CHAPTER 3

Seebeck Effect Demonstration

In this chapter, Seebeck effect was described in more detail as a thermocouple and thermoelectric module. The Seebeck effect was conducted experiment and calculated the Seebeck coefficient. This study divided for two parts for experimental setup. First, it presents the experiment for Seebeck coefficient calculating with a simple metal wire. Second, it presents the experiment of thermoelectric device which construct by a commercial thermoelectric module (TEC1-12708). In this part, the voltage and electric current that generated by thermoelectric module were used to calculate the Seebeck coefficient. It is organized as follow. In section 3.1, it reviews thermoelectric theory that involved the Seebeck effect. Section 3.2 describes experimental design and equipments of experiment. Then, section 3.3 reports the experimental results and discussion. Finally, section 3.4-3.5 present conclusions and implementation to teaching. Full details are described in the following sections.

3.1 Thermoelectric theory

According to Thomas Johann Seebeck (1821), who discovered the thermocouple. It concern the thermoelectric effect which is interchange of thermal and electrical energy. Thermocouple is a basic thermoelectric device consisted of two dissimilar metal wires connected at two difference temperature junctions [74]. When one end of metal wire is heated to a high temperature than the opposite end, the electron at the hot end are more thermal energy that the other one. It caused the electrons diffuse to the cooler. This distribution construct an electric potential difference between the junctions as shown in the Figure 3.1. It refers to the Seebeck effect that make the thermocouple operation.

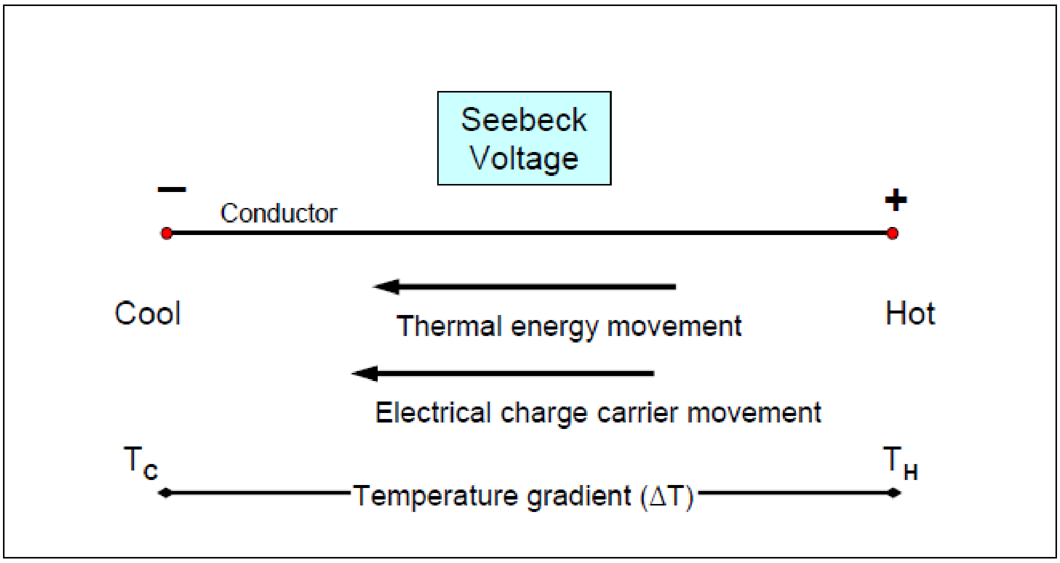

Figure 3.1 The basic diagram for Seebeck effect causing [75]

The electrons continue moving to the colder side until the charge distribution neutralize and reach to the equilibrium. The ratio between the voltage difference and the temperature difference is call Seebeck coefficient. The Seebeck coefficient is define as

$$S = \frac{\Delta V}{\Delta T} \tag{1}$$

where ΔV is a potential difference (μV), ΔT is the temperature difference (K) and S is the Seebeck coefficient (μV/K). From the literature review, the Seebeck coefficients of some materials at 0^{O}C (273.15K) are listed in the Table 3.1.

