ENR 370
REPORT

SEEBECK EFFECT : CHARACTERIZATION OF THE INDUCED VOLTAGE WITH RESPECT TO THE TEMPERATURE GRADIENT

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ABSTRACT

Based on the theoretical predictions given by the Boltzmann transport equation and the concept of energy bands, natural phenomenon such as thermoelectric effects such as the Seebeck Effect, the Peltier Effect, Thomson Effect are a very inquisitive mode of study for these theoretical predictions. Thermoelectrics play a very important role in our day to day life. Seebeck Effect is the phenomenon of generating emf from a temperature gradient across two dissimilar metals. Peltier effect is the inverse of Seebeck Effect where a heat current is generated due to the induction of emf in dissimilar metals. These phenomenon can be used in real world applications to create clean ways of producing energy since these can be paired up with other renewable energy sources and carbon neutrality can be achieved. Since the only drawback of thermoelectric generators is very low efficiency of around 15-20% [1], with the increment in our understanding of materials and resources, better and more efficient products can be created to help us into a better lifestyle. Seebeck and Peltier effects are the most widely used and applied transport phenomenon for the purposes of Thermoelectric Power Generation and Thermoelectric Refrigeration. The applications range from measuring temperatures as temperature sensors, cooling electronic circuits in computers as peltier coolers, controlling the optimum temperature for various HVAC applications, cryogenics, climate control systems to regulate temperature, thermal imaging cameras etc. The experiment performed was initially constructed to use as a demonstration experiment to budding physicists and engineering students as an economical yet very enlightening experiment to pique their interests in the physics and instrumentation of thermoelectric phenomenon and understand their practical applications. The experimental was later on was expanded to measure the characteristics of the induced voltage versus the given temperature gradient.

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NOMENCLATURE

Table 1. Nomenclature Symbols and Abbreviations

Acronym/Symbol	**Term**	**Definition**
S	Seebeck Coeffecient	The Seebeck coefficient of a material is a measure of the magnitude of an induced thermoelectric voltage in response to a temperature difference across that material, as induced by the Seebeck effect
ΔT	Temperature Difference	The temperature difference between both the ends of the thermcouple
ΔV	Voltage Drop	The Open circuit Voltage drop across the capacitor
HVAC	Heating, Ventilation, and Air Conditioning	It contains technologies to regulate and maintain optimal indoor conditions in various settings
Boltzmann constant	k_B	The fundamental physical constant that relates the average kinetic energy of particles in a gas to the temperature of the gas.
Temperature	T	The measure of the average kinetic energy of particles in a system, determining the degree of hotness or coldness.
Elementary charge	e	The fundamental electric charge carried by a single electron or proton.
Electrical conductivity	σ	The measure of a material's ability to conduct electric current.
Fermi energy level	E_F	The energy level that represents the highest occupied state at absolute zero temperature in a system, often referred to as the Fermi level.

INTRODUCTION

In this section we will review the theoretical understanding behind the Seebeck Effect and the tranport equations required to understand the Seebeck Coefficient.

Seebeck Effect

- The Seebeck effect or the thermoelectric effect is a scientific phenomenon which takes places between two dissimilar metals when they are joined together and a heat current is passed between them. This heat current causes electrons to vibrate and spreading energies to the next electrons in line generating an emf between the hot junction and the cold junction which can be measured using a voltmeter.

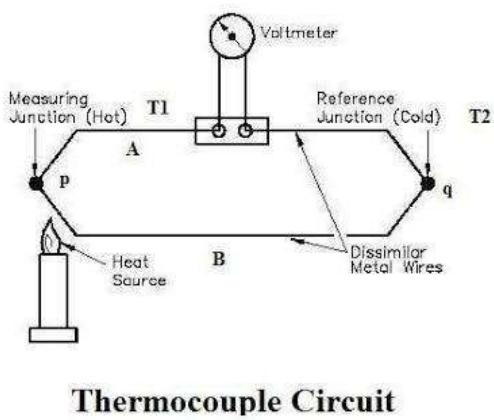


Figure 1. Thermocouple Circuit

- As we can from Fig. 1, there are two dissimilar metals which have been used in the thermocouple circuit. The two dissimilar metals in our experimental investigation are Aluminum(Al) and Copper(Cu).

