Design of an Experiment to Calibrate a Peltier Element and Measuring Thermal Conductivity

Maryam Abdollahpour

Submitted to the
Institute of Graduate Studies and Research
In partial fulfilment of the requirements for the Degree of

Master of Science
in
Mechanical Engineering

Eastern Mediterranean University
January 2014
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

____

Prof. Dr. Elvan Yılmaz
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

____

Prof. Dr. Uğur Atikol
Chair, Department of Mechanical Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

____

Prof. Dr. Hikmet Ş. Aybar
Supervisor

Examining Committee

---

1. Prof. Dr. Fuat Egelioğlu ________________________________

2. Prof. Dr. Hikmet Ş. Aybar ________________________________

3. Assoc. Prof. Dr. Hasan Hacışevki ________________________________

ABSTRACT

Peltier element, which is a thermoelectric component, is a device that can pump heat from its cold side to the hot side depending on the direction of current. Therefore, it is a kind of heat pump of solid state. The amount of heat transfer, which can be pumped by this device, is certainly depending on the electrical power supplied to it. Thus, it can be used in many different experiments as either a heating or cooling unit. In order to use a Peltier element as a thermal unit, calibration of this device would be necessary. In the current study, an experimental method is developed in order to calibrate a Peltier element. In this study, a Peltier element of model TEC1-4905 and size $25mm \times 25mm$ was used for the calibration process. The calibration method was based on measuring the amount of heat generated by the element according to different electrical currents. The results, then, were analyzed and presented as graphs for some important parameters of this device. Based on the calibration results, in order to verify them, another experiment was performed to measure the thermal conductivity of a sample.

Keywords: Peltier element, calibration, thermal conductivity

ÖZ

Termoelektrik bileşen olan peltier elementi, akımın yönüne bağlı olarak, soğuk taraftan sıcak tarafa ısı pompalayan cihazdır. Bu yüzden, peltier elementi katı haldeki ısı pompasının çeşididir. Bu cihaz tarafından pompalanan, ısı transferinin miktarı kesinlikle elektrik güç sağlayıcısına bağlıdır. Böylece ısıtma veya soğutma gereken birçok farklı deneylerde kullanılabilir. Peltier elementini termal ünite gibi kullanabilmek için, bu cihazın ayarlanması gerekmektedir. Şimdiki çalışmalarda, peltier elementini ayarlamak için, deneysel metotlar geliştirilmiştir. Bu çalışmada, TECI-4905 modeli peltier elementi kullanılmıştır. Ayarlama metodu, farklı elektrik akımlarına göre element tarafından oluşturulan ısı miktarını ölçmenin temelidir. Sonuç olarak, bazı önemli parametrelere oluşturulan grafiklere göre bu cihazın analizleri ve sunumları vardır. Ayarlama sonuçları temeli, onları doğrulamak ve diğer deney örneğinin termal iletkenliğini ölçmek için yapılmıştır.

Anahtar Kelimeler: Peltier element, Ayarlama, termal iletkenliğini

To My Family

ACKNOWLEDGMENT

First, I would like to thank Prof. Dr. Hikmet Ş. Aybar who has supported me through my thesis and for his excellent guidance and knowledge. Without his invaluable supervision, it would have been impossible for me to complete this work.

I would also like to thank my husband Mehdi Moghadasi Faridani for his considerable helps and encouragement; also I would want to show my gratitude to all of my friends who helped me through this study.

Finally, I extend my special thanks to my family for their unconditional support, both financially and emotionally through my degree.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A	Area (m^2)
c	Specific heat of water (J /kg.℃)
$\dot{E}$	Energy transfer (W)
h	Heat transfer coefficient ($W/m^2.K$)
I	Electrical current (Amp)
k	Thermal conductivity (W/m.℃)
m	Mass (kg)
$\dot{Q}$	Heat transfer (W)
t	Time interval (sec)
T	Temperature (℃)
x	Length (m)
V	Volume (m^3)

Greek Symbols

ρ	Density (kg/m^3)

Subscript

c	Cold
in	Inlet
h	Hot
s	Surface
st	Stored

Chapter 1

INTRODUCTION

Peltier element, which is a thermoelectric component, is a device that can pump heat from its cold side to the hot part depending on the direction of current. Therefore, it is in fact, a kind of heat pump of solid state. The power of a Peltier element comprises of the scalability of its cooling elements, its location independence, and its reliability and precision control. Moreover, there are no moving parts in a Peltier element which essentially makes it free of vibration and noise. The major advantage of using Peltier elements over compressor-cooling systems is elimination of hazardous and harmful refrigerants. However, the efficiency of the Peltier systems are still remarkably lower than the compressor cooling systems. On the other hand, Peltier technology is appropriate for a range of special applications, such as refrigeration units installed in luxury automobiles, while it's not a substitute for the compressor units in applications such as household refrigerators yet, due to its lower efficiency.

Peltier element works based on the Peltier Effect. It states that the passage of an electric current through the junction of two dissimilar wires can either cool or heat the junction depending on the direction of current. If two wires with different electric conductivities are connected at both ends and one of them has different temperature than the other, an electric voltage will be created between the two ends. This effect is used in thermocouples for temperature measurement and the elements are called thermal elements. If a voltage is applied in the assembly, an electric current will flow, transferring heat from one connection point to another one. Therefore, the junction, from which heat is being transferred, cools down while the other one heats up. This heat transfer is caused by the electrons flow. These devices are the so called Peltier elements (the law of nature of the intermediary metals and of the intermediary temperatures). Thus, materials with higher electrical and lower thermal conductivity are more appropriate for Peltier elements. Figure1.1 shows the mechanism of a Peltier element.

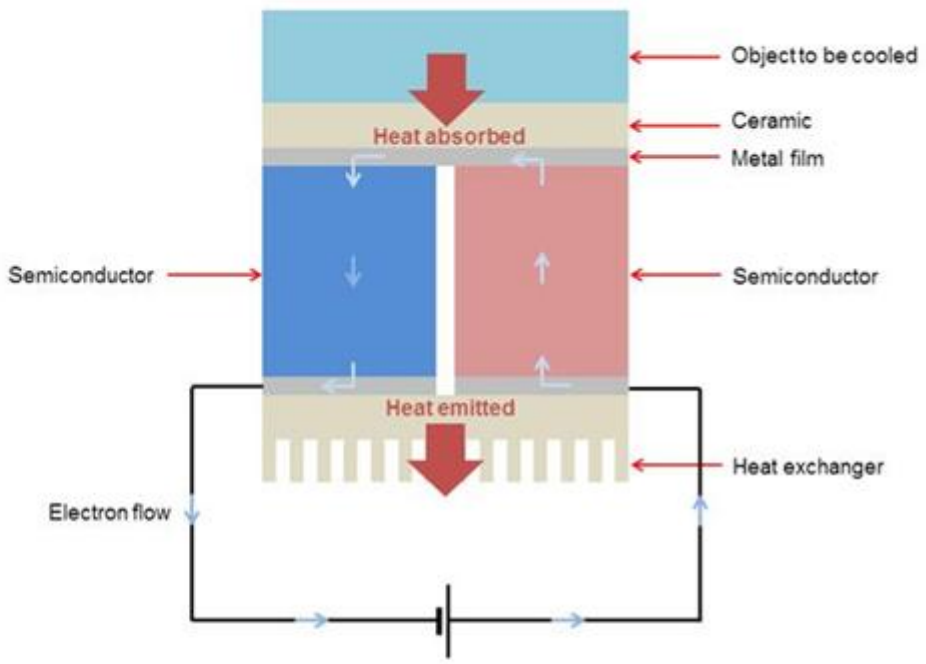

Figure 1. 1 Peltier element structure.

In general, Peltier elements are very reliable, low maintenance and durable due to the absence of moving parts subject to wear. In addition, they operate quietly and vibration-free and could be small and lightweight even when combining several modules into one element. Other major advantage of them includes low-cost manufacturing which shows reliability for their future development. Peltier systems contain no flammable refrigerants, ozone depleting or agents that contribute to the greenhouse effect. Also the entire cooling system with compressor, inductor, large evaporator, and condenser components can be eliminated by using them. Peltier elements are maintenance-free and quick and easy to replace in case of failure.

State-of-the-art control technology makes it possible to meter the cooling effect more accurately in comparison with the conventional compressors. It is also possible to reverse the function of the system by reversing the polarity, i.e. the cooling element can be turned into a heating element.

With Peltier modules, technically there is no way to get around the fact that the hot and cold sides are very close together. In practice, today’s Peltier modules are only 3 to 5 mm thick. This fact makes it particularly important to efficiently conduct the heat into and from the module. Technically, this is handled by large heat sinks with fans. The performance of a Peltier module is directly related to the required temperature difference. The greater this temperature difference, the lower the pumping capacity until it (based on the present state of Peltier technology) comes to a complete standstill at approximately 70 K. Larger temperature differences can only be accomplished by complex multistage elements.

1.1 Calibration of a Peltier Element

A comparison process between measurements of two relative parameters is called calibration. These parameters are measured so that one of them is obtained with a device with an acceptable accuracy and the other one is gained from another device which is to be calibrated. The device which gives the values at an acceptable range is called the standard device. Calibration process is necessary for most of the devices and equipment, especially, for those which are exposed to extreme conditions and time, and uses other than their standard applications. That is the reason why all the equipment companies, especially, electronic instrument companies, assign validity of accuracy for their products. Electronic devices are very sensitive because their special parts in the real world are exposed to electromagnetic fields, humidity, dust, and heat. Therefore, calibration is needed to be performed regularly, to ensure that their accuracy is within the standard range. Another necessity of calibration is to determine the main parameters and characteristics of a device. Several experiments with high accuracy need to be conducted for each parameter. The important point is to determine a parameter from an experiment, all other related parameters needed to be set as constants. Since Peltier elements are usually used for their cooling or heating effects, they have important parameters such as their voltage and current. Therefore, to carry out the calibration for a Peltier element, it is important to determine the way of controlling this device. As indicated in the most of the instruction manuals of Peltier elements, they can often be controlled by setting the voltage according to their maximum allowed voltage and changing the current.