Table 3.1 The Seebeck coefficients of some material [76]

Materials	S (μV/K)	Materials	S (μV/K)	Materials	S (μV/K)
Aluminum	3.5	Gold	6.5	Rhodium	6.0
Antimony	47	Iron	19	Selenium	900
Bismuth	-72	Lead	4.0	Silicon	440
Cadmium	7.5	Mercury	0.6	Silver	6.5
Carbon	3.0	Nichrome	25	Sodium	-2.0
Constantan	-35	Nickel	-15	Tantalum	4.5
Copper	6.5	Platinum	0	Tellurium	500
Germanium	300	Potassium	-9.0	Tungsten	7.5

Furthermore, this study is using the commercial thermoelectric module to construct the thermoelectric device for generate the voltage and temperature difference. Thermoelectric module are typically formed of semiconductor materials, and has its structure formed to increase the current density and hence the output power. It is manufactured from materials such as tellurium, antimony, germanium and silver, with high doping to create semiconductor materials. These in turn are welded in a sandwich of two ceramic plates, ensuring heat transfer and sufficient mechanical strength. Figure 3.2 shows how the temperature difference formation of the tablet, with P-N junctions connected in series.

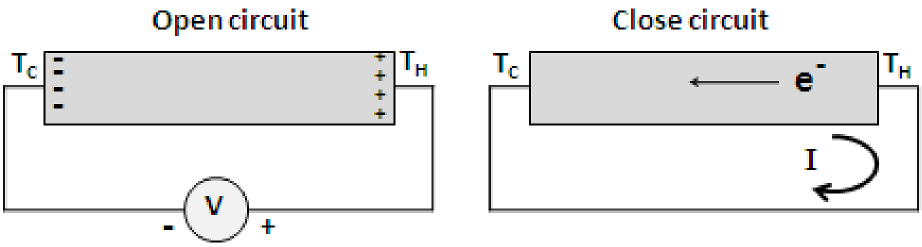

Figure 3.2 Illustration of Seebeck effect [77]

By giving a temperature greater on one side there is a current flow constant over the semiconductor material, and therefore a voltage formed by the connection of various factors. Three thermo-electric effects (Seebeck effect, Peltier effect and Thomson effect) and two irreversible effects (Joule effect and Fourier effect) can be studied to better understand the functioning of these materials [75]. There have the electrical current in the material is

$$J_{nx} = \sigma_n d\left(F_n / q\right)/ dx \tag{2}$$

Where σ_n is conductivity = $1/\rho_n$. Alternatively, there can reform the equation to

$$d\left(F_n / q\right)/ dx = \rho_n J_{nx} + \alpha \frac{dT_L}{dx} \tag{3}$$

Thermoelectricity involves the flow of charge and heat, so in addition to the equation for the charge current, there needs an equation for the heat current as

$$J_{Qx} = -\kappa_0 dT/dx \tag{4}$$

$$J_{Qx} = (S_n \sigma_n T_L)\frac{d(F_n/q)}{dx} - \kappa_0 \frac{dT_L}{dx} \tag{5}$$

Both electrons and the lattice (phonons) carry heat. These equations refer only to the portion of the heat carried by the electrons. Temperature gradients give rise to an open circuit voltage, which is recognized as the Seebeck effect. Expect a positive voltage for a n-type semiconductor (and negative voltage for a p-type semiconductor.)

The Seebeck coefficient is proportional to the difference between the energy at which current flows and the Fermi energy. From equation 3 there can rewrite the equation to

$$S_n(T_L) = \left(\frac{k_B}{-q}\right)\left[\frac{(E_C - F_n)}{k_B T_L} + \delta_n\right] \tag{6}$$

and

$$\Delta V = \int_{T_{L1}}^{T_{L2}} S_n(T_L)\,dT_L \tag{7}$$

when $J_{nx} = 0$ The relation of the Seebeck effect coefficient the Fermi energy as shown in the Figure 3.3

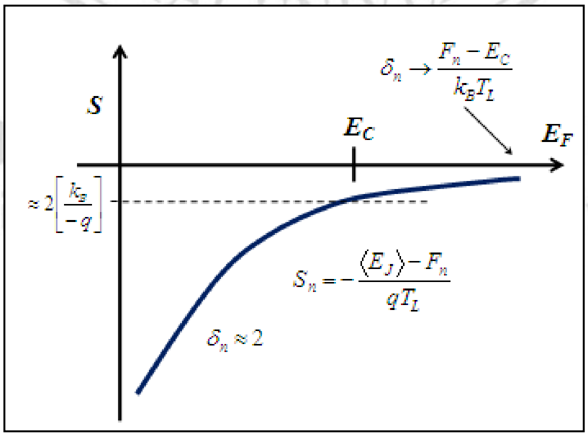

Figure 3.3 Seebeck effect coefficient and the Fermi energy [75]

3.2 Experimental design

In this experiment, the objective of this study is to conduct experiment for Seebeck coefficient calculating. There are two parts of experiments which are consist of the basic thermocouple and thermoelectric module. The details of experimental design for each part are described in the following subsection.