- Again from Fig. 1, we can also see a heating source for the circuit. In our experimental investigation, hot water was used as a heat source to produce a temperature gradient across the ends of the thermocouple.

Seebeck Coefficient

- The Seebeck Coefficient can be defined as the voltage build up when a small temperature gradient is applied to the thermocouple at a steady state when the current density is zero throughout the thermocouple.

- The Seebeck Coefficient is given by the equation

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

- The Seebeck coefficients generally vary as function of temperature and depend strongly on the composition of the conductor. For our experimental investigation the Seebeck Coefficient for Aluminum and Copper are given as $-1.5\mu V/°\text{C}$ and 1.5 $\mu V/°\text{C}$ respectively at 0°C.

- Seebeck coefficient's sign is the sign of the potential of the cold end with respect to the hot end.

- The underlying theory behind the Seebeck Coefficient is given by the Boltzmann Transport Equation and the equation for the same assuming single band model and low electric fields is given by

$$S = -\frac{\pi^2 k_B^2 T}{3e} \left(\frac{d \ln \sigma}{dE} \right)_{E=E_F} \tag{2}$$

METHODOLOGY

Instrumentation

- Keithley 2450 Sourcemeter
  - The Keithley 2450 Source is a four quadrant power supply with the built in capabilities for supplying voltages up to 200 Volts and 1 Ampere, which is shown in the Fig. 2

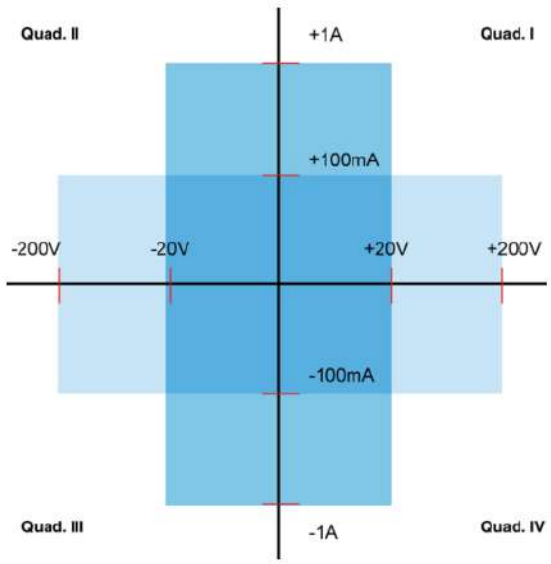


Figure 2. Keithley 2450 Sourcemeter Power Capabilities

  - The Keithley 2450 Sourcemeter also works as a digitial multimeter with built in ammeter, voltmeter, and ohmmeter. It can measure upto the resolution of 10 Nano Volts for the voltmeter, 10 Femto Amperes for the ammeter. All of these readings are done with maximum 6.5 significant digits with 1 reading per second to 3.5 digits at 1700 readings per second.
  - The Source Measurement unit can measure voltage, current, resistance, and power by either giving a source voltage or a source current by using a four probe measurement. The unit can also do a two probe measurement when it can measure the same quantities without giving a source voltage or source current.

- For our experimental investigation, two probe measurement for measuring the induced voltage was used with the resolution of 1 reading per second with 6.5 significant digits.