1.2 Objectives

In this study, an experimental method is developed in order to calibrate a Peltier element. The method is based on measuring the heat generation of the peltier element. This measurement is performed such that a lump system is adhered to the Peltier element so that it can absorb the heat generation. A Peltier element of model TEC1-4905 and size $25mm \times 25mm$ is calibrated. According to the obtained results, the total heating and electrical power, generated by the Peltier element, is measured. Also, the cooling power was calculated regarding the energy balance of the device. The energy balance was based on the operation of a heat pump. Then, the coefficient of performance, as the electrical power over the heating power, was calculated. Also, the maximum and minimum temperature created at the hot and cold sides of the Peltier element are measured. Based on the calibration results, in order to verify them, another experiment is performed to measure the thermal conductivity of a sample.

1.3 Thesis Organization

In Chapter 1 a brief introduction about the structure and mechanism of a thermo-electric unit, especially, a Peltier element is given form two points of views: electrical and thermal. In Chapter 2, a history of thermo-electric devices and equipment are explained. In Chapter 3, first, the experimental methodology of calibration process beside the theoretical explanations and relative equations is given. Then, the experimental setup including all the equipment needed in this experiment is mentioned. In Chapter 4, the results of the experiment are presented with their discussions and analysis. A case study is presented which shows a method of measuring thermal conductivity. Finally, in Chapter 5, a brief conclusion and overview of this study is presented.

Chapter 2

LITERATURE REVIEW

Thomas Johann Seebeck, in 1821, found out that an electrical circuit that is created of two different metals, having connections with temperatures different than each other, affects the magnet of a compass [1]. At first, Seebeck believed this was because of magnetism that induced by the temperature difference and assumed that it might be related with the magnetic field of earth. Although, he could suddenly prove that a "Thermoelectric Force" would induce the electrical flow which can deflect the magnet according to the law of Ampere. Precisely, the temperature difference between the junctions generates an electric voltage which can produce an electric current in a circuit. This effect is called the effect of Seebeck. The voltage generated is a function of the temperature difference that is created between connections.

Gustav Magnus in 1852 found out that the voltage produced by Seebeck effect is not related with the temperature distribution in the metal lengths between the junctions [2]. This indicates that the thermo-power is a point (or state) function. In other words, this is the working principle of the temperature sensors or thermocouples.

Then, French physicist Jean Charles Athanase Peltier, found the reverse effect which was the formation of a temperature difference at two different electrical conductors, having contact points, with an electric current [3]. At that time, Peltier could not appropriately explain the effect, which William Thomson (also known as Lord

Kelvin, namesake of the SI unit of temperature) subsequently provided with his theory of thermoelectric currents in 1860 [4].

Lenz, in 1838, proved that according to the direction of electrical current, heat transfer can occur from a connection and cool it, or in the reverse direction of the electrical flow, heat transfer can occur to the connection which is the heating process. The amount of heat removed or generated at the junction is a function of the electrical flow. The proportionality factor is so called the Peltier coefficient [5].

Abram Fedorovich Ioffe, in 1949, developed the theory of thermo-electricity ending with the discussions on Semiconductor Thermo-elements and Thermo-electric Cooling [6]. Ioffe also developed the application of the semiconductors in thermo-electric devices.

In 1954, the first experiment, using thermo-element device that resulted cooling to 0^0C, was performed by H. Julian Goldsmid [7]. Goldsmid authored several introductory literatures and books that contain introduction to thermo-electricity.

Recently, new ideas in the field of thermo-electricity were presented which improved researches in thermo-electric materials, particularly, at the nanometer scale. Also, new versions of more complex thermo-electric materials were developed [8].

Moreover, global interests in the application of thermo-electric materials which are environmentally friendly raised [9].

Chapter 3

EXPERIMENTAL INVESTIGATION

3.1 Experimental Setup

3.1.1 Thermal Element

A pair of Peltier elements of TEC1-4905 of size $25mm \times 25mm$ is selected for calibration experiment. Figure.2 shows this type of Peltier element. The nominal characteristics of this Peltier element are given in Table 3.1.

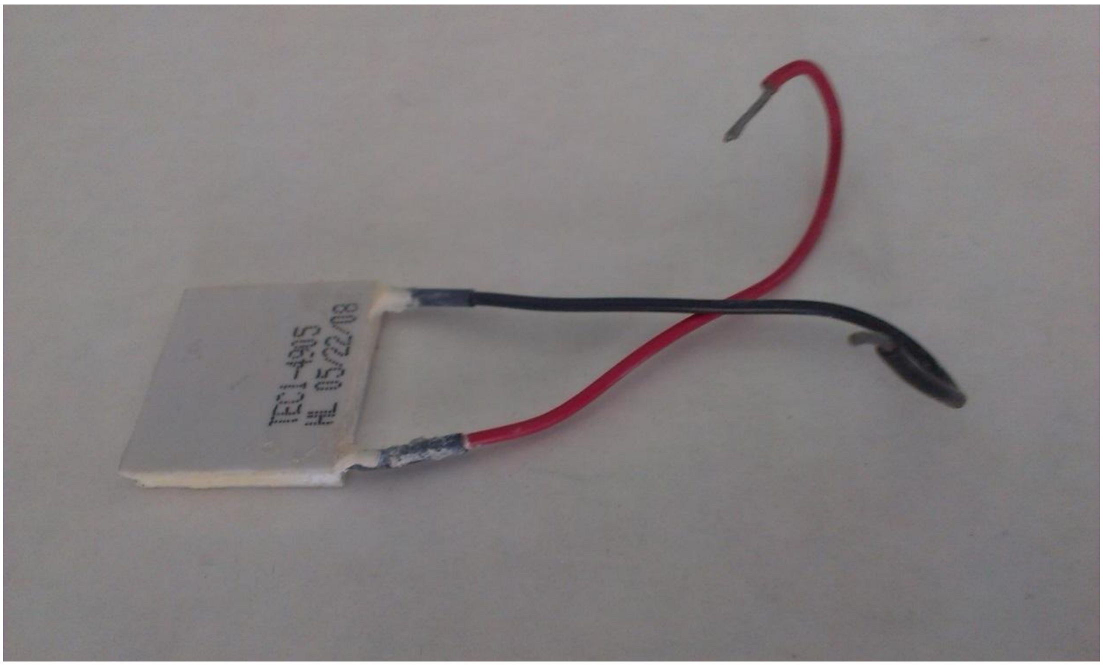

Figure 3. 1 Peltier element TEC-4905 used in the experiment

Table 3.1 Characteristic of Peltier element.

Type	**Length(mm)**	**Width(mm)**	**Height(mm)**	**Wire Length(mm)**
TEC1-4905	25	25	3.9	300
	Imax(A)	**Umax(V)**	**Qcmax(W)**	**Tmax(^{0}C)**
	5.5	5.0	27.5	66

3.1.2 Power Supply

A power supply is a device that supplies specific voltage and current according to the experiment and its electrical load. It is commonly applied to electric converters that convert one type of electrical energy to another. An ordinary power supply is the one that controls the output voltage and/or current to a specific value. The controlled value is nearly kept constant in spite of variations in the load current or the voltage supplied by the energy source of the power supply.

3.1.3 Thermocouple

Thermocouple is the smallest model of a thermal element. It is made of two conductors with different values of Seebeck coefficients such that this system generates the maximum accessible thermo-electric voltage. For the calibration experiment, a K-type thermocouple with 1 mm is used to measure the temperature.

3.1.4 Thermal Paste

Thermal paste is a specific adherent material with a very high heat conductivity that is used to connect two objects to get a good thermal contact. However, its thermal conductivity is not as high as a good conductor such as copper. Thus, very thick thermal paste can disturb the conductive heat transfer between two materials.

3.1.5 Data Acquisition System

Data acquisition process is the procedure of gathering signals which can measure real physical conditions and convert them into digital and/or numeric values that can be processed by a computer. Data acquisition systems (or DAQ systems) typically can convert analog waves into digital values in order to process them. The DAQ device used in this experiment is an Omega device of model OM-DAQ-USB-2400 series. It has 16 single channels or 8 differential channels at higher accuracy. It measures the temperature with the accuracy of ±0.01 ^{0}C.

3.2 Experimental Procedure

As to the importance of the calibration procedure, one has to measure the heat transfer generated by the Peltier element. As mentioned earlier, a Peltier element works as a heat pump and due to the effect of heat pump, it creates a finite temperature difference between its two sides. Regarding the restrictions and difficulties of heat measurement, a method for heat measuring could be established. The method can be arranged such that the heat generated at the hot face of the Peltier element can be absorbed to a material and as a result, rises its temperature. An appropriate choice of the heat absorbing material can be a kind of so called “Lump system”. A Lump system is an object with relatively small size and high thermal conductivity in which the inside temperature gradient is very low. Thus, the whole material has almost a uniform temperature. Therefore, an Aluminum cube was prepared for calibrating the Peltier element. To measure the heat generated by the Peltier element, the cube should be attached to its hot side, while the other five sides are fully isolated. To improve the heat transfer between cube and Peltier, the cube sides (or at least one side of it) should be exactly same as the Peltier side area. Also, a thermal paste was applied in order to connect both surfaces together. Creating a hole into the center of the cube, it made possible to connect a thermocouple and measure its temperature. Another important point is when a Peltier element is connected to the power supply and starts transferring heat from its cold side to the hot side, these two sides have restrictions in heat absorption and emission due to their low surfaces. Therefore, it would enhance the heat transfer to increase their surface areas by connecting any kind of fin (i.e. heat sink) to them. Thus, for the calibration experiment, the hot side of the Peltier element was connected to the cube side while the cold side was joined to a heat sink. The heat sink can be a conventional CPU heat sink with a fan. Then the Peltier element connected to a power supply which restricted the voltage and adjusted the electrical current. For each current, the Peltier element started to transfer heat from its cold side to the hot side and the temperature at the center of the cube was changed as time passed. Measuring central temperature of the cube lead us to use the theory of a Lump system which states that the total heat transferred to the cube is equal to the total heat stored in it. Figure.3 illustrates the experimental set up.

