Optimization of Electrical Energy Harvesting from Focused Infrared light using Thermoelectric module with Uniform Heat Distribution

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***Abstract*— Thermoelectric (TE) module is a harvester which converts heat energy into electrical energy. Heat energy dissipation is everywhere from electronic appliances to mechanical engines and machines, and considered is a wasted energy. However, TE module can be used to recover the heat energy and converted into useful electrical energy. In this paper, infrared (IR) light is being used as the heat source mimicking the sunlight optimum spectrum of heat production and applied on TE module to generate electrical energy. In order to maximize the heat generation from IR light, a convex lens was used to focus the light beam onto the hot-side surface of TE module. The temperature of IR light and focused IR light was plotted in the graph and compared. This followed by three experiment set-ups to investigate the optimum arrangement of TE module which is TE module without heat distributor on its hot-side surface and TE module with heat distribution. The heat distributor can distribute uniformly the heat from the focused IR light on the hot-side surface of the metal and propagate to the TE module underneath. An electrical output power of 10μW was measured for TE module with a metal block as heat distributor compared to 2μW for TE module without proper heat distribution.**

***Index Terms*— Coefficient on performance (COP), Convex lens, Energy Harvesting, Seebeck Effect.**

I. INTRODUCTION

TE module is a harvester convert heat energy into electrical energy. Most of the heat dissipate from any system will be wasted, so TE module can be reuse by convert into electrical energy. Besides, heat dissipates from sunlight is not fully utilized by using solar panel as a harvester. However, sunlight spectrum also can be reused by using TE module.

Sunlight has a wide spectrum which includes UV, visible, and IR light. The solar irradiation on earth is 5% UV, 43% visible and 52% Infrared. In term of wavelength, ultraviolet is in between 0.2μ – 0.39μm, visible is in between 0.39 μ – 0.78μm, whereas infrared is in between 0.78μ - 100μm[1]. Most of the PV cell cannot produce electrical energy from UV spectrum, so it will be a waste. Therefore, this paper intent is to prove the IR light bulb can produce electrical energy by using TE module.

From the previous paper, many researchers suggested different method and place can generate electrical energy by using thermoelectric such as chimney from the plant[2], heat pipes [3], cookstove [4], and exhaust pipe[5]. B.K.Rajeh and B.Kiran [2] suggested generating electrical energy from chimney from industry plant. The hottest temperature can obtain from the chimney is about 150°C. The surface of the chimney was made from copper because copper has higher heat dissipation. The range of temperature applied on the hot surface of TE module is between 70°C until 150°C. Besides, the cold surface was maintained by using cold water. The open circuit voltage obtain from this paper is 0.0744V/°C and the maximum power is 3.42W when the temperature gradient is 85°C. T.Ishiyama and H.Yamada [3] proposed using heat pipes to generate the electrical energy The heat source is the hot water supply into heat pipes and the cold surface was attached to the heat sink. The temperature of the heat source is between 30°C until 75°C. The open circuit voltage generated from TE module is 0.00667v/°C and the power produced is 1mW when the temperature gradient is 18°C. M.Risha and at el [4] discovered cook stove is a potential heat source to generate the electrical energy. Thus, the TE module was attached to the surface of the chamber and the cold surface was attached to the aluminum heat sink. The open circuit voltage is 0.0416v/°C and the power generated is 0.5w when the temperature gradient is 50°C. Besides, A.J.S.Priscilla and at el [5] proposed to generate electrical energy from the exhaust pipe. There are 12 TE modules were used and connected electrically series. Exhaust pipe applied heat on the hot surface of TE module and the cold water maintains the temperature of the cold surface. The open circuit voltage produced in this paper is 0.15v/°C and the power generated is 36W when the temperature gradient is 120°C.

II. LITERATURE REVIEW

A. Thermoelectric Module

The TE harvester is based on the Seebeck effect to convert heat energy into electrical energy. The Seebeck effect is named by Thomas Seebeck in 1821. The Seebeck effect is generated voltage output based on the temperature gradient applied on two dissimilar metal or semiconductor. Usually, the two dissimilar metals will be used as thermocouple to measure the temperature based on the voltage output generated from a couple of the dissimilar metal. However, these dissimilar metals can change into semiconductor because semiconductor has higher Seebeck coefficients. Therefore, it can produce more voltage output compares to dissimilar metal [6,7].