- MAX6675 Module With K Type Thermocouple Sensor

Figure 3. MAX6675 Module with K Type Thermocouple Sensor

  - The MAX6675 Module K Type Thermocouple Temperature sensor makes use of the Maxim MAX6675 K-Thermocouple to digital converter IC to provide a micro controller compatible digital serial interface (SPI compatible) for giving an accurate temperature compensated measurement of the supplied K-Type thermocouple sensor.
  - It has a 12-bit resolution providing temperature readings from 0°C to 1024°C (max temperature of the supplied sensor is 450°C) with a resolution of 0.25°C.
  - It is then connected to an Arduino board in this case an Arduino UNO R3 which is a standard development board to work with sensors using the Serial Peripheral Interface(SPI).

– For our experimental investigation two of these modules were attached to both of the hot and cold junctions of the thermocouple. The delay for the readings was set to one second so that the readings from the source meter and the thermocouple sensor readings can be interfaced and a scientific analysis of Induced Voltage versus Temperature gradient from the difference of the temperatures of the hot junction and cold junction can be carried out.

- Arduino UNO R3

  – The Arduino Uno is a popular open-source micro controller board that simplifies the process of building electronic circuits. It combines a physical programmable circuit board, typically featuring a micro controller, with software code running on a computer. The board is powered by the ATmega328P micro controller, an 8-bit chip with a flash memory capacity of 32k bytes. It offers 14 digital input/output pins, 6 analog inputs, and utilizes a 16 MHz quartz crystal oscillator. The pinout of the Arduino UNO R3 is shown in the Fig. 4

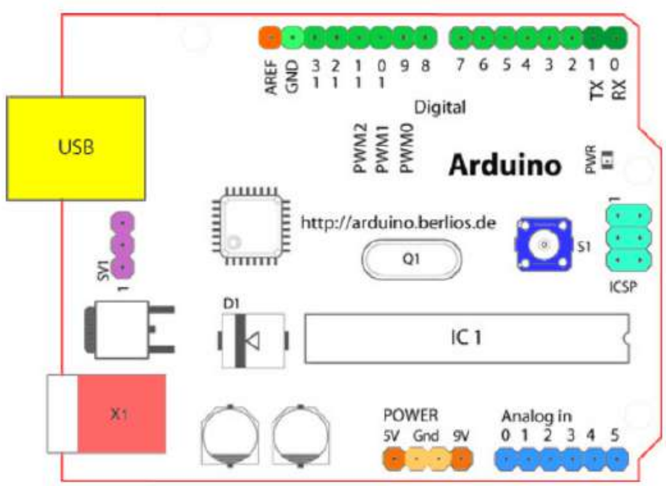


Figure 4. Arduino UNO R3 pinout diagram

   * It connects with the computer using a USB B to USB A connector which is used to send data to the computer using the Serial Peripheral Interface and the computer

in turn is used to power the controller.

* The temperature data is then logged using the serial monitor of the Arduino IDE, from where it was collected and stored in a text file. Later on it was interfaced with the data from the Keithley source meter.
* The code for the same is given as follows

```
#include <max6675.h>

int thermoSO1 = 13;
int thermoCS1 = 12;
int thermoSCK1 =11;
int thermoSO2 = 6;
int thermoCS2 = 5;
int thermoSCK2 = 4;


MAX6675 thermocouple1(thermoSCK1, thermoCS1, thermoSO1);
MAX6675 thermocouple2(thermoSCK2, thermoCS2, thermoSO2);


void setup() {
  Serial.begin(9600);
  Serial.println("MAX6675 temperature");
  // wait for MAX chip to stabilize
  pinMode (Pwr,OUTPUT);
  digitalWrite (Pwr,HIGH);
  delay(500);
}

void loop() {

  Serial.print("C of thermocouple 1 = ");
  Serial.println(thermocouple1.readCelsius());
```

```
  delay (1);
  Serial.print("C of thermocouple 2 = ");
  Serial.println(thermocouple2.readCelsius());
  delay(1000);
}
```