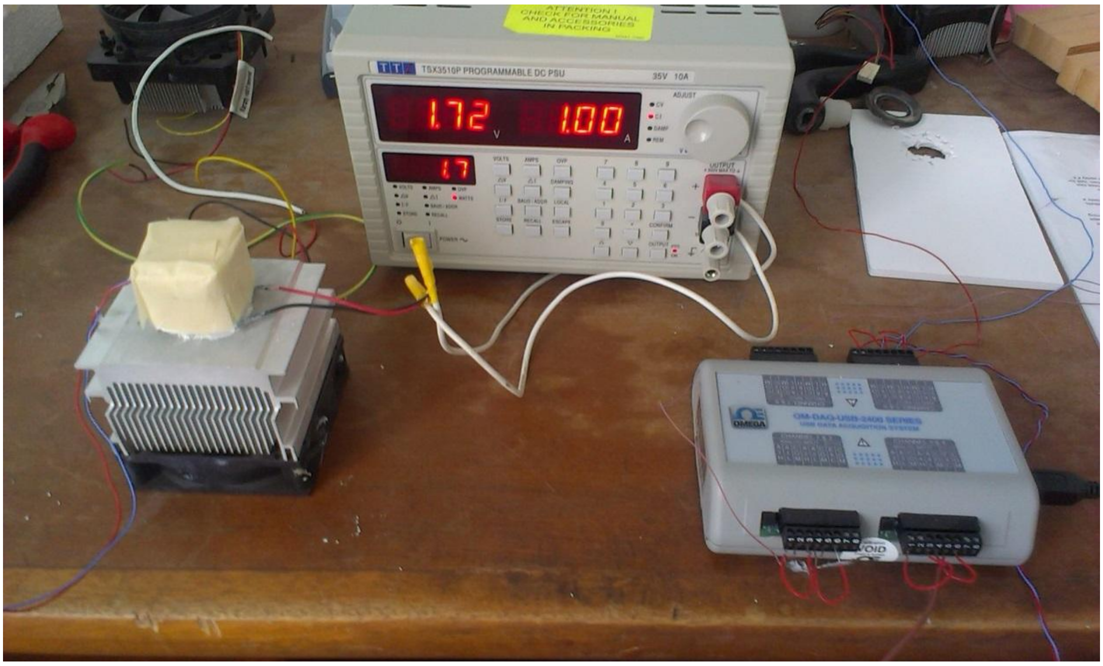

Figure 3. 2 Experimental setup.

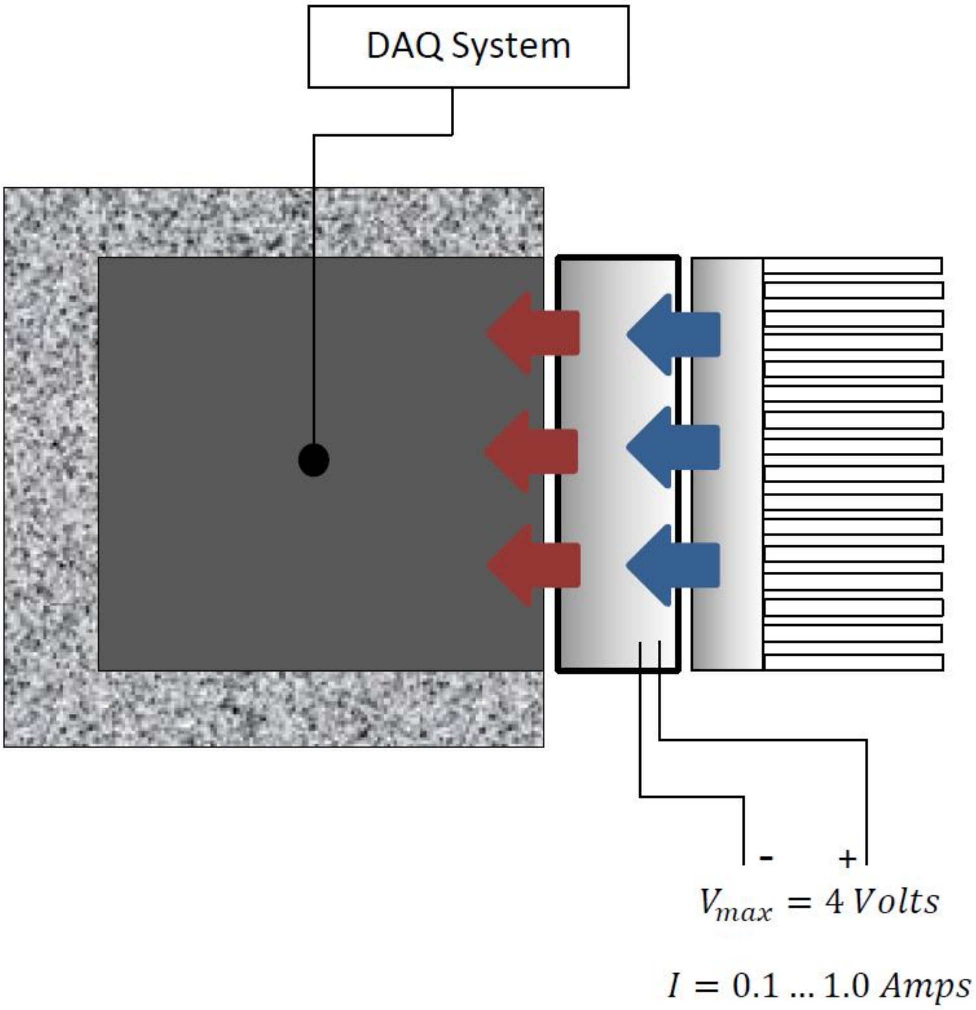

Figure 3. 3 schematic diagram of experiment.

3.3 Mathematical Modeling

Transient (time dependent) conduction occurs when a body experiences a sudden change in thermal environment. If the solid body is small, the temperature gradients within the body can be neglected. Theoretically, time dependent temperature can be verified by performing an overall energy balance on the solid. This means the following:

$$\dot{E}_{in} = \dot{E}_{st} \tag{3.1}$$

Where $\dot{E}_{in}$, is the heat generated by the Peltier element. In terms of the definitions of the energy transport from the solid, the above energy balance reduces to

$$\dot{E}_{in} = mc\frac{\Delta T}{\Delta t} = \rho V c\frac{\Delta T}{\Delta t} \tag{3.2}$$

Where ρ, V, c, and t are the density, volume, specific heat, and time, respectively. According to the Lump system theory, Biot number, Bi, is a non-dimensional number which can be defined as:

$$Bi = \frac{hL_c}{k} \tag{3.3}$$

Where parameters h and k are the coefficient of heat transfer (when subjected to convective heat transfer) and thermal conductivity of the material, respectively. Also, for any geometry, the characteristics length L_c is the ratio of volume over the surface area of the material as:

$$L_c = \frac{V}{A_s} \tag{3.4}$$

The necessary condition of a lump system is that the Biot number should be less than 0.1. The cubic specimen will be heated by Peltier element to a certain extent and let it cool down to reach the ambient temperature. The energy transfer generated by the Peltier element depends on the properties of the cube and the electrical power applied to it.

Chapter 4

RESULTS AND CASE STUDY

4.1 Results

The calibration experiment has been carried out such that the Aluminum cube of 25 mm sides was the heat absorbing sample. It has the mass of 43 gr and specific heat of 903 J/kg.K. A hole of 2 mm diameter was drilled at the center of one side until it reached the center of the cube in order to enter the thermocouple and measure the temperature at the center. The Peltier element, then, was adhered from its heating side to one of the cube sides (not the one with the hole) using some thermal paste. All the other sides of the cube should have been fully isolated and covered with a good isolative material such as thermal foam. The cooling side of the Peltier element was adhered to a CPU heat sink having a 12-Volt fan. The heat sink and the fan, as mentioned earlier, enhance the total heat pumping of the Peltier device. The Peltier element was connected to the power supply, and because of its voltage restrictions, the power supply voltage was set to 4 Volts. The thermocouple, which was differentially connected to the DAQ system, was also connected to the center of the cube having some thermal paste at its tip to increase its thermal contact. The experiment was started with setting the electrical current to 0.1 Amps and the Peltier element started heating the cube from its one side for 60 seconds. The DAQ system, which was connected to a computer, automatically recorded the temperature of the cube with respect to the elapsed time. Waiting for the cube to get the temperature of environment, the new set started with the current of 0.2 Amps for same period of time. This procedure was repeated for electrical currents of 0.3 to 1.0 Amps with the step of 0.1 Amps. According to the given equation of transient heat absorption in the previous section, the total heat generated by the Peltier element entering the cube can be calculated. The results of heat generation of the Peltier element for all the values of electrical current for 60 seconds are presented in TableA.1 in appendix and illustrated in Fig.4.1. According to this figure, for all the currents, the heat generation has scattered values at the beginning of heating, leading to approximately stable values as the time passes.

