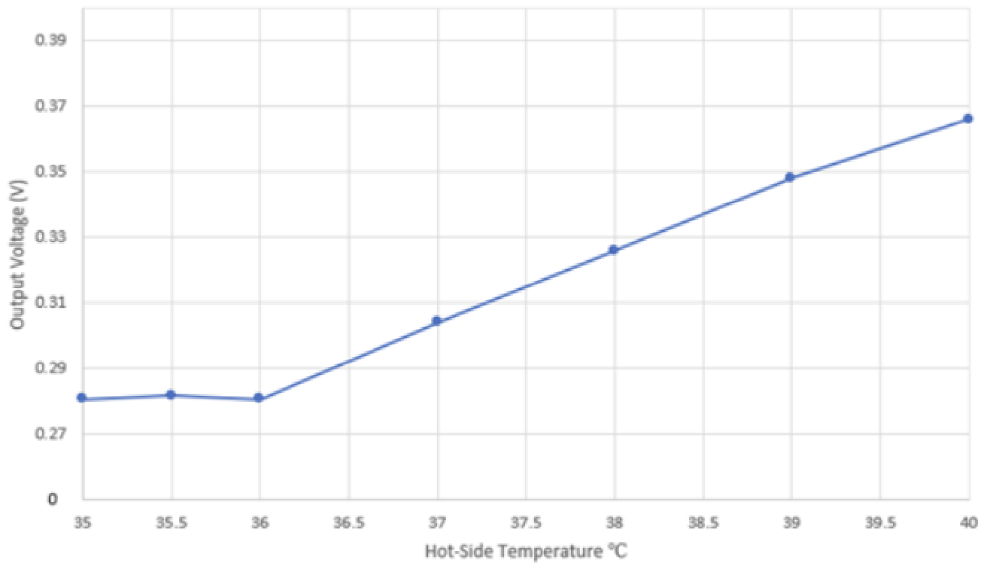

Fig. 13. Output voltage respected to hot side temperature

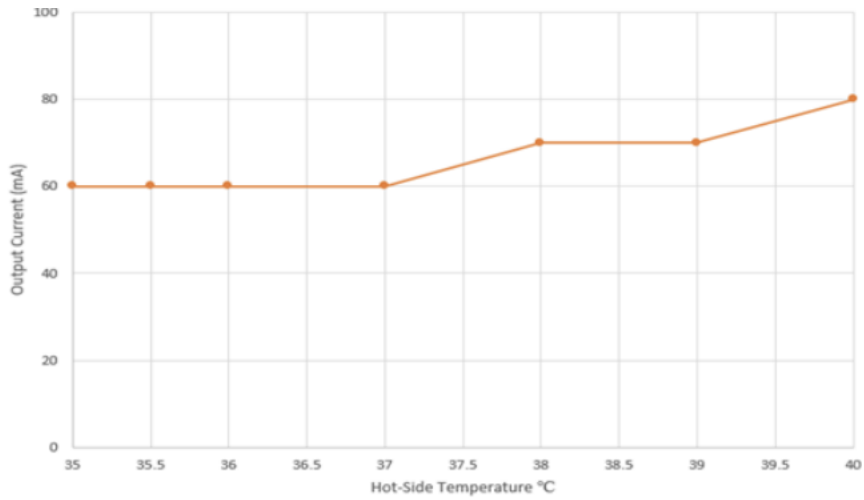

Fig. 14. Output current respected to hot side temperature

The electrical power and current were plotted against voltage using the simulation data to develop an I-V curve, as shown in Figures 15 and 16. The power generation selected at the highest temperature at 40°C shows that single TEM can generate power of 30 mW and the output of voltage and current at 0.37 V and 0.08 A respectively.