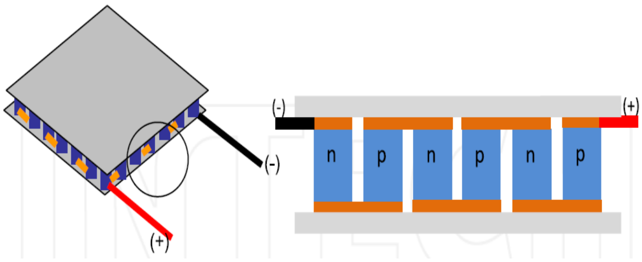

Figure1. Thermoelectric module [7].

Figure 1 shows the schematic diagram of TE module. TE module combines pairs of thermocouple, one pair of P-N junction consider as one thermocouple. The thermocouple connected electrically in series and thermally in parallel. Besides, ceramic plate is used to cover the top and bottom of the module. Since the ceramic plate good in conducting heat and resistive of electricity [7].

When one of the ceramic surfaces is applied heat and another ceramic surface is dissipated heat, the voltage will be generated by TE module. In addition, the Seebeck coefficient, α, is defined as the change in voltage per degree of temperature gradient [6,8,9]:

$$\alpha = \frac{dV}{dT} \text{ volts/K} \tag{1}$$

Seebeck coefficient also included in voltage V_s produces from a TE module while it is applied temperature gradient which is T_h as hot temperature and T_c as cold temperature [7,9]:

$$V_s = \alpha(T_h - T_c) \tag{2}$$

The power generated by TE module can be calculated using following formula [2,10]:

$$P_o = I_o{}^2 \times R_L \tag{3}$$

P_o is the power generated by the TE module, Io is the current generated and R_L is the load resistor that applied in the closed circuit.

Additionally, the efficiency of the TE module is also known as coefficient of performance, it can be calculated using equation [2,10]:

$$\eta = \frac{P_o}{Q_h} \tag{4}$$

Where,

P_o is the power output of the TE module, and

Q_h is the total heat input on TE module

Q_h can be calculated by using the formula as below [2,10]:

$$Q_h = (S_M \times T_h \times I_o) - (0.5 \times I_o{}^2 \times R_M) + (K_M \times \Delta T) \tag{5}$$

S_M is the Seebeck coefficient of the module, T_h is hot temperature applied on TE module, I_o is the output current, R_M and K_M are resistance and thermal conductivity of the module respectively. Lastly, ΔT is temperature gradient applied on TE module.

B. *Sunlight Spectrum*

The sunlight spectrum is including UV, visible light, and IR light spectrum. The solar irradiation, wavelength and photon energy of the spectrum are recorded in the table below:

Table I
Solar irradiation, Wavelength and Photon energy of spectrum sunlight [1]

Spectrum Sunlight	Solar Irradiation (%)	Wavelength (µm)
Ultraviolet	5	0.2 – 0.39
Violet	43	0.39 – 0.78
Blue		
Green		
Yellow		
Orange		
Red		
Infrared	52	0.78 - 100

Table I shows the solar irradiation, wavelength and photon energy of spectrum sunlight. IR light consists highest solar irradiation from the sunlight spectrum which is 52%. Therefore, IR light bulb is suitable is used to simulate sunlight spectrum in this paper.

III. EXPERIMENTAL SET-UP

The characterization in this paper will use heater as heat source for TE module, and this method has been tested by A.K.Ali Mohammed and et al [11] and A.M.Yusop and et al [12].TE module used in this paper is from Laird UltraTEC series, the diameter of the TE module is 53mm width and 53mm length. First of all, the TE module was characterized by using the heater to measure the voltage output of it. Because the Seebeck coefficient of TE module is disclosed form the manufacturer, so the Seebeck coefficient was calculated from the open circuit voltage output from TE module and based on the temperature gradient applied on the module.