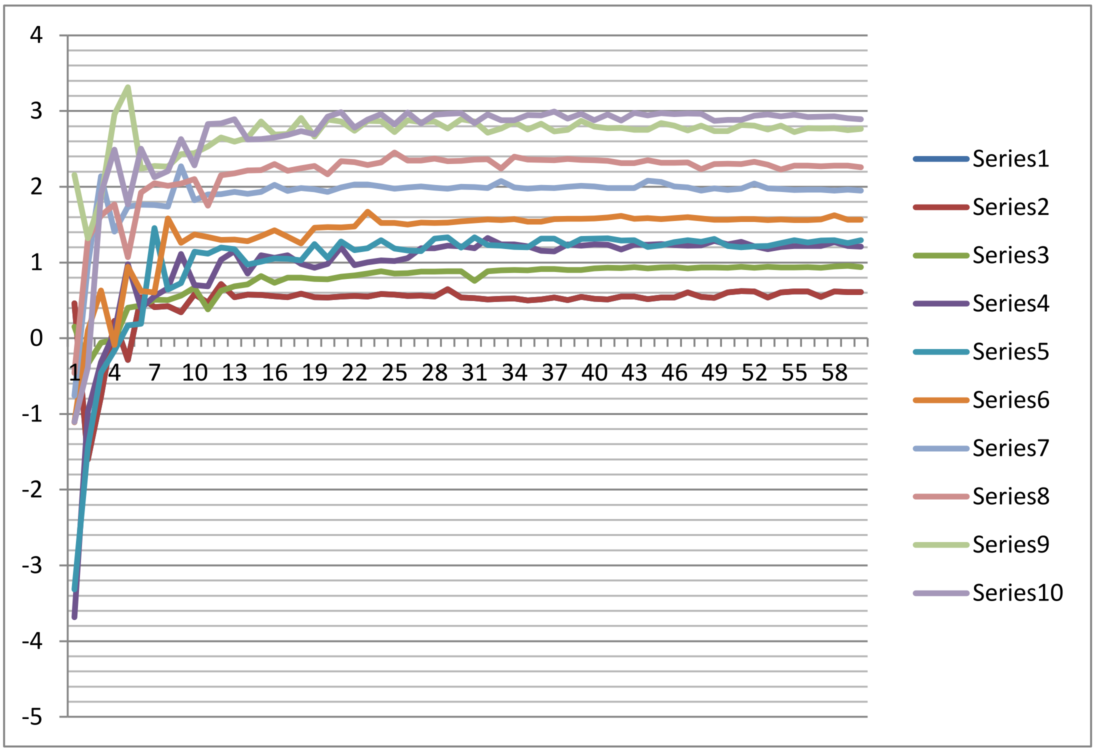

Figure 4. 1 Heat generated in the cube for different electrical current vs. time.

Then the values of heating power (i.e. heat generation) for each current, obtained from the stabilized graphs, are given in Table4.1 and shown in Fig4.2.

Table 4.1 Heating power vs. current

Electrical Current (Amp)	**Heat Generated (Watt)**
0.10	0.56
0.20	0.56
0.30	0.86
0.40	1.14
0.50	1.22
0.60	1.52
0.70	1.98
0.80	2.29
0.90	2.77
1.00	2.88

A linear curve fitting seems to be suitable for these set of data which represents the heating power as a function of electrical current. According to Fig4.2, the slope of this straight line is about 2.8. Also, the power supply device gives the amount of electrical power supplied for each current.

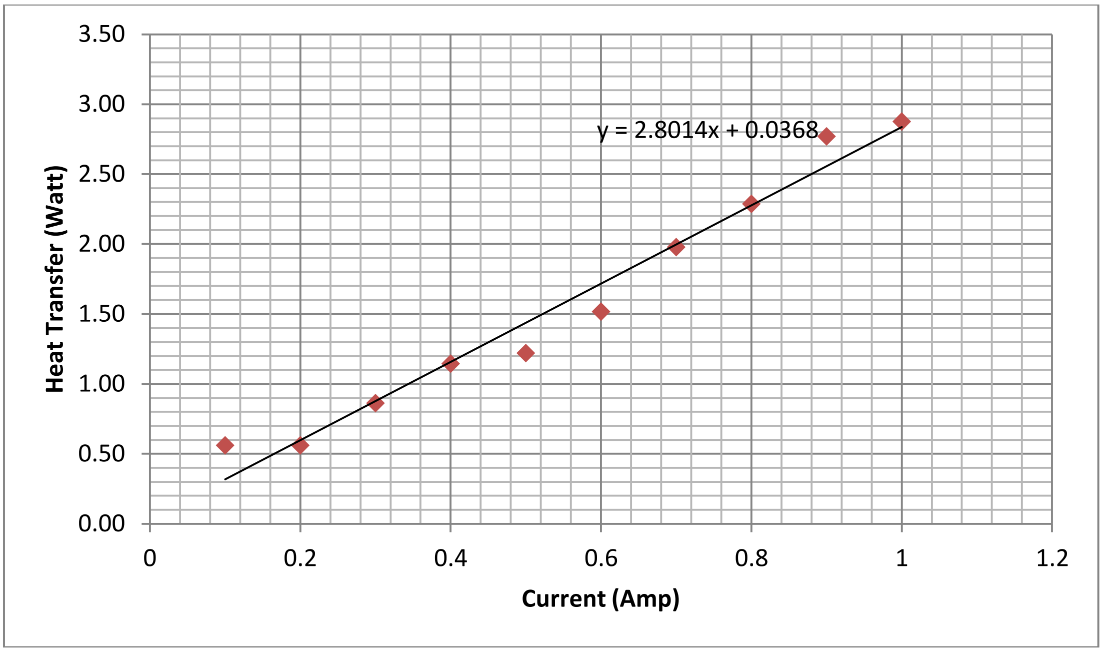

Figure 4. 2 Heating power vs. current.

The electrical power can also be obtained from multiplication of current and voltage for each electrical current which are shown in Table4.2 and Figure4.3. The equation of the line, shown in this figure, is a quadratic equation which states that the electrical power is a quadratic function of electrical current.

Table 4.2 Electrical power vs. current.

Electrical Current (Amp)	**Electrical Power(Watt)**
0.10	0.02
0.20	0.04
0.30	0.12
0.40	0.20
0.50	0.40
0.60	0.50
0.70	0.70
0.80	0.90
0.90	1.10
1.00	1.40

Another important parameter of the Peltier element is its cooling power. Due to the fact that a Peltier element is a heat pump, the first law of thermodynamics can be applied to it as following:

$$\dot{Q}_{cooling} = \dot{Q}_{heating} - \dot{W}_{electrical} \tag{4.1}$$

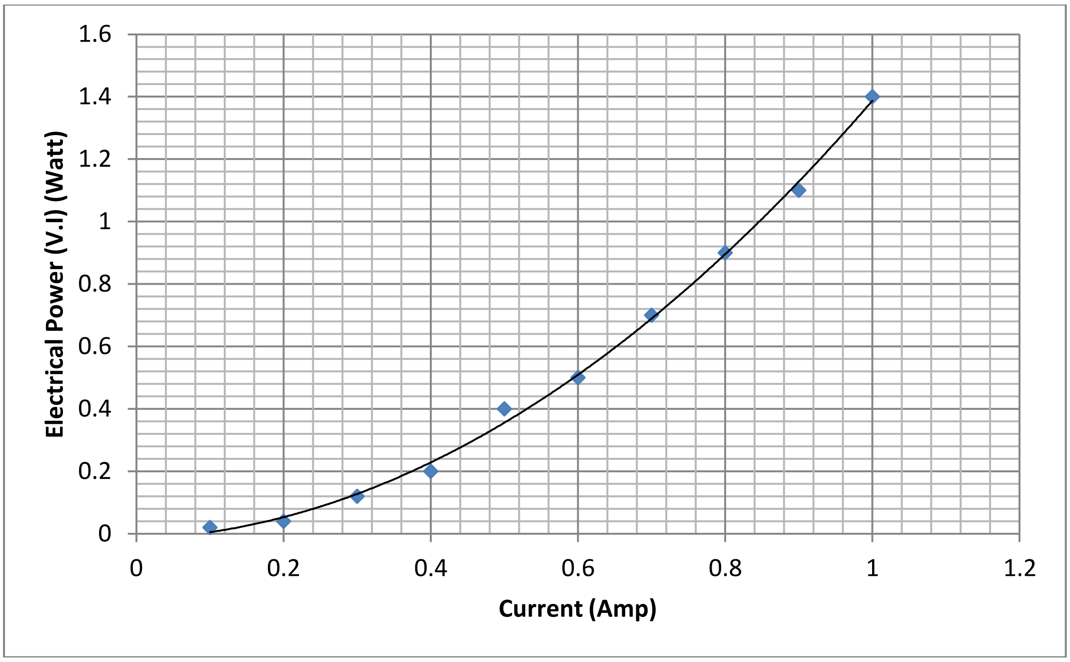

Figure 4. 3 Electrical power vs. current.

According to Eq.4.1, the cooling power values for each current are calculated. Then the results compared to the heating power results and shown in Table4.3 and Fig.4.4. A linear curve fitting is made for the cooling power results and the slope is obtained as 1.27. Recalling that the slope of the heating power was 2.8, which is about twice the cooling power.

Table 4.3 Heating and cooling power vs. current.

Electrical Current (Amp)	**Heating Power (Watt)**	**Cooling Power (Watt)**
0.10	0.56	0.54
0.20	0.56	0.52
0.30	0.86	0.74
0.40	1.14	0.94
0.50	1.22	0.82
0.60	1.52	1.02
0.70	1.98	1.28
0.80	2.29	1.39
0.90	2.77	1.67
1.00	2.88	1.48

Also, it can be concluded from this figure that as the electrical current increases, the difference between heating and cooling rises. This is due to the fact that the electrical power is a quadratic function of the current and its slope increases as the current rises.