3.2.1 The basic thermocouple

The equipment of experiment used for this part is shown in the Figure 3.4.

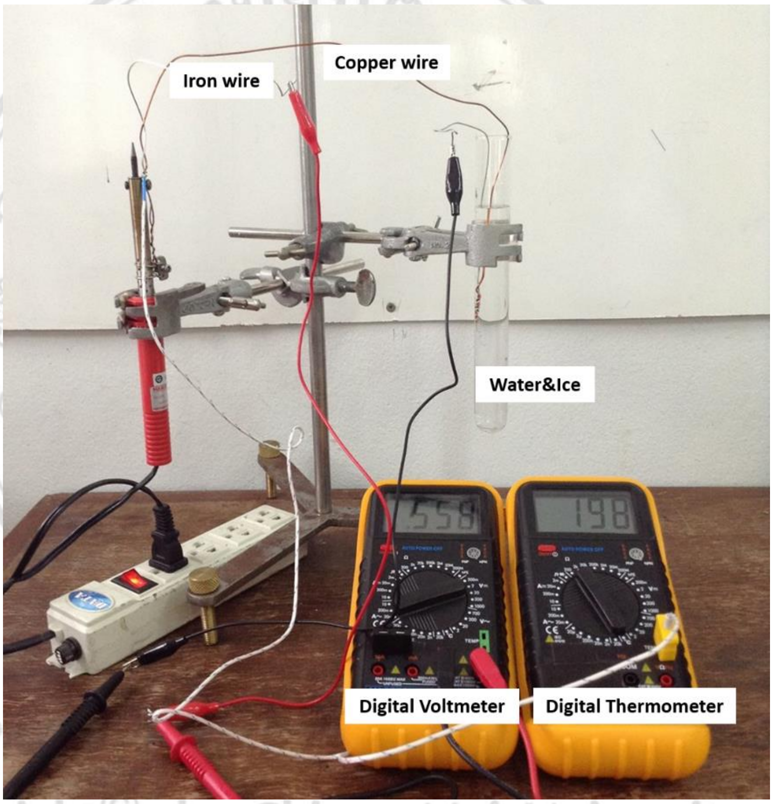

Figure 3.4 The Seebeck effect of metal wire set up

It consist of the sensitive digital voltmeter, the digital temperature, the copper wire and iron wire which are 25cm of length and 1.625 mm of diameter, the soldering iron, the alligator with electric wire, water and ice. For set up this experiment, it connect the copper wire with the iron wire for two junctions. The one end of junction was submerges in the ice with water for keep the temperature equal to $0^{o}C$ as the cold junction (T_C). The other one end junction was attach with the soldering iron for heat the electric wire as the hot junction (T_H). Then, the alligators were used to connect the end of copper wire with the digital voltmeter. The digital thermometer was used to record the temperature at the hot junction. When the soldering iron operated with AC220V, the voltmeter and thermometer were collect the data for every 1.0 min. The data was collect for 8.0 minutes because of the over heat of the soldering iron. The experimental set up is shown in the Figure 3.5.

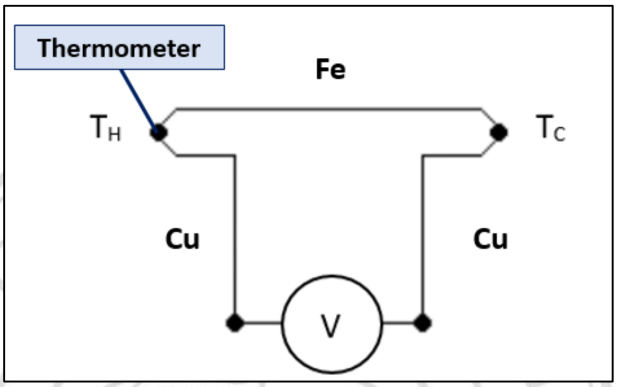

Figure 3.5 The experimental set up for metal wire

After the operation, the voltages from voltmeter and the temperature from thermometer were used to data analyzing. The data was used to plot the graph between the voltage and the difference temperature. The graph was fit to the linear equation and it obtained the slope of the graph by using the spread sheet program. Then, the slope represent to the Seebeck coefficient by the equation (1).