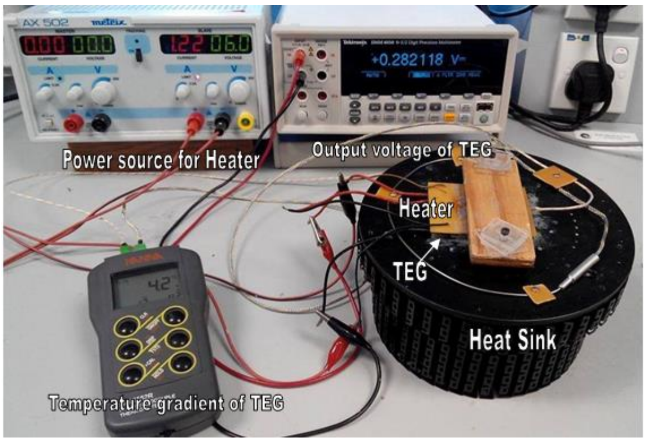

Figure2: Experiment set-up for characterization of TE module

Figure 2 shows the characterization of TE module, the DMM measured the output voltage of TE module, and the thermometer measured the temperature gradient of TE module. By using the equation (2), the Seebeck coefficient was calculated.

After that, the IR light bulb was used as heat source applied on TE module. There are four experiments related to the IR light bulb as a heat source. Firstly, the temperature IR light and focused IR light were measured and plotted in the graph. Next, the focused IR light was applied on TE module directly. After that, heat distributor was added on the top of TE module to ensure the focused IR light can dissipate uniformly on TE module. There are two heat distributors were used in the paper which is aluminum sheet and metal block. Therefore, aluminum sheet and metal block were placed on the top of TE module respectively.

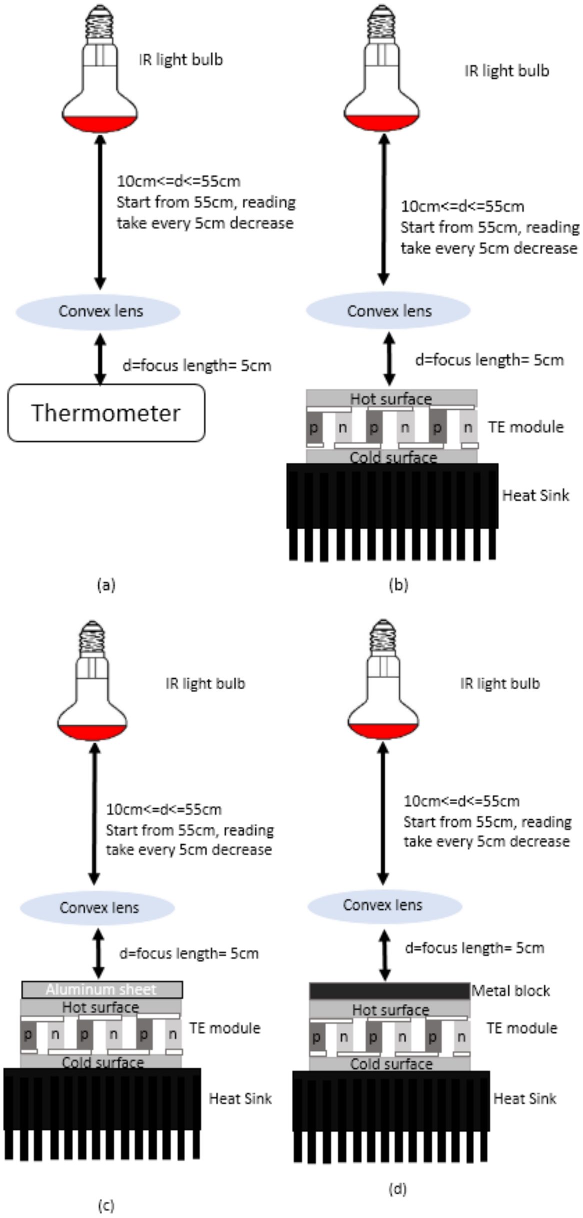

Figure 3: Illustration of (a) measuring temperature of radiated IR light and focused IR light (b) Focused IR light on TE module directly (c) Focused IR light on TE module with aluminum sheet on top (d) Focused IR light on TE module with metal block on top