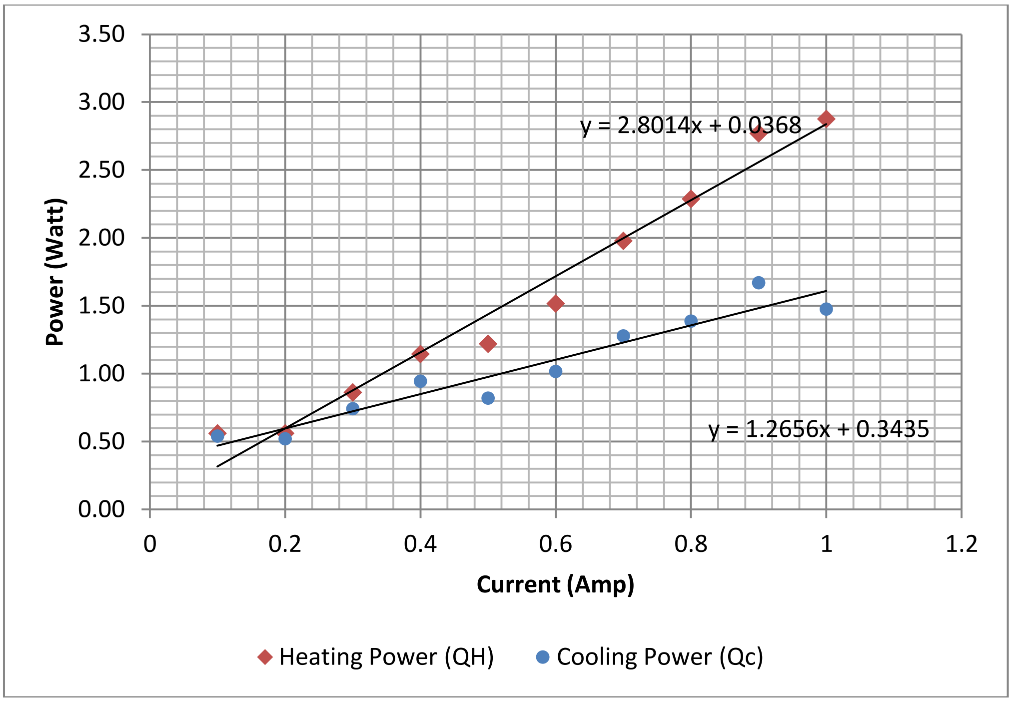

Figure 4. 4 Heating and cooling power vs. current.

Regarding the heating and cooling power lines, root mean square error (i.e. RMS error) can be calculated. These calculations are presented in appendix.

Another important parameter of the Peltier element is its performance. Since it works as a heat pump, the "coefficient of performance" (i.e. COP) can be defined as the ratio of total heating power over the supplied electrical power.

$$COP_{HP} = \frac{\dot{Q}_{heat}}{\dot{W}_{electric}} \tag{4.2}$$

It is also calculated for different electrical currents and illustrated in Table4.4 and Fig.4.5.

Table 4.4 Coefficient of performance (COP) vs. current.

Electrical Current (Amp)	**Coefficient of Performance (COP)**
0.10	28.03
0.20	14.01
0.30	7.19
0.40	5.72
0.50	3.05
0.60	3.03
0.70	2.83
0.80	2.54
0.90	2.52
1.00	2.05

According to this figure, the values of COP are at high ranges for lower electrical current. For instance, the COP for the current of 0.1 is about 28. As the electrical current increases, the COP values decrease so that they lay within a range of about 2.5.

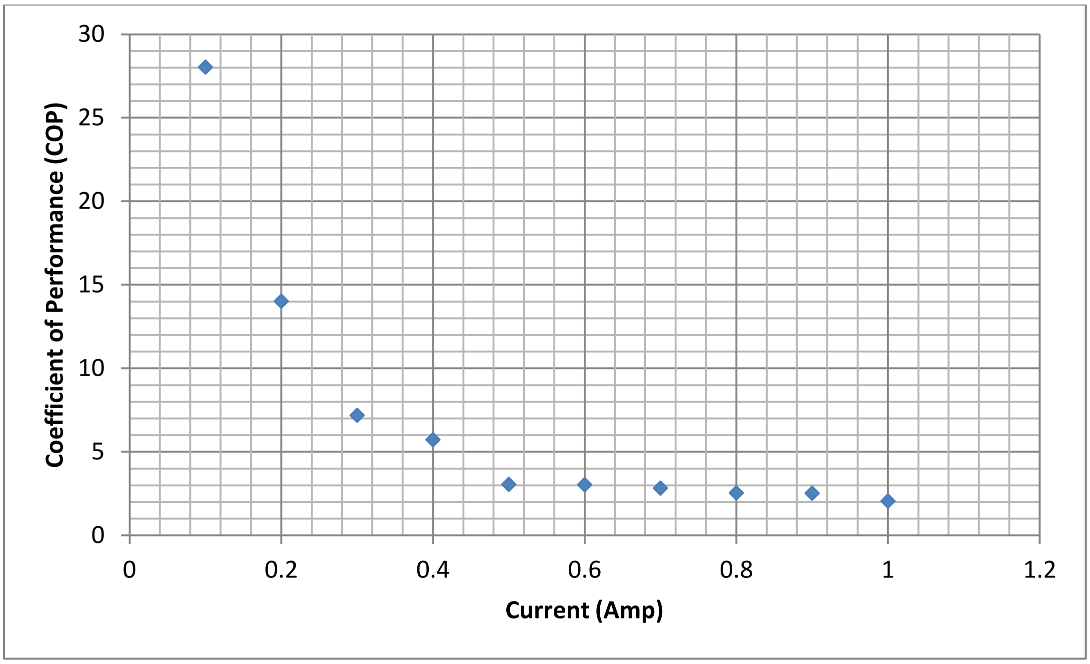

Figure 4. 5 Coefficient of performance (COP) vs. current

Moreover, it is possible that the maximum temperature at the hot face of the Peltier be measured. Since the Aluminum cube is small enough, from the temperature at its center, the temperature at the Peltier face can be determined from the equation of conduction as:

$$Q = kA\frac{T_{hotface} - T_{center}}{\Delta x} \rightarrow T_{hotface} = T_{center} + \frac{Q.\Delta x}{kA} \quad (4.3)$$

However, regarding high thermal conductivity of Aluminum, the difference between these two temperatures can be negligible. Also, the Peltier element was connected to the cube from its cold side to cool the cube down and this cooling effect can be directly measured. Measuring the temperature difference with respect to time, the cooling effect and the minimum temperature can be calculated. The results are demonstrated in Table4.5 and Fig.4.6.

Table 4.5 Maximum and minimum temperatures vs. current.

Electrical Current (Amp)	**Maximum Temperature (^{0}C)**	**Minimum Temperature (^{0}C)**
0.10	31.07	20.72
0.20	31.03	20.88
0.30	32.94	19.13
0.40	35.22	17.53
0.50	37.34	18.51
0.60	39.09	16.96
0.70	41.35	14.89
0.80	43.20	14.03
0.90	44.76	11.79
1.00	47.40	10.99

Figure.4.6 shows the minimum and maximum temperatures of the Peltier element according to the different currents to be 47.40 and 10.99 at the current of 1.00 Ampere.

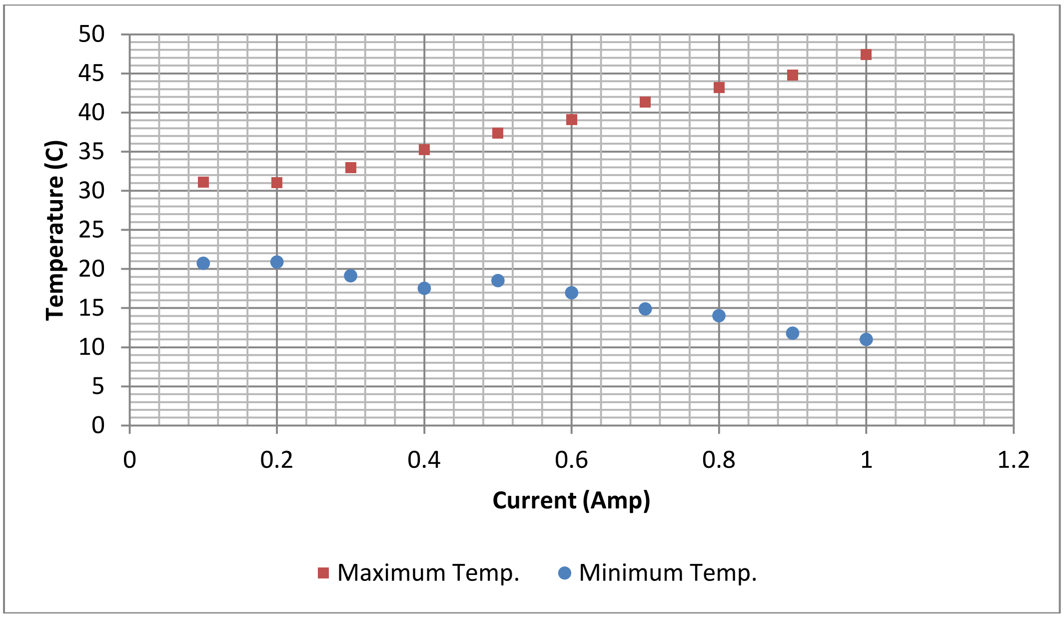

Figure 4. 6 Maximum and minimum temperatures of Peltier element.

4.2 Case Study

After calibrating the Peltier element, thermal conductivity of a sample material can be measured. The correctness of the Peltier calibration results can be verified due to these thermal conductivity measurements. Therefore, two metal samples were selected from Aluminum and Brass. The sample shapes were rectangular cubes of cross sections of 25 mm × 25 mm. Also, their heights are 67 and 78 mm, respectively. The experiment is designed such that two Peltier elements were attached to the top and bottom of the cube, while, the side walls of the cube were fully isolated. Then, the Peltier elements were subjected to heating from the top and cooling from the bottom in a way that a constant heat flowed within the cube and steady state condition was achieved. Since steady state condition is of concern for this experiment, the heating power to the top and cooling power from the bottom have to be equal. For instance, regarding Fig.7, when the current is 1 Amp, the cooling power is equal to the heating power at 0.6 Amps. It can be written as

$$I = 1\ Amp \rightarrow \dot{Q}_{cooling} = 1.5\ W \tag{4.4}$$

$$I = 0.6\ Amps \rightarrow \dot{Q}_{Heating} = 1.5\ W \tag{4.5}$$

Therefore, the current of the Peltier element at the top is set to 0.6 Amps and for the Peltier element at the bottom is set to 1 Amp, to have approximately constant heat flux within the sample. Figure4.7 shows the schematic of this experiment.

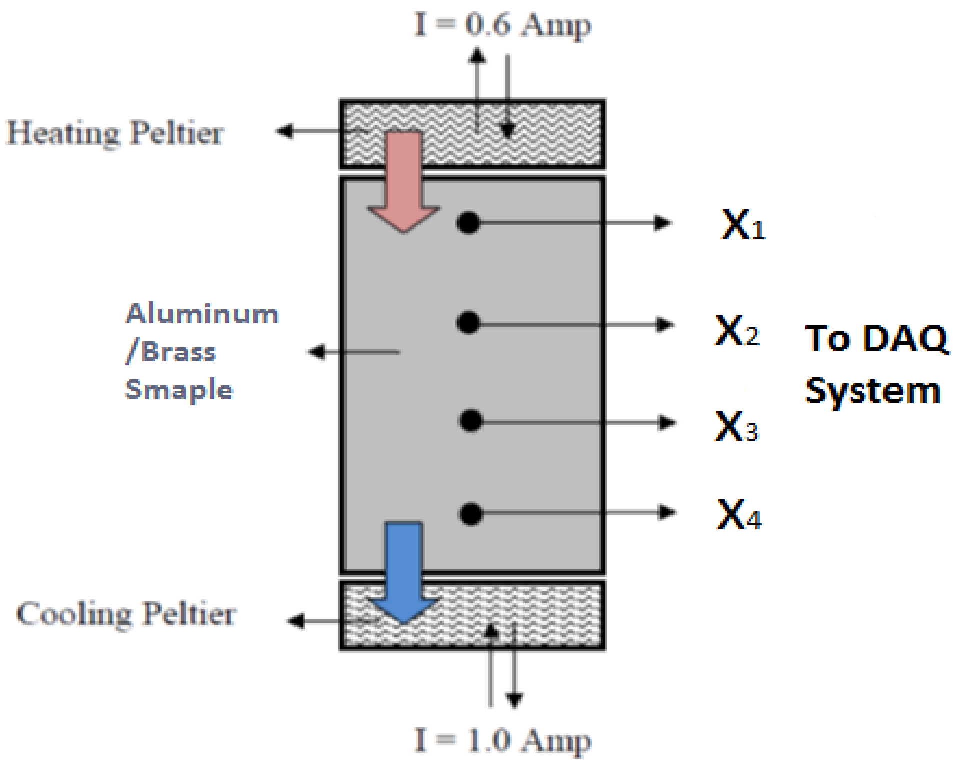

Figure 4. 7 Measuring thermal conductivity of Aluminum/ Brass samples.

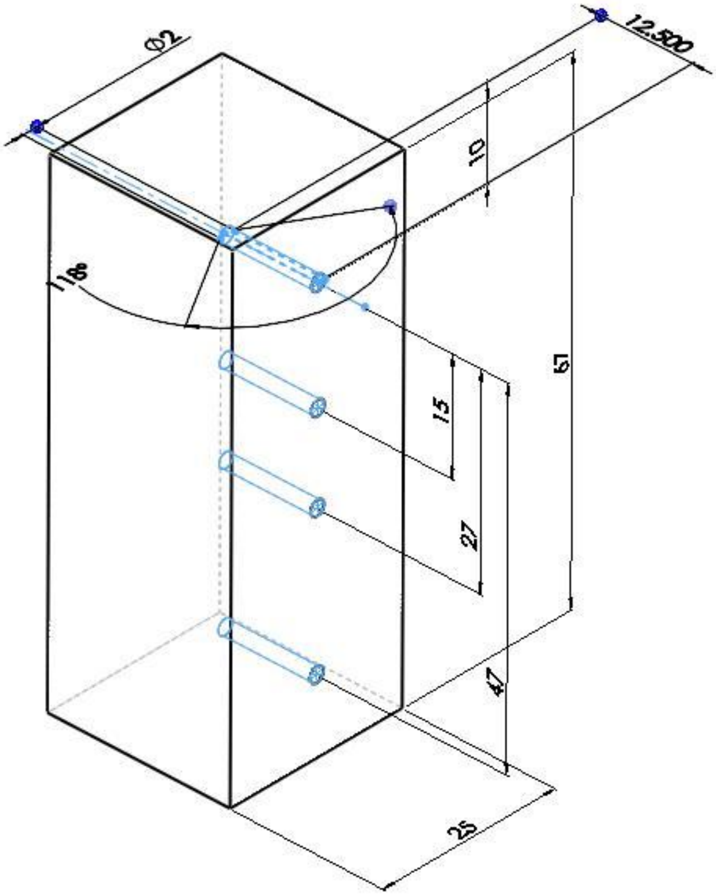

Figure 4. 8 schematic of sample Cubic Prism.

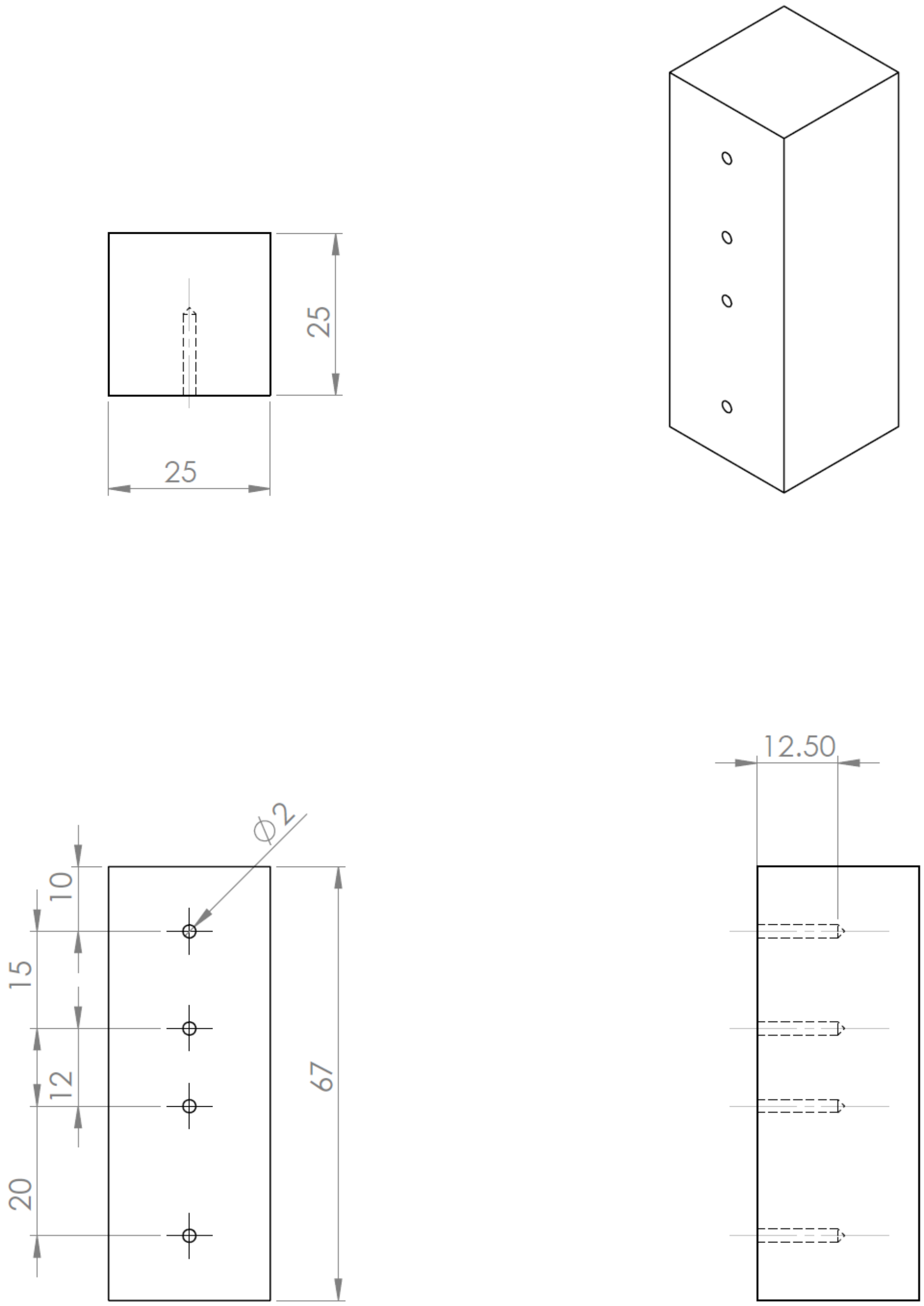

Figure 4. 9 schematic of sample Cubic Prism.

The DAQ system started to record temperatures until the steady conditions were obtained. It has to be emphasized that, in the steady conditions, the temperature distribution within the sample should be linear which means a constant temperature gradient. Another important point about these experiments is that because of constant heating and cooling from the top and the bottom of the samples, the temperature in the sample would hardly change, meaning that the sample would neither be heated nor cooled. Therefore, the range of temperatures can be controlled by starting heating or cooling earlier. After about 1 hour, the temperatures at the four points were constant with respect to time and thus, the steady conditions achieved.