Experimental Setup

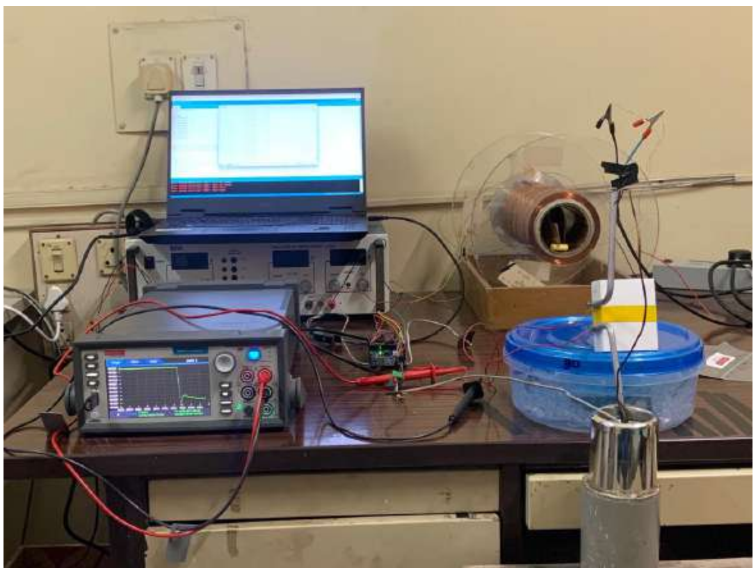


Figure 5. Experimental Setup

The recording apparatus was placed in a room where environmental factors were taken into consideration. We set up the thermocouple in such a way that the hot junction was dipped into the water which was collected in a stainless steel container as shown in Fig. 5 The environmental conditions and the inherent static noise were also taken into consideration during our experimental investigation. The possibility of another aluminum-chromium junction and natural convection were also taken into consideration for the analysis of the data sets.

The data was collected for five configurations:

- Test 1: Data for the Cooling Curve was collected(Heated water at 62 degree Celsius was directly used to test the cooling curve)

- Test 2: Data for Cooling Curve was collected(Heated water at 45 degree Celsius was directly used to test the cooling curve)
- Test 3: Data for the Cooling Curve was collected(Heated water at 85 degree Celsius was directly used to test the cooling curve)
- Test 4: Data for the Cooling Curve was collected(Heated water at 72 degree Celsius was directly used to test the cooling curve)

Error Factors

There were several error factors including setup limitations and environmental factors which affected the readings for the experiment.

- Changes in Ambient Temperature
  - Due to the weather conditions several fluctuations in the ambient temperature were observed which affected the readings taken by the thermocouples. The ambient temperature readings fluctuated from the temperature of 28 °C to 33 °C.
- Chromium Aluminum Junction
  - A chromium wire was used to measure the induced voltage through the Aluminum Junctions of the Aluminum Copper Junctions, which caused deviations for the measurement of Seebeck Coefficient of the given thermocouple. Thus the Seebeck Coefficients for different conditions vary depending on the junction conditions and the ambient conditions.
- Natural Convection

- The water was heated and then kept in open environment to test the cooling characteristics of the thermocouple which would lead to the water having natural convection due to the temperature difference as the surface of the water slowly cools down making hot water rise up.
- This would lead to different readings depending on the depth at which the hot junction of the thermocouple was dipped into the water. This error was accounted for in our measurements and only the tip of the thermocouple was submerged into the hot water.

• Inherent Noise in the Surroundings

- Due to the testing room being in the main building and the copper wires acting like an antenna, there was some inherent noise present in the readings at the ambient temperature.
- To counter for the same, the experiment should be performed in a clean room without any electromagnetic fluctuations.