Figure 3 shows the schematic diagram of the four experiments were carried out after the characterization of TE module. The focus length of the convex is fixed as 5cm and the distance between IR light and convex lens is variable between 55cm until 10cm. Figure 3(a) is measuring the temperature of IR light bulb and focused IR light. Next, there are three different methods to apply heat on TE module, which are Figure 3(b), Figure 3(c), and Figure 3(d). Figure 3(b) shows the focused IR light directly apply on TE module, Figure 3(c) shows the focused IR light apply on an aluminum sheet, and Figure 3(d) shows the focused IR light apply on a metal block. Besides, a heat sink was placed on the cold surface of TE module to maintain the temperature gradient of the module. Additionally, the output from Figure 3(b)-(d) were compared and discussed.

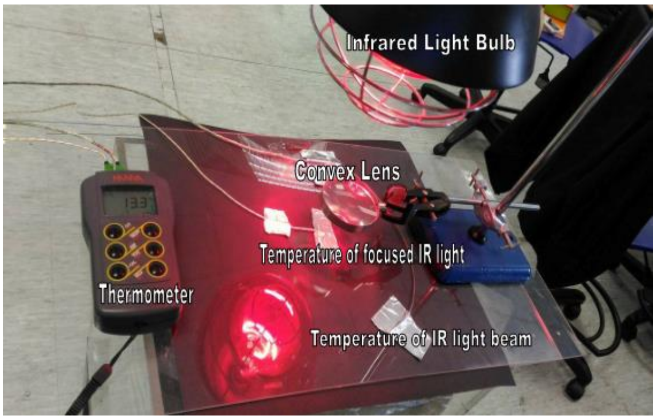

Figure 4: Measuring temperature of IR light and focused IR light.

Figure 4 shows the first experiment which using IR light as heat source. There are two different temperature were recorded which are temperature IR light and focused IR light. One of the thermocouple was put on the bottom of the convex lens and another thermocouple was put outside of the focus area of IR light. Next, both of the temperature readings were plotted in the graph and compared.