As to the Aluminum sample, the thermocouple positions from the bottom are 10, 25, 37, and 57 mm. Each hole is drilled to the center of the cube and thus the depth of them is 12.5 mm. According to the obtained temperature results, the average temperatures at the points were 41.20, 41.00, 40.81, 40.55 degree Celsius. The temperature distribution is also illustrated in Table4.6 and Fig.4.8.

Table 4.6 Temperature distribution in the Aluminum sample.

Thermocouple Position (mm)	**Temperature (^{0}C)**
10	41.20
25	41.00
37	40.81
57	40.55

It is better to separate the four points to two sets to get the more accurate slopes. The more close the slopes, the more accurate the results. According to this figure, the two lines have absolute slopes of 13.33 ^{0}C/m and 13 ^{0}C/m. Then, it is appropriate to take the average of temperature gradients about 13.17 ^{0}C/m. Therefore, the thermal conductivity of Aluminum can be calculated from:

$$k = \frac{\dot{Q}}{A.\frac{dT}{dx}} \tag{4.6}$$

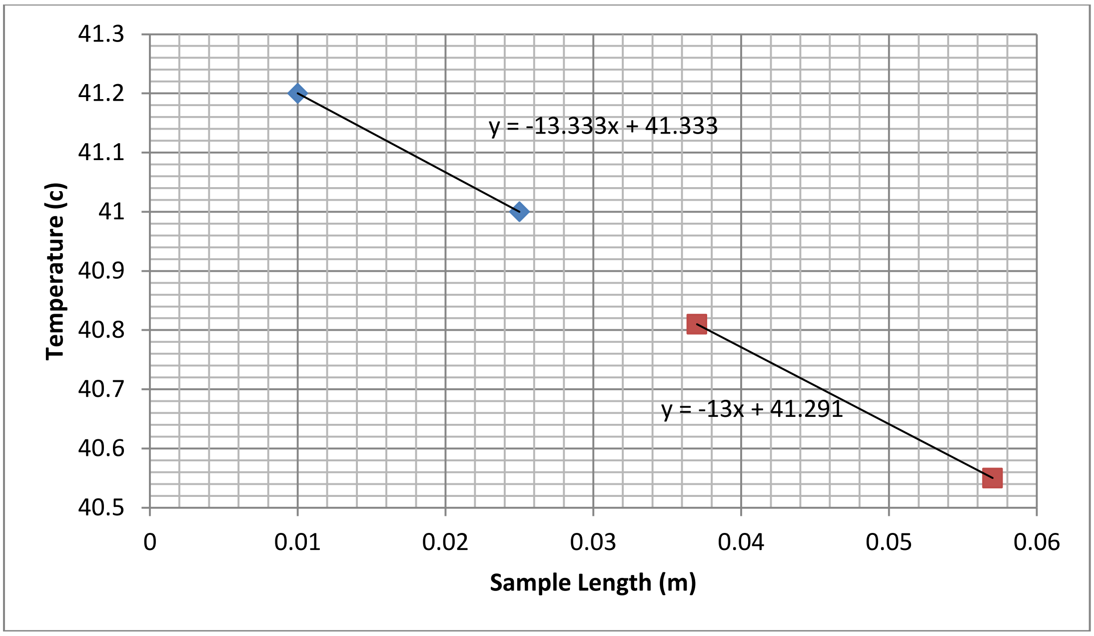

Figure 4. 10 Temperature distribution within the Aluminum sample.

According to Fig.4.8, the temperature gradient can be obtained as:

$$\frac{dT}{dx} = 117\ ℃/m\ , \qquad A = 0.000625\ m^2\ , \quad Q = 1.5\ W \tag{4.7}$$

Therefore, thermal conductivity of Aluminum can be calculated as 182.23 W/m. ^{0}C, which is given in the literature as about 190 W/m. ^{0}C. Thus, the relative error amount of this experiment is:

$$Error = \frac{|190-182.23|}{190} \times 100 = 4\% \tag{4.8}$$

This error was produced form different sources such as uncertainty in the amount of heat transfer including power supply and Peltier elements, insulation weakness, incomplete contact heat conduction with the Peltier elements, temperature reading errors, and human errors.

Also, as to the Brass sample, the thermocouples positions were 8.50, 28, 47.50, and 67 mm. The corresponding temperature obtained at each thermocouple is shown in Table4.7.

Table 4.7 Temperature distribution in the Brass sample.

Thermocouple Position (mm)	**Temperature (^{0}C)**
8.50	37.50
28.00	37.03
47.50	36.54
67.00	36.06

The temperature gradient is calculated and illustrated in Fig.4.9. The upper and lower slopes are calculated as 24.10 ^{0}C/m and 24.62 ^{0}C/m. Therefore, regarding Eq.4.6, thermal conductivity of Brass can be obtained as 98.53 W/m. ^{0}C. Then the error can be calculated according to the given thermal conductivity of Brass as 105 as W/m. ^{0}C:

$$Error = \frac{|105-98.53|}{105} \times 100 = 4.5\% \qquad (4.9)$$

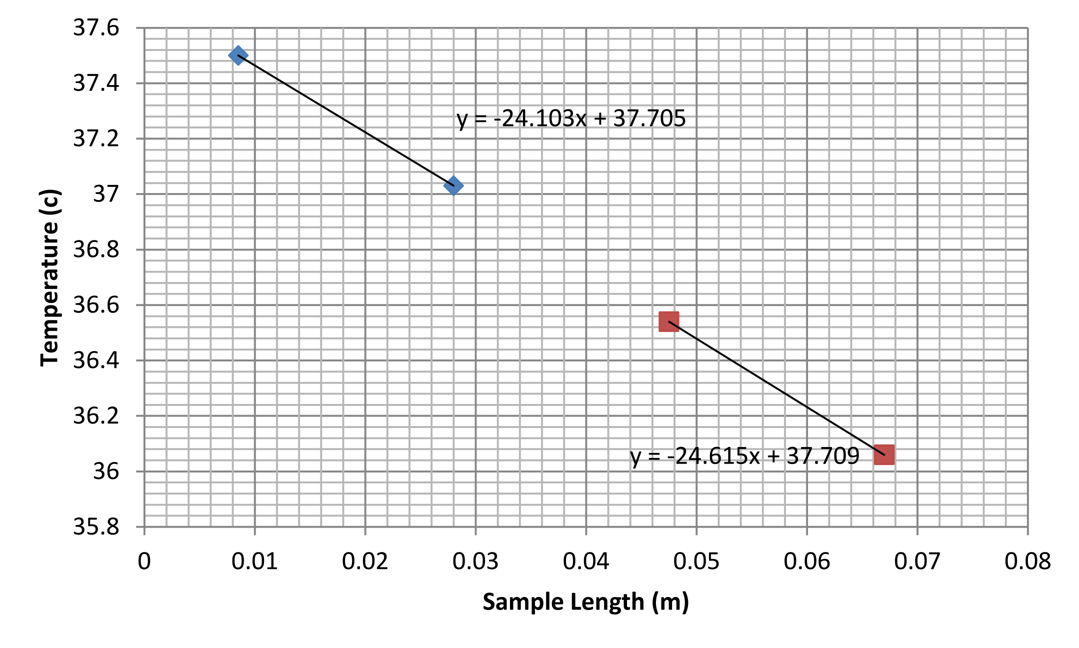

Figure 4. 11 Temperature distribution within the Brass sample.

4.3 Uncertainty and Error Analysis

Regarding the uncertainties of the measured parameters such as temperature, length, and electrical voltage and current, an error occurs when calculating thermal conductivity of the samples. Therefore, the error related to the uncertainties can be calculated as following:

For a parameter 'z' which is a function of two parameters 'x' and 'y' such as z = x.y or z = x/y, the uncertainty of 'z' can be expressed as:

$$\frac{\Delta z}{z} = \sqrt{\left(\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2\right)} \tag{4.10}$$

Then, the relation of thermal conductivity from Fourier's law can be shown as

$$k = \frac{Q}{A\frac{dT}{dy}} = \frac{F}{G} \tag{4.11}$$

The uncertainty of 'k' can be

$$\frac{\Delta k}{k} = \sqrt{\left(\left(\frac{\Delta F}{F}\right)^2 + \left(\frac{\Delta G}{G}\right)^2\right)} \tag{4.12}$$

F is the heat transfer within the sample and ΔF is the uncertainty of heat transfer. The heat transfer was previously determined from temperature increase in the cube as

$$Q = mc\Delta T \tag{4.13}$$

Parameter 'c' is assumed to be constant and uncertainty of 'Q' depends on the uncertainties of the cube mass and the temperature which come from the scaling device and DAQ system, respectively. Taking Δm = 0.0001 and ΔT = 0.0001, the heat transfer error is

$$\frac{\Delta F}{F} = \frac{\Delta Q}{Q} = \sqrt{\left(\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta m}{m}\right)^2\right)} = \sqrt{\left(\left(\frac{0.0001}{30}\right)^2 + \left(\frac{0.0001}{0.043}\right)^2\right)} = 5.4 \times 10^{-6} \tag{4.14}$$

Moreover, uncertainty of the parameter G is calculated according to the Eq.4.11 from uncertainty ΔA. 'A' is the area of the sample and equals 25 mm × 25 mm. It is appropriate to take the uncertainty of each side to be Δx = 0.1 mm.

$$\frac{\Delta G}{G} = \frac{\Delta A}{A} = \sqrt{2\left(\frac{\Delta x}{x}\right)^2} = \sqrt{2.\left(\frac{0.1\times 10^{-3}}{25}\right)^2} = 5.7 \times 10^{-6} \tag{4.15}$$

Finally, the total uncertainty is calculated as following

$$\frac{\Delta k}{k} = \sqrt{\left(\frac{\Delta F}{F}\right)^2 + \left(\frac{\Delta G}{G}\right)^2} = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta A}{A}\right)^2} = 5.5 \times 10^{-6} \qquad (4.16)$$

Then the uncertainty of thermal conductivity (i.e. Δk) is

$$\Delta k_{Aluminum} = 0.0011 \qquad (4.17)$$

$$\Delta k_{Brass} = 0.0005 \qquad (4.18)$$

Chapter 5

CONCLUSION

In this study, an experimental method is developed in order to calibrate a Peltier element. To do so, a Peltier element of model TEC1-4905 and size $25mm \times 25mm$ was used for the calibration process. The calibration method was performed based on measuring the amount of heat generated by the element according to different electrical currents. According to the obtained results, the total heating and electrical power, generated by the Peltier element were measured. Also, the cooling power was calculated regarding the energy balance of the device. The energy balance was based on the operation of a heat pump. Then, the coefficient of performance, as the electrical power over the heating power, was calculated. Also, the maximum and minimum temperature created at the hot and cold sides of the Peltier element were measured. Based on the calibration results, in order to verify them, another experiment was performed to measure the thermal conductivity of a sample. The energy equation is also solved within the sample using the experimental thermal conductivity to demonstrate and compare the experimental and numerical temperature profiles within the sample.