Data Analysis

For all the sections in data analysis, six plots were taken from each test data set. The time reading for all these plots was taken as the relative time recorded between each of the recordings taken by the Keithley 2450 Sourcemeter. The readings and inferences drawn from the data analysis were finding the variables such Voltage Drop, Temperature Gradient, and the Seebeck Coefficient for each of the test data sets. Then correlation graphs were plotted between each of these variables and curve analysis was performed. Curve fit was done using the scipy library of python, and five curves linear, quadratic, cubic, exponential, and logarithmic decay were taken as the standard curves. Each of these curves were defined in the following way:

• Linear

$$y = ax + b \tag{3}$$

- Quadratic

$$y = ax^2 + bx + c \tag{4}$$

- Cubic

$$y = ax^3 + bx^2 + cx + d \tag{5}$$

- Exponential

$$y = ae^{bx} + c \tag{6}$$

- Logarithmic

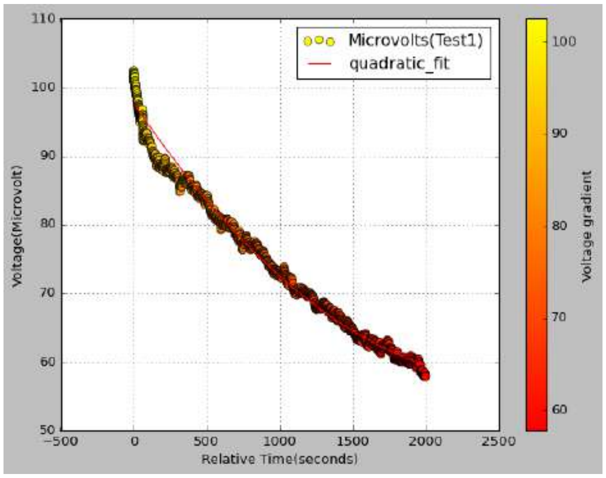
$$y = alogbx + c \tag{7}$$

After this all the correlation plots have been discussed separately in the given subsection with the best fit for each resulting plot along with the coefficients obtained for these plots.

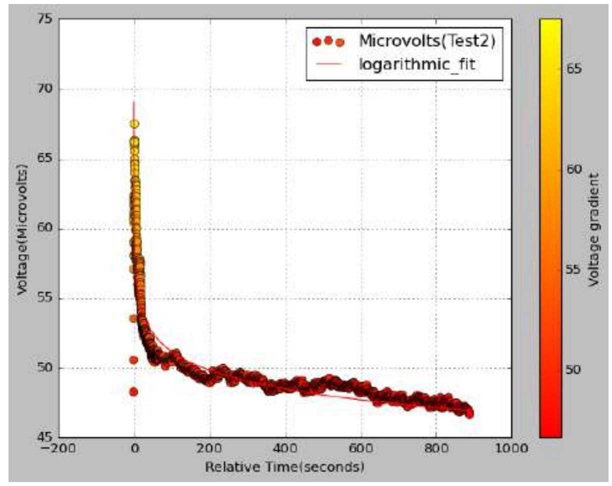
Graphs And Tables

Table 2. Curve Fit for Time Versus Voltage Analysis

Test Set	**Fit Curve**	**Coefficients**			
		a	**b**	**c**	**d**
1	Quadratic	-3.12862772e-02	6.10439647e-06	9.76836592e+01	0
2	Logarithmic	-1.93992919	27.68239251	66.55866725	0
3	Quadratic	-4.35322383e-02	6.39324488e-06	1.28542497e+02	0
4	Logarithmic	-3.55059457	64.72210119	87.06002236	0