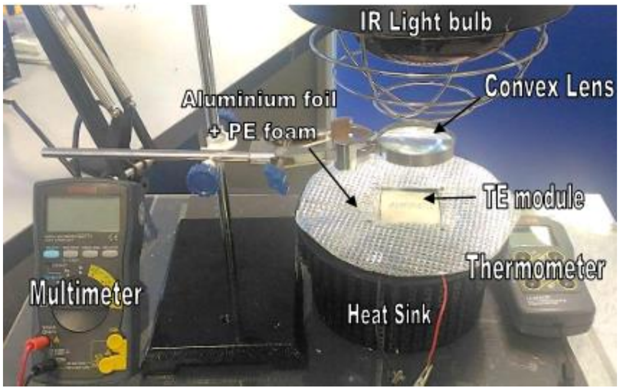

Figure 5: Focused IR light is focused on TE module directly

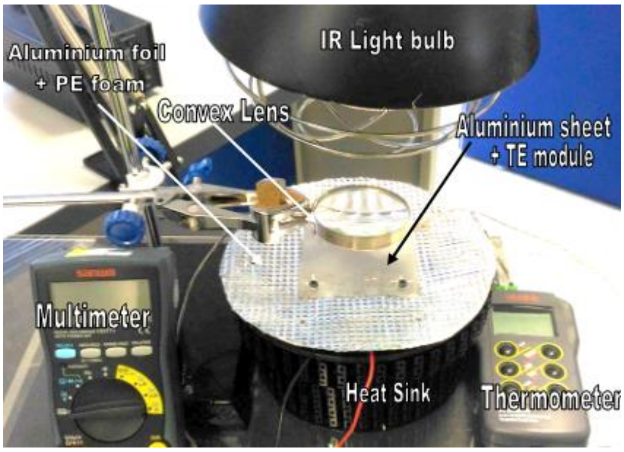

Figure 6: Focused IR light is focused on aluminum sheet

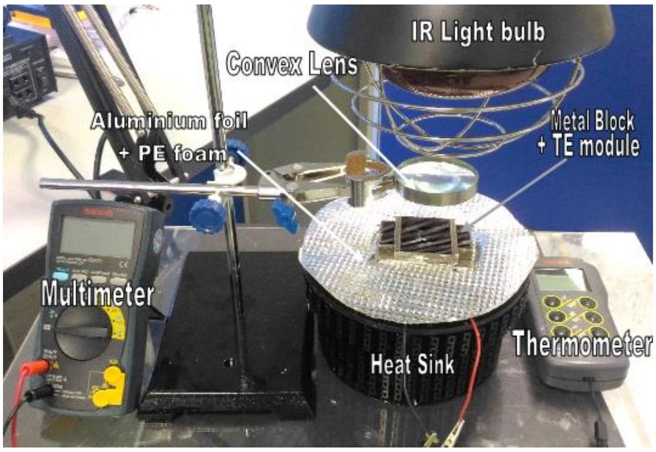

Figure 7: Focused IR light is focused on metal block

Figure 5, 6 and 7 shows the experimental set-up of focused IR light on TE module without heat distributor, with aluminum sheet and metal block respectively. Aluminum foil and PE foam were used to reflect and resist the heat from the heat sink, to maintain the cold surface of the TE module. Aluminum sheet and metal block were used to gather the heat from focused IR light and dissipate the heat evenly on the TE module. From these experiments, the open circuit output voltage was measured and plotted in the graph.

Next, the variable resistor, ammeter, and voltmeter were connected to the TE module to measure the current flow and voltage output. Besides, the distance between IR light bulb and convex lens is fixed as 30cm.

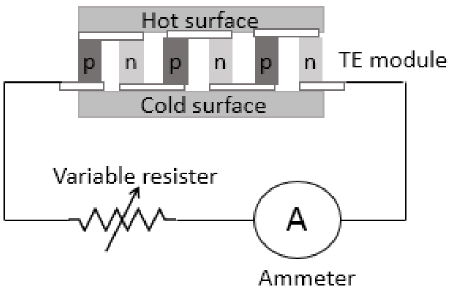

Figure 8: Schematic diagram to measure voltage and current output of TE module.

Figure 8 shows the measuring diagram of TE module. The output current with variance resistance was measured. By using equation (3) the output power of TE module was calculated. Additionally, the TE module was tested by using different cover and without cover. Therefore, it can conclude which method can optimize the output power of TE module. Before calculates the coefficient of performance of the TE module, the heat flow Q_h is calculated by using equation (5). Lastly, the coefficient of performance was calculated by using equation (4).

IV. Experimental Results and Discussion

Firstly, the voltage output from the characterization of TE module is plotted. Then, the Seebeck coefficient of the TE module is calculated by using equation (1).

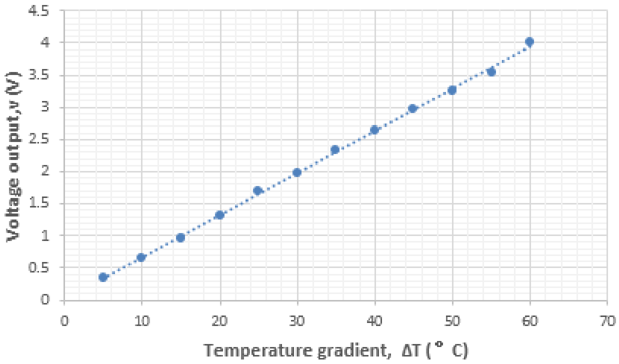

Figure 9: Voltage output of TE module by applied variance of gradient temperature

Figure 9 shows the voltage output of the TE module, voltage output is directly proportional to the temperature gradient applied on TE module. From the equation (1), it shows the gradient of the line graph is Seebeck coefficient of the TE module. Therefore, the Seebeck coefficient of the TE module is 0.066727V/°C. In addition, the Seebeck coefficient will be used in Q_h calculation.