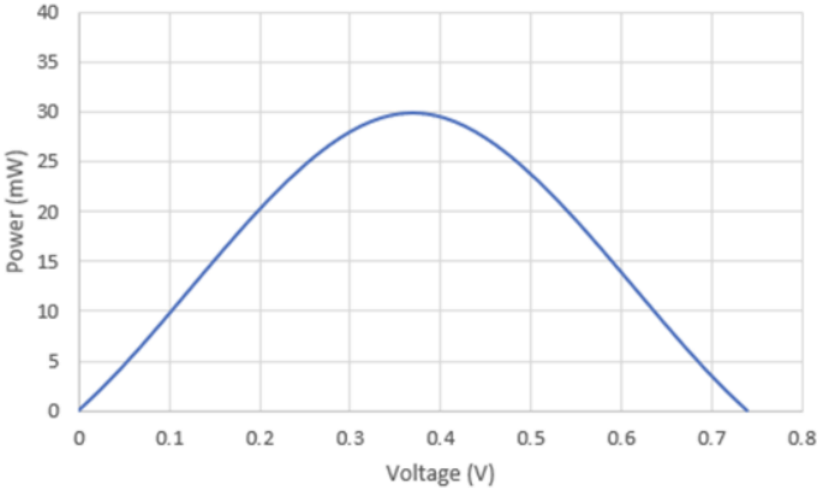

Fig. 15. Simulation result of output power respected to voltage at 40°C

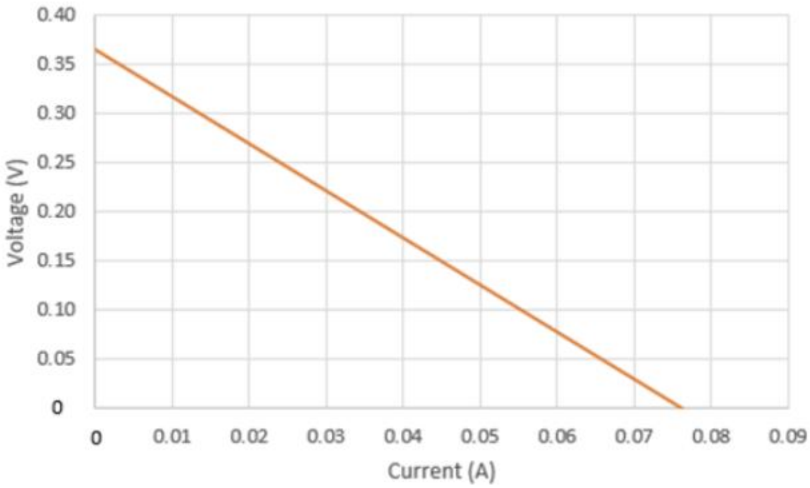

Fig. 16. Simulation result of output voltage respected to current at 40°C

4.2 Comparison between External Wall and Ceiling Bottom Surface

Based on Figure 17, the performance of the TEG with power output generate throughout 14 days at the mean value of 0.02 W and the standard deviation of 0.3 % was depicted. The highest power output produced was 0.025 W. Figure 18 shows the ceiling bottom surface with the mean value of 0.025 W and the standard deviation of 0.4 %. The highest output power produced was 0.03 W. From both results, we agreed that the experiment could be used due the standard deviation value was below 1 %. For the comparison between both conditions shown in Figure 19, the mean values at the ceiling bottom surface were slightly higher than the external wall surface, thus selecting ceiling as the place for the TEG system.