3.2.2 The thermoelectric device

The thermoelectric module: model TEC1-12708 was used in this study as shown in the Figure 3.6.

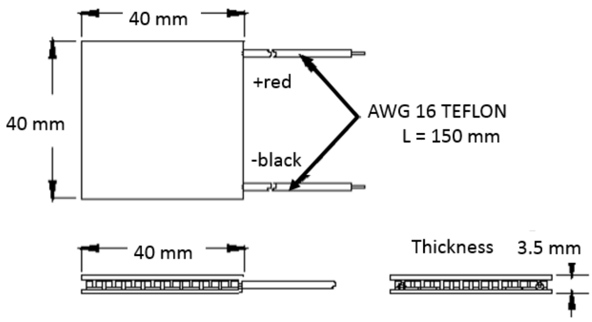

Figure 3.6 Thermoelectric module: TEC1-12708 [78]

It constructs from ceramic material: Alumina (Al_2O_3) and solder construction is 138ºC with Bismuth Tin (BiSn). It was produce from Hebei International Trading (Shanghai) Co., Ltd. China.

Thermoelectric module: TEC1-12708 has technical datasheet as shown in the Table 3.2.

Table 3.2 Thermoelectric Module: TEC1-12708 Technical Datasheet

Parameter	Performance Value
Hot Side Temperature(^{O}C)	80
ΔT_{max}(^{O}C)	≥64
Q_{max}(w)	≥71.4
I_{max}(A)	8
V_{max}(VDC)	15.4
Resistance at ambient temperature 25^{O}C(ohm)	1.5±0.2
Width of the module(mm)	40±0.25
Length of the module(mm)	40±0.25
Thickness of the module(mm)	3.5±0.15
Flatness(mm)	≤0.05
Parallelism(mm)	≤0.05
Upright pressure(kg/cm^2)	10.8(=150 psi)
Permanent Marking (Hot side)	TEC1-12708 : BCyymm
Norms to be fulfilled	Directive 2002/95/EC (RoHS) 2005/618/EC
Wire standard	1. Material:20AWG UL1674 105^{O}C PVC insulation 2. Length of red positive wire and black negative wire are 350±10mm 4. Stripped customer end in 8±2mm

The thermoelectric device consisted of the commercial thermoelectric module: model TEC1-12708 as shown in the Figure 3.6, the 0-15V AC-adapter, USB port connector, small fan, Aluminum heat sink, polarity switching controller and red-green LED. The Stainless Steel Temperature probe with the Lab-Quest App software from Vernier Software & Technology was used to displays and collects data. The apparatus and supplies of this experiment for this part are shown in the Figure 3.7.