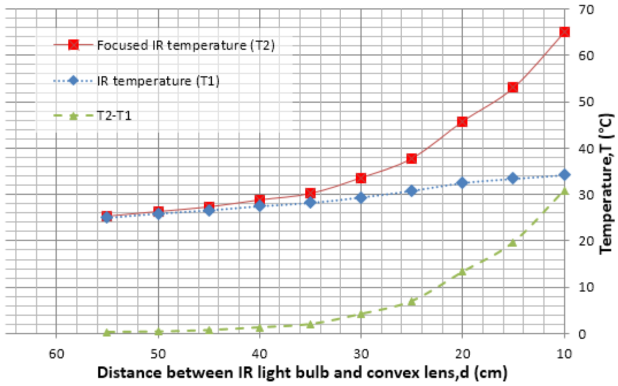

Figure 10: Temperature (°C) versus distance between IR light bulb and convex lens

Figure 10 shows the temperature IR light, focused IR light, and the different both of the temperatures. The distance between IR light bulb and convex lens is taken from 55cm until 10cm. From the graph above, it shows the dramatical changes of the temperature is started from 30cm distance. Before the 30cm, the temperature difference has not much different. Moreover, the temperature difference between the IR light and focused IR light is 30.9°C when the distance is 10cm. Therefore, it shows the convex lens can optimize the temperature gain from the IR light bulb.

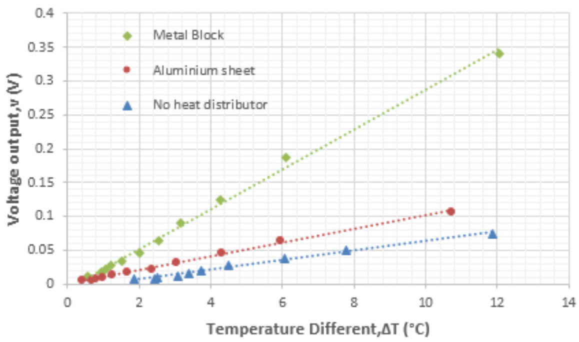

Figure 11: Voltage output of TE module with different cover on TE module

Figure 11 shows the open circuit voltage output of TE module while focused IR light applied temperature gradient on it. TE module without heat distributor has the lowest output voltage which is 0.00496V/°C. Moreover, using the aluminum sheet as heat distributor of TE module has slightly higher voltage output compare to no cover on TE module. The voltage output of TE module by using the aluminum sheet as heat distributor is 0.00978V/°C. However, the voltage output of TE module is 0.0286V/°C by using the metal block as heat distributor. The voltage output above is triple higher than voltage output of TE module by using aluminum sheet as heat distributor.

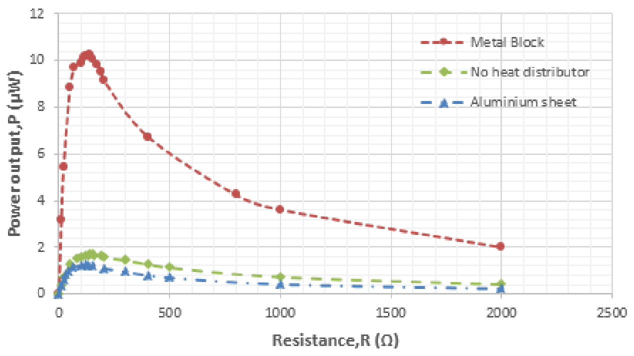

Figure 12: Power output of TE module from variance resistor load

Figure 12 shows the power output of the TE module. The power output is calculated by using equation (3). The TE module produced the highest power while the load resistor match with the internal resistor of TE module. Although, the open circuit voltage output of TE module with aluminum sheet is higher than the TE module without heat distributor. However, the power output of TE module with no distributor is slightly higher than TE module with aluminum sheet. The highest power output of TE module with no distributor is 1.71µW and the matching load is 150Ω while the highest power output of TE module with aluminum sheet is 1.28µW and the matching load is 120Ω. Additionally, the power output of TE module is 10.24µW by using heat sink as heat distributor whereas the matching load is 140Ω. TE module with metal block obtain highest output power compare to TE module without heat distributor and TE module with aluminum sheet.