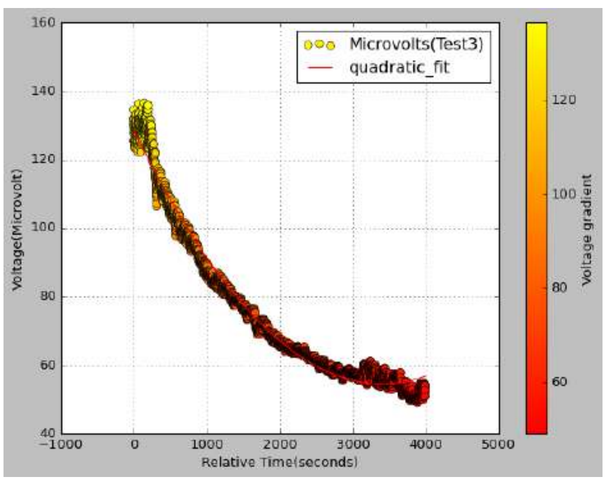


(a) Test 1

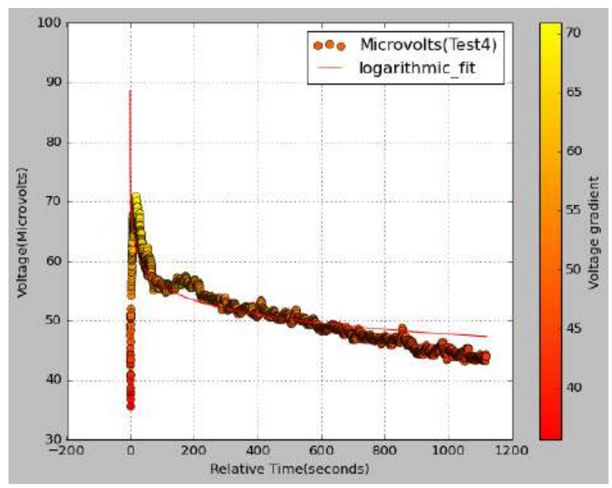


(b) Test 2

Figure 6. Voltage Versus Time Part 1



(a) Test3

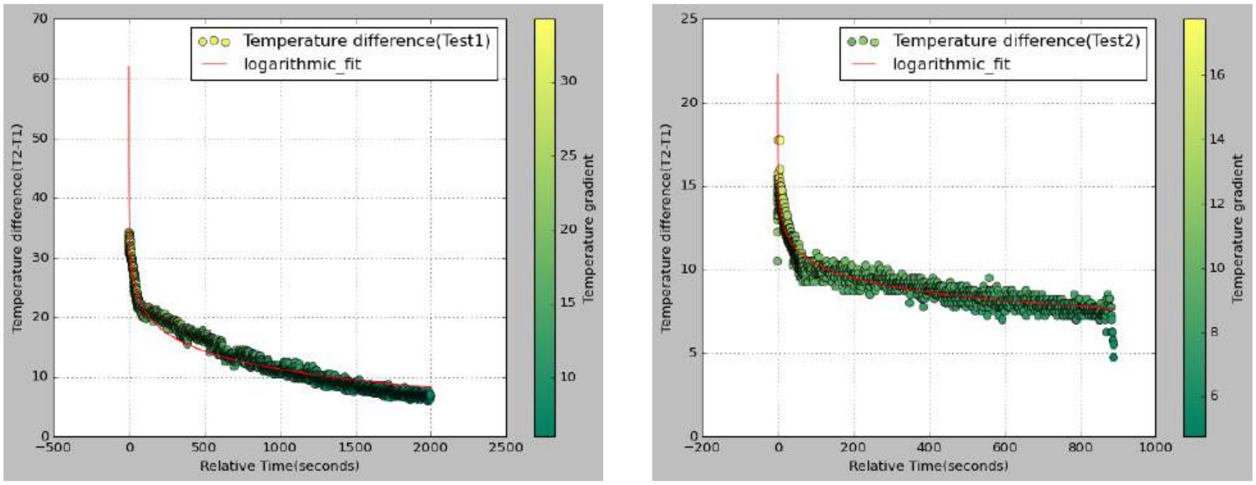


(b) Test4

Figure 7. Voltage Versus Time Part 2

Table 3. Curve Fit for Time Versus Temperature Gradient Analysis