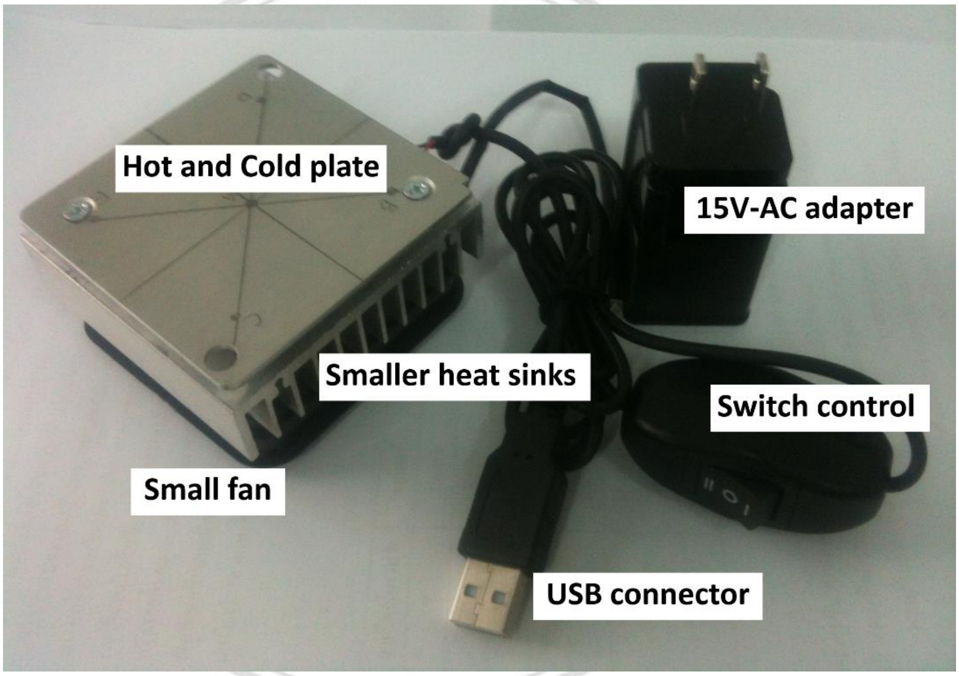

Figure 3.7 Thermoelectric device set up

The thermoelectric device was used for two ways of this experiment. First, it is a demonstration of the thermoelectric cooling and heating. The thermoelectric device was applied 0-15 Volts from the AC-adapter. Each experiment was operated for 10 minutes. The data from the temperature probe was used to plot the graph between temperature at the two heat sinks of thermoelectric device and time. The IR- camera was used to collect the temperature of the cold- hot plate and also record the photo for every 0.5 minute. Second, it is a determination of the Seebeck coefficient. The digital voltmeter was used to measure the voltage generated by the thermoelectric device. The measurement collects the temperature difference between the hot-cold sides of thermoelectric device. The data was used to fit the graph between the voltage and the temperature difference. Then, the slope was calculated and represented to the Seebeck coefficient with respect to the equation (7).

3.3 Experimental results and discussion

In the first part of this study, after the soldering iron operated, the voltmeter and thermometer were collect the data for every 1.0 minute. In this experiment the ambient temperature is 25 ^{O}C and it repeats the experiment for five times. The average data is shown in the Table 3.3.

Table 3.3 The electric potential difference (ΔV) and temperature difference (ΔT) of metal wire

Time (min)	T_H (^{O}C)	T_C (^{O}C)	ΔT (K)	ΔV (mV)
0.0	27	0	27	0.2
1.0	49	0	49	0.4
2.0	74	0	74	0.6
3.0	109	0	109	0.9
4.0	129	0	129	1.0
5.0	131	0	131	1.0
6.0	140	0	140	1.1
7.0	148	0	148	1.2
8.0	151	0	151	1.2

From the result in the Table 3.3, the electric potential difference (ΔV) and temperature difference (ΔT) were used to plot the graph as shown in the Figure 3.8. It used the spread sheet program to fit and create the linear equation. Then, the slope of graph represent to the Seebeck coefficient is 0.0079 $mV.K^{-1}$ or 7.9 $\mu V.K^{-1}$.

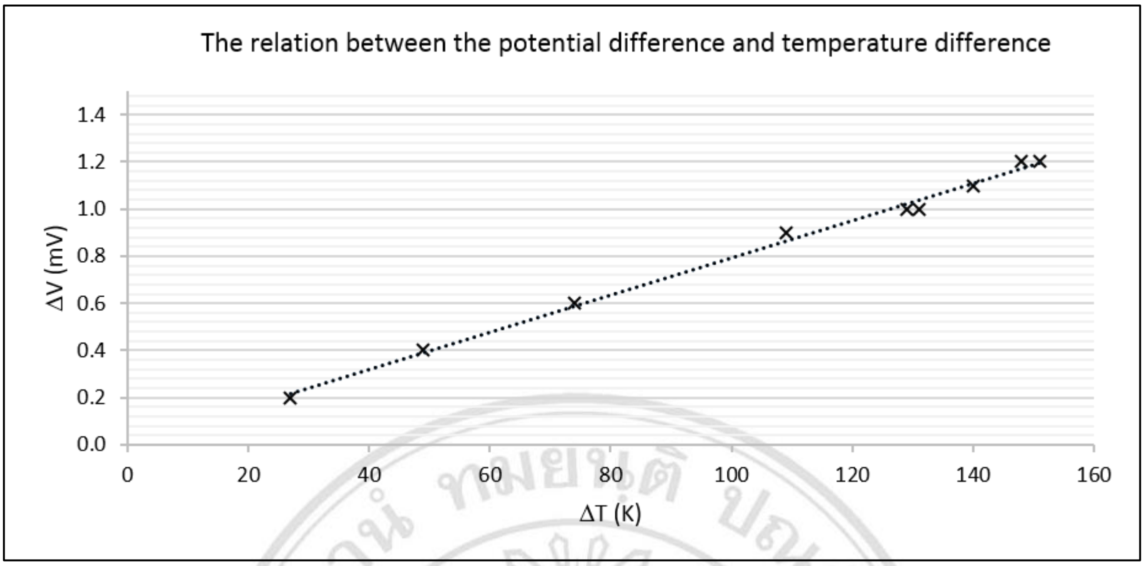

Figure 3.8 The Seebeck coefficient of copper wire

As the result of the experiment, the magnitude of electric potential difference produced between the two junctions depends on the material and the temperature difference (ΔT) through the linear relationship. It can be used to define the Seebeck coefficient for the material.