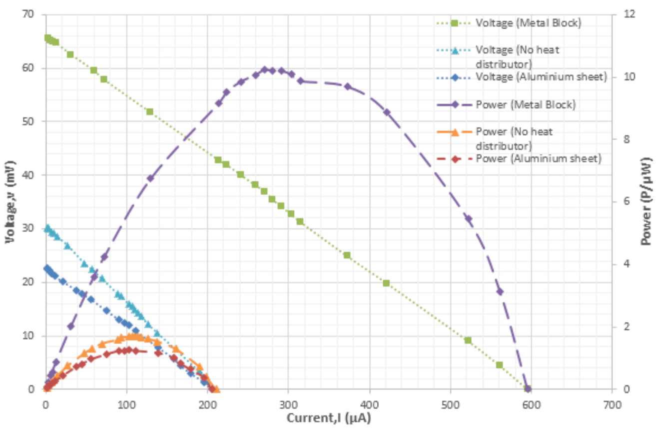

Figure 13: Typical current-voltage and power curve for TE module

Figure 13 shows the I-V characteristic of the TE module. It shows the TE module with metal block has highest output power, current, and voltage. However, it shows the output current of TE module without cover is higher than TE module with aluminum sheet cover. When the voltage is 20V, the output current of TE module without heat distributor is 20µA whereas the output current of TE module with aluminum sheet is 70µA. Therefore, the output power of TE module without heat distributor is higher than TE module with aluminum sheet.

Table II

Parameter for Qh calculation

TE module cover	T_h (°C)	T_c (°C)	ΔT (°C)	S_M (V/°C)	R_M (Ω)	R_C (W/mK)
No cover	31.25	26.75	4.5	0.066727	1.97	1.20
Aluminum sheet	29.30	27.00	2.3	0.066727	1.97	1.20
Heat sink	29.70	27.15	2.55	0.066727	1.97	1.20

Table II shows the parameter used to calculate the total heat input, Qh on the TE module. Qh can be calculated by using equation (5). Besides, the variance of resistances were connected with the TE module to obtain the Io. Next, the efficiency is also called as coefficient of performance, COP was calculated by using equation (4).

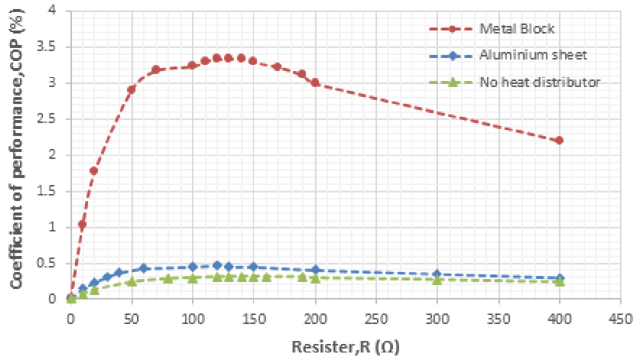

Figure 14: Efficiency of the TE module

Figure 14 shows the efficiency of the TE module with different heat distributor. The efficiency of TE with aluminum sheet and without heat distributor is lower than 0.5%. Which means both of the methods have no optimized the functionality of the TE module. Although the highest efficiency of the TE module with aluminum sheet is 3.34%, it is 6 times higher than TE module without heat distributor and TE module with aluminum sheet. Therefore, the TE module with metal block is the better method to optimize the efficiency of TE module.

V. CONCLUSION

The above result shows that the convex lens is useful to focus the heat energy on a point, therefore, higher temperature can be obtained. From the experiment, the output voltage of TE module with metal block is highest compared to TE module with aluminum sheet and TE module without heat distributor. It was also found out that the open circuit output voltage of TE module with aluminum sheet is 0.00978V/°C and it is higher than open circuit voltage TE module without heat distribution which is 0.00496V/°C. Next, the highest output power of TE module is TE module with metal block which is 10.24µW. But, the output power and coefficient of TE module without cover is higher than TE module with aluminum cover. In concluding, the heat sink is the most suitable cover for TE module to dissipate the heat uniformly.

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