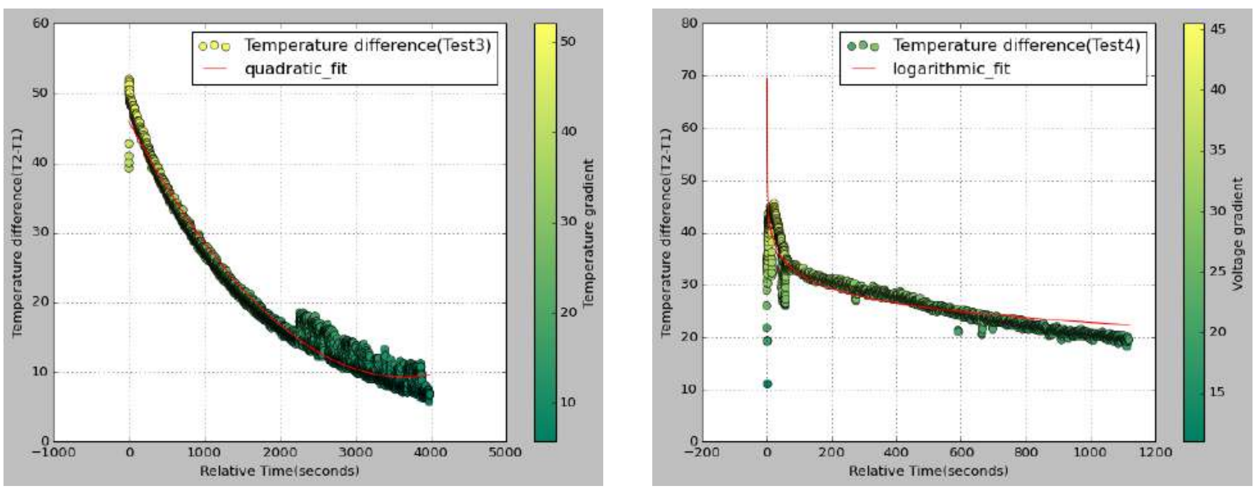
Test Set	**Fit Curve**	**Coefficients**			
		a	**b**	**c**	**d**
1	Logarithmic	-4.4040795	6.93492223	50.25657557	0
2	Logarithmic	-1.23105508	12.60326595	19.15007931	0
3	Quadratic	-2.00473157e-02	2.73424078e-06	4.59595110e+01	0
4	Logarithmic	-4.05220376	44.33976309	66.1442041	0