In the second part, a simple set up of this experiment aimed to performing the 2 ways of thermoelectric module properties. First, after the operation, the cold side was found to reach its minimum temperature in about ten minutes. The average minimum temperature is 17.2^{O}C. The same experiment can be repeated with the power supply's polarity switched to reverse the cold and hot sides of the device. The hot side reaches to maximum temperature. The average maximum temperature is 53.5^{O}C.The ambient temperature for this experiment is 26.0 ^{O}C. The data of temperature and time are shown in the Table 3.4. Then, the data also used to plot the graph that present the relation between temperature difference and time as shown in the Figure 3.9.

Table 3.4 The average temperature and time of thermoelectric module

Time (min)	T_H (^OC)	T_C (^OC)	ΔT (K)
0.0	29.3	29.3	0.0
1.0	42.7	24.8	17.9
2.0	48.6	21.9	26.7
3.0	50.9	20.4	30.5
4.0	52.5	19.8	32.7
5.0	52.9	19.3	33.6
6.0	53.4	18.8	34.6
7.0	53.8	18.6	35.2
8.0	54.0	18.4	35.6
9.0	54.5	18.2	36.3
10.0	54.8	17.9	36.9

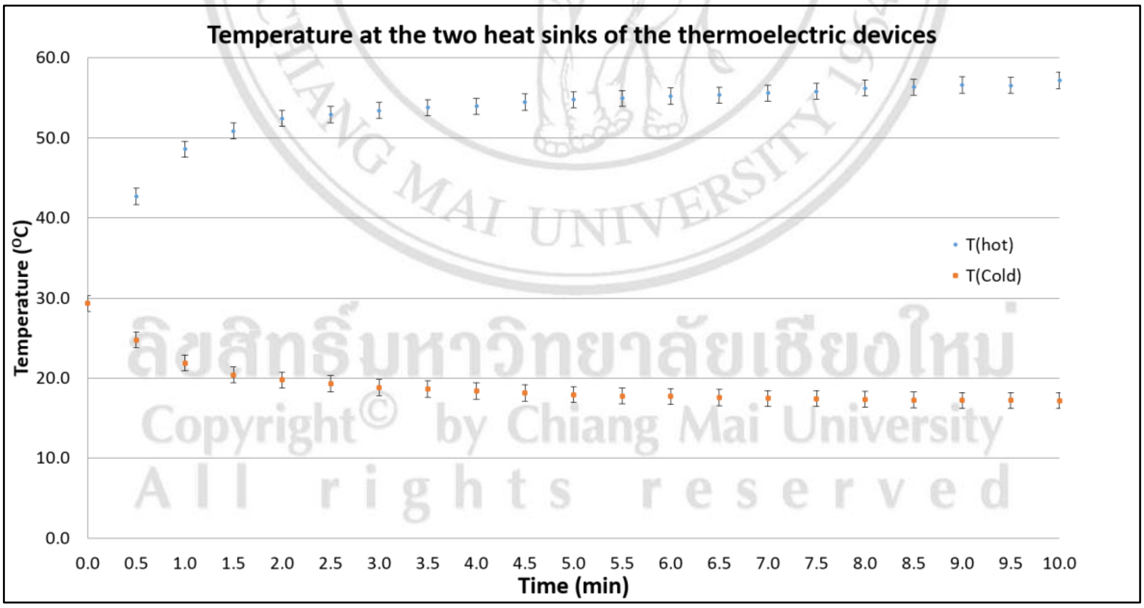

Figure 3.9 Two heat sinks Temperature versus time of the thermoelectric module

There were observed the temperature change of the devices with IR-camera and the pictures are also recorded. The temperature change of thermoelectric module is shown in the Figure 3.10 in difference color to represent the temperature gradient. There found that the temperature has distributed on the surface of the thermoelectric devices.