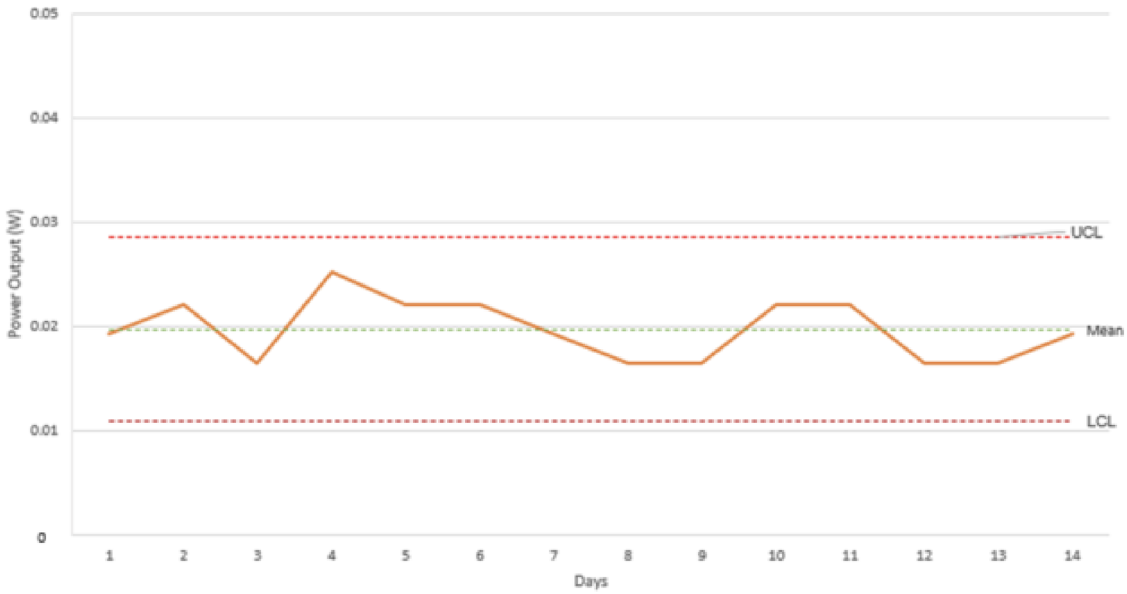

Fig. 17. Performance curve of TEM at external wall surface

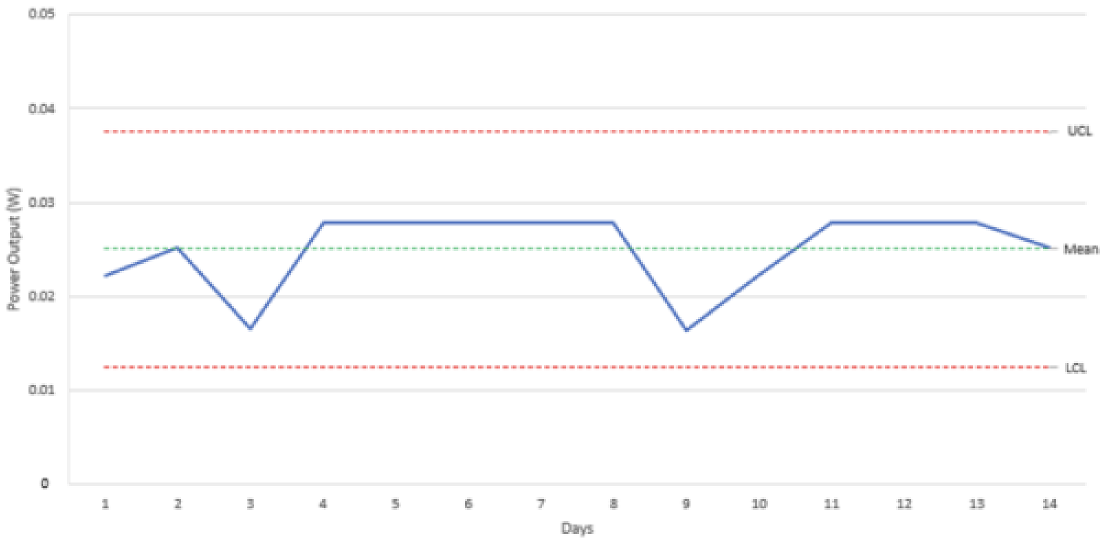

Fig. 18. Performance curve of TEM at ceiling bottom surface

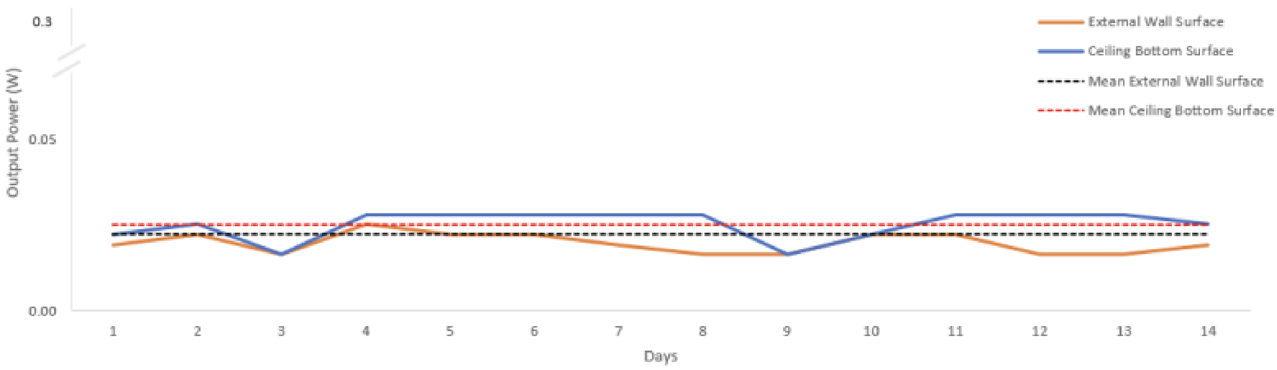

Fig. 19. Comparison performance between external wall and ceiling bottom surface

4.3 Prediction of TEG System

To illustrate the TEG system to operate in the living room area, SketchUp software was used in designing the system. Figure 20 shows the view of the TEG system to be placed in the living room area. The desirable placement of the TEG system should be mounted at the ceiling bottom surface as the previous result shows that the ceiling has higher output power produced. 16 modules of TEG were designed in this study as it was enough to power small devices like sensors or controllers which needed less than 5 V to operate.

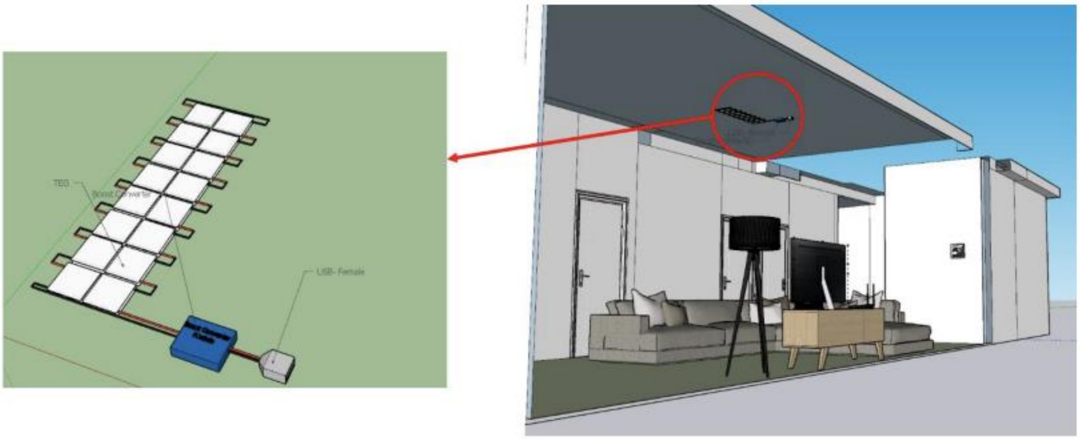

Fig. 20. A view of the TEG system to place in living room area

5. Conclusions

Heat energy harvesting is a potential method that is gaining popularity. This study created a simulation setup to evaluate TEG at a range of operating temperatures that are typical of applications in building for tropical climate. This study has been conducted analytically to model and determine TEG performance for application in living room area. The base-dependence equations have been simulated in a Simulink block, and a graph representation of the output can be constructed using multiple MATLAB command window codes. The primary result was supported with the datasheet given by the manufacturer, demonstrating that the modelling and values from manufacturing data verified the numerical simulation, thus it can be used for the selection of targated application. From the simulation result, the suggested TEG system's power generation regarding the research is that a single module could generate an average electric power of 0.03 W. The highest output voltage generation amounted to 0.37 V, and highest output current generation amounted to 0.08 A. The desirable option to install the TEG block is at ceiling bottom surface as the ceiling receives more heat than wall for tropical climate in Malaysia. The most significant factor to consider while installing the TEG block is whether the area is well-heated during the day and well-cooled by the environment at night [4].

In conclusion, the prediction quantity of TEG block in the system at 16 modules with the average generated power output values of 0.03 W and voltage of 0.35 V. For activation of modern digital and radio-frequency circuits, it requires voltages of 1–2 V, but high-performance analogue circuits require voltages of 2–3 V.

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