(a) Test 1

(b) Test 2

Figure 8. Temperature Gradient Versus Time Part 1



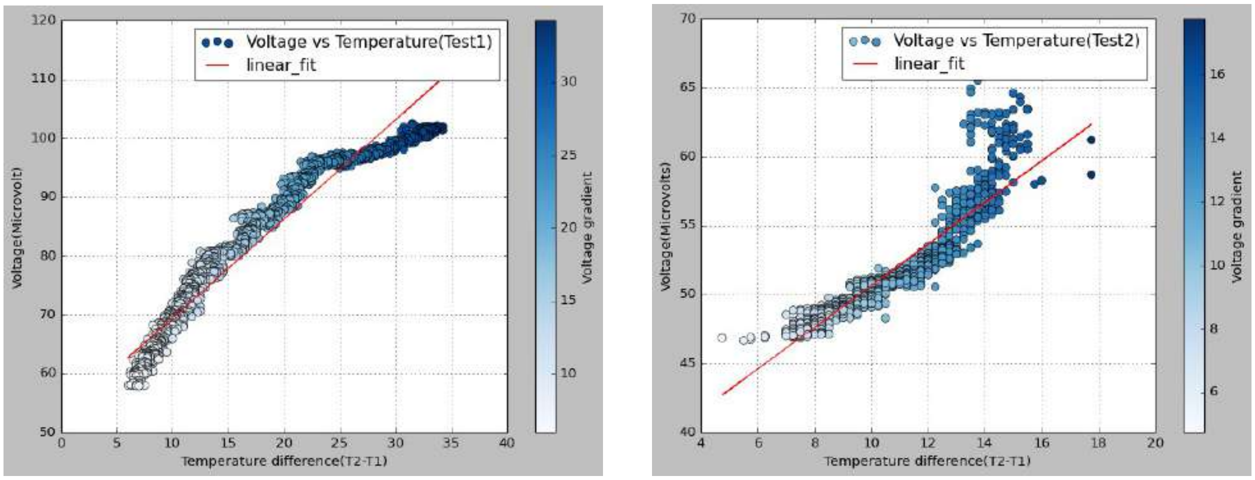
(a) Test3

(b) Test4

Figure 9. Temperature Gradient Versus Time Part 2

Table 4. Curve Fit for Induced Voltage versus Temperature Gradient

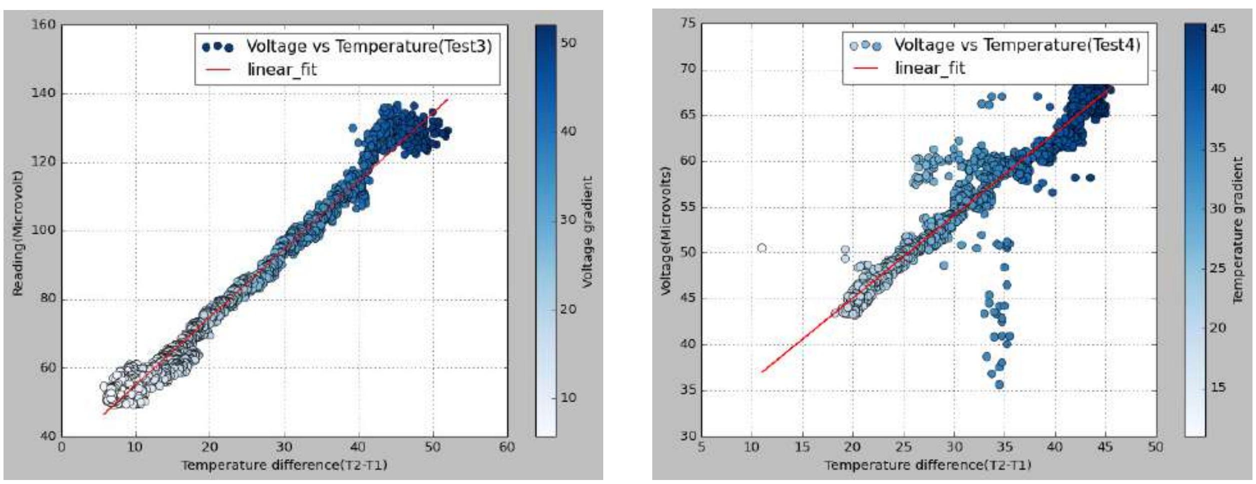
Test Set	**Fit Curve**	**Coefficients**			
		a	**b**	**c**	**d**
1	Linear	1.6837847	52.55988265	0	0
2	Linear	1.5106583	35.51719899	0	0
3	Linear	1.98624261	34.95554861	0	0
4	Linear	0.89937781	27.05879282	0	0



(a) Test 1

(b) Test 2

Figure 10. Voltage Versus Temperature Gradient Part 1



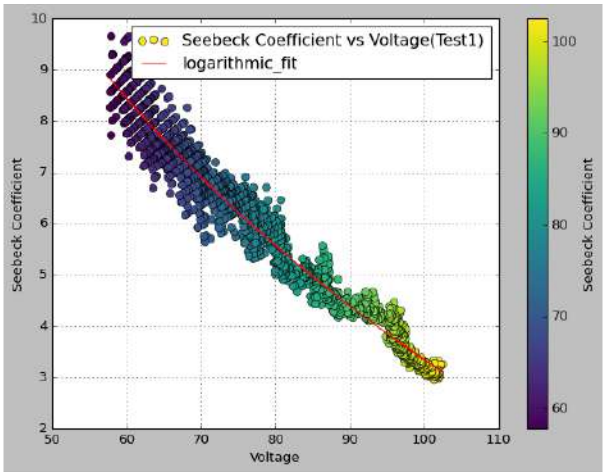
(a) Test3

(b) Test4