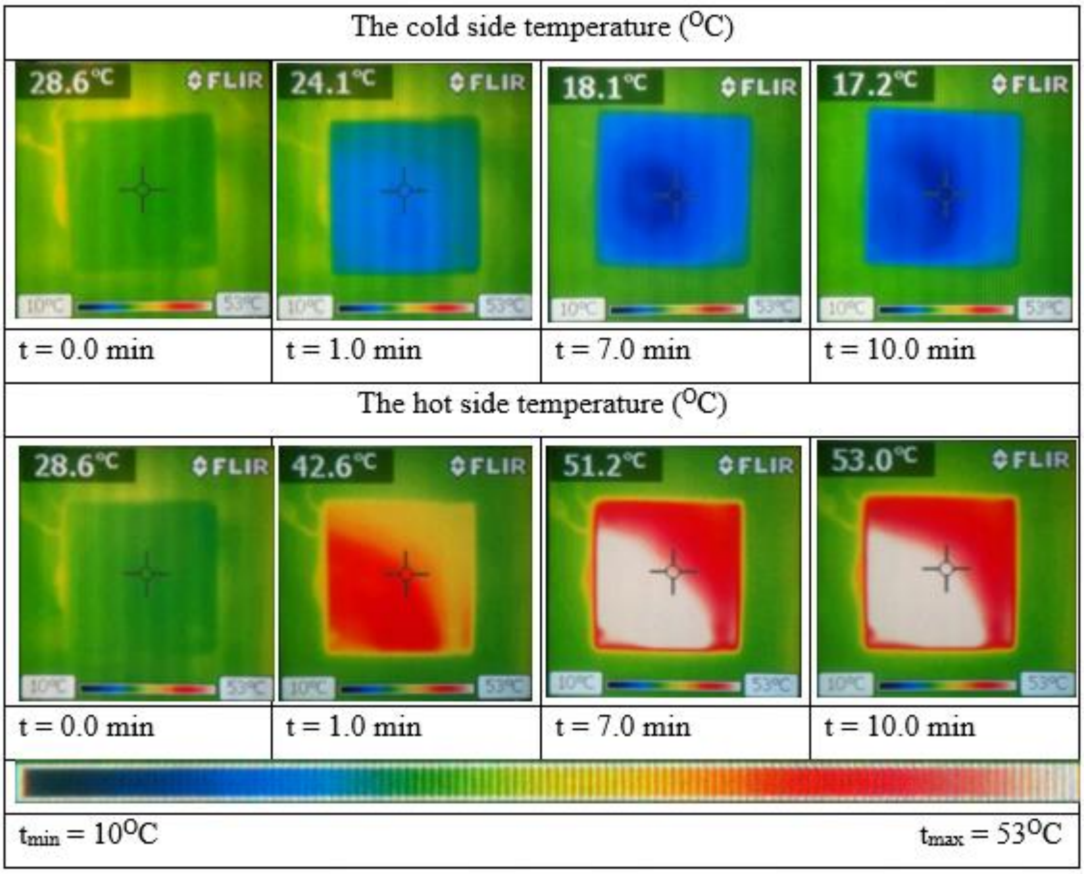

Figure 3.10 The IR photos of thermoelectric devices

From the result, the temperature of hot side and cold side of thermoelectric were change rapidly on 0.0 - 4.0 minute and also change slowly on 7.0 – 10.0 minute. The maximum high temperature (T_{Hmax}) is 54.8^{O}C and the minimum low temperature (T_{Cmin}) is 17.9^{O}C.The difference temperature (ΔT) is 36.9 ^{O}C.

Second, the digital voltmeter was used to measure the voltage generated by the thermoelectric module. The thermometer collects the temperature difference between the hot-cold sides of thermoelectric module. The data of temperature difference and voltage are shown in the Table 3.5. Then, the data also used to plot the graph that present the relation between temperature difference and voltage as shown in the Figure 3.11.