REFERENCES

[1] Velmre, E. (2007). Thomas Johann Seebeck (1770–1831). Journal of Proceedings of the Estonian Academy of Sciences. Eng., 1-3.

[2] http://en.wikipedia.org/wiki/Heinrich_Gustav_Magnus.

[3] Slack, G. (1995). CRC Handbook of Thermoelectrics. CRC Press .

[4] Thomson, W. (1851). On the Dynamical Theory of Heat. Transactions of the Royal Society of Edinburgh, 7-10.

[5] Ur, R. R. (1961). Thermoelectricity: Science and Engineering. Intercience Publishers.

[6] Iordanishvili, M. V. (1998) AF Ioffe and origin of modern semiconductor thermoelectric energy conversion. 17th International Conference on Thermoelectric. Nagoya: Thermoelectrics. (pp. 37-42).

[7] Douglas, H. J. (1954). The use of semiconductors in thermoelectric refrigeration. British Journal of Applied Physics, 386.

[8] Toberer, G. J. (2008). Complex Thermoelectric Materials. Journal of Nature Materials, 105-114.

[9] Bell, L. (2008). Cooling, Heating, Generating Power, and Recovering Waste Heat with Thermoelectric Systems. Journal of Science Vol.321, 1457-1461.

APPENDIX

Table A.1. Averaged heating power with different currents (shown in Fig.4).

Time (sec)	**Current (Amp)**									
	0.100	**0.200**	**0.300**	**0.400**	**0.500**	**0.600**	**0.700**	**0.800**	**0.900**	**1.000**
1.000	0.460	0.460	0.153	-3.686	-3.316	-1.110	-0.758	-0.460	2.157	-1.104
2.000	-1.599	-1.599	-0.343	-0.967	-1.441	0.104	0.961	1.309	1.318	-0.385
3.000	-0.768	-0.768	-0.060	-0.317	-0.455	0.632	2.137	1.619	1.838	1.905
4.000	0.230	0.230	-0.023	0.078	-0.166	-0.087	1.406	1.767	2.952	2.491
5.000	-0.286	-0.286	0.403	0.978	0.169	0.944	1.739	1.068	3.312	1.767
6.000	0.540	0.540	0.432	0.392	0.191	0.621	1.762	1.923	2.239	2.503
7.000	0.410	0.410	0.508	0.553	1.456	0.603	1.758	2.045	2.275	2.125
8.000	0.424	0.424	0.505	0.659	0.645	1.582	1.739	2.013	2.265	2.207
9.000	0.343	0.343	0.561	1.110	0.729	1.261	2.269	2.043	2.432	2.629
10.000	0.580	0.580	0.668	0.704	1.142	1.370	1.821	2.101	2.444	2.282
11.000	0.470	0.470	0.380	0.686	1.114	1.335	1.896	1.748	2.530	2.826
12.000	0.713	0.713	0.627	1.036	1.195	1.298	1.901	2.151	2.651	2.837
13.000	0.542	0.542	0.683	1.148	1.174	1.303	1.932	2.178	2.597	2.890
14.000	0.574	0.574	0.709	0.855	0.974	1.282	1.907	2.215	2.645	2.624
15.000	0.572	0.572	0.821	1.093	1.012	1.349	1.932	2.221	2.860	2.631
16.000	0.553	0.553	0.730	1.062	1.054	1.426	2.024	2.298	2.687	2.652
17.000	0.541	0.541	0.800	1.095	1.047	1.342	1.944	2.210	2.696	2.682
18.000	0.587	0.587	0.799	0.981	1.029	1.250	1.980	2.244	2.906	2.736
19.000	0.541	0.541	0.783	0.929	1.241	1.460	1.964	2.272	2.663	2.693
20.000	0.535	0.535	0.778	0.983	1.060	1.465	1.932	2.165	2.886	2.923
21.000	0.549	0.549	0.813	1.201	1.277	1.461	1.992	2.339	2.861	2.985
22.000	0.559	0.559	0.827	0.966	1.165	1.477	2.031	2.323	2.740	2.783
23.000	0.548	0.548	0.854	1.003	1.189	1.668	2.028	2.285	2.870	2.888
24.000	0.585	0.585	0.886	1.029	1.293	1.522	2.003	2.319	2.864	2.959
25.000	0.575	0.575	0.856	1.019	1.186	1.523	1.975	2.450	2.724	2.824
26.000	0.560	0.560	0.860	1.057	1.159	1.501	1.989	2.344	2.879	2.980
27.000	0.564	0.564	0.878	1.189	1.151	1.527	2.002	2.345	2.855	2.835
28.000	0.551	0.551	0.879	1.187	1.314	1.522	1.986	2.371	2.863	2.948
29.000	0.647	0.647	0.884	1.220	1.330	1.526	1.975	2.338	2.768	2.961
30.000	0.536	0.536	0.884	1.215	1.196	1.541	2.001	2.342	2.890	2.969
31.000	0.528	0.528	0.758	1.187	1.331	1.556	1.996	2.359	2.863	2.842
32.000	0.514	0.514	0.885	1.322	1.229	1.569	1.981	2.362	2.713	2.955
33.000	0.522	0.522	0.894	1.238	1.220	1.559	2.076	2.241	2.770	2.877
34.000	0.523	0.523	0.899	1.238	1.207	1.572	1.991	2.396	2.854	2.879
35.000	0.501	0.501	0.897	1.211	1.200	1.541	1.974	2.359	2.754	2.947
36.000	0.513	0.513	0.914	1.156	1.314	1.539	1.987	2.353	2.830	2.941
37.000	0.539	0.539	0.913	1.145	1.314	1.572	1.983	2.348	2.732	2.994
38.000	0.503	0.503	0.899	1.237	1.220	1.576	1.997	2.367	2.752	2.900
39.000	0.546	0.546	0.901	1.221	1.309	1.575	2.013	2.355	2.871	2.962
40.000	0.521	0.521	0.923	1.239	1.313	1.581	2.003	2.351	2.792	2.877

41.000	0.512	0.512	0.928	1.235	1.319	1.594	1.983	2.342	2.775	2.956
42.000	0.550	0.550	0.928	1.170	1.288	1.613	1.982	2.312	2.775	2.875
43.000	0.550	0.550	0.937	1.236	1.294	1.576	1.982	2.314	2.751	2.974
44.000	0.517	0.517	0.921	1.234	1.203	1.586	2.078	2.349	2.750	2.941
45.000	0.538	0.538	0.933	1.242	1.227	1.574	2.062	2.315	2.839	2.972
46.000	0.537	0.537	0.937	1.230	1.270	1.587	2.002	2.316	2.805	2.957
47.000	0.607	0.607	0.921	1.221	1.295	1.597	1.989	2.321	2.743	2.966
48.000	0.546	0.546	0.934	1.225	1.272	1.579	1.950	2.234	2.807	2.964
49.000	0.531	0.531	0.935	1.284	1.310	1.565	1.978	2.300	2.736	2.871
50.000	0.606	0.606	0.929	1.238	1.219	1.564	1.955	2.304	2.734	2.882
51.000	0.621	0.621	0.942	1.273	1.200	1.573	1.974	2.299	2.815	2.882
52.000	0.619	0.619	0.929	1.215	1.212	1.574	2.040	2.328	2.805	2.936
53.000	0.537	0.537	0.943	1.174	1.217	1.560	1.977	2.290	2.756	2.956
54.000	0.605	0.605	0.933	1.206	1.254	1.567	1.968	2.229	2.805	2.930
55.000	0.618	0.618	0.935	1.218	1.293	1.561	1.958	2.280	2.722	2.952
56.000	0.617	0.617	0.940	1.220	1.264	1.560	1.960	2.278	2.771	2.923
57.000	0.546	0.546	0.931	1.216	1.288	1.567	1.961	2.271	2.770	2.924
58.000	0.619	0.619	0.947	1.269	1.293	1.622	1.950	2.278	2.773	2.929
59.000	0.610	0.610	0.954	1.220	1.254	1.566	1.961	2.278	2.749	2.904
60.000	0.609	0.609	0.940	1.209	1.293	1.566	1.950	2.257	2.766	2.893
AVG	0.561	0.561	0.862	1.145	1.220	1.516	1.978	2.287	2.770	2.876

B. Root Mean Square Error Calculations

According to the curve fittings applied to the heating and power values (i.e. Fig.4.4), deviations occur at each point. The root mean square error of a parameter ‘x’ which has ‘n’ values, can be calculated as following

$$RMS = \sqrt{\frac{\sum x_i^2}{n}} \tag{B.1}$$

Regarding Table.4.3, the above formula is calculated for heating and cooling lines as 1.78 and 1.11, respectively.