Table 3.5 Voltage (mV) generated by the thermoelectric module versus the temperature difference (ΔT)

ΔT (K)	V(mV)
0.0	0.0
2.0	14.9
4.0	29.8
6.0	44.7
8.0	59.9
10.0	74.8
12.0	89.7
14.0	104.7
16.0	119.5
18.0	134.5
20.0	149.5

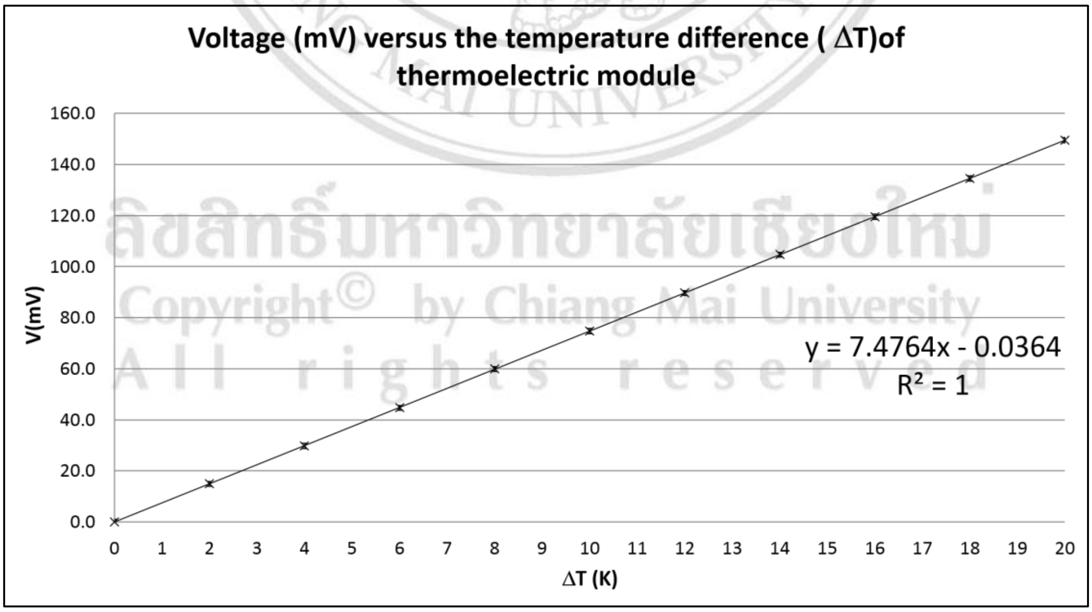

Figure 3.11 Voltage (mV) generated by the thermoelectric module versus the temperature difference (ΔT)

From the data in the Table 3.5 and the graph in the Figure 3.11, it can be calculate the Seebeck coefficient of the thermoelectric module by the slope of the graph between voltage and temperature difference is 7.4764 $mV.K^{-1}$.

3.4 Conclusion

In the first experiment, it presents the simple and usefulness of metal wire as an equipment to use for demonstrate the Seebeck effect. The result can be used to calculate the Seebeck coefficient of metal wire. For this experiment, it used the copper wire because it really known the value of the Seebeck coefficient and it can easy to be find in the electronic shop. The Seebeck coefficient of copper from this experiment has a difference with the Seebeck coefficient value in the Table 3.1 about 1.4 $\mu V.K^{-1}$. It approximate 17.72% of difference value. For this result, the errors of this experiment are conclude that: (1) the ambient temperature is concerned the temperature difference of metal wire, so the experiment was set up in the constant temperature room. The ambient temperature must keep to be unchanging. (2) the components of metal wire affect the Seebeck coefficient. It must clear to be know the component of metal wire. For improvement for the basic thermocouple demonstration, it can be used another metal wire that know a Seebeck coefficient to compare the result with different type of metal wire. The thermocouple was set up in the constant temperature to reduce the effect to the temperature changing.

For the second experiment, it demonstrates the temperature difference of hot side and cold side and voltage generated by thermoelectric module. Thermoelectric module was significant tool for display the temperature difference. It shown the temperature changing that convenience to observe and record by IR- camera. Furthermore, it can generate the voltage that can be used to calculate the Seebeck coefficient.

3.5 Implementation to teaching

In this experiment, the Seebeck effect was demonstrate and the Seebeck coefficient was calculate for the metal wire and thermoelectric module. It used to display the voltage that generated by temperature changing. This experiment shows basic ways for determining main parameters for the theory and utilization for the Seebeck effect. For the demonstration, it described good prospect for teaching the Seebeck effect and the use of a data was convenient to calculate the Seebeck coefficient. It enhances the students to hand-on the Seebeck effect experiment and create the method to measure the voltage and temperature changing. The measurements were use a short time and repeated for timeless. It can be design and develop for others experiment in thermoelectric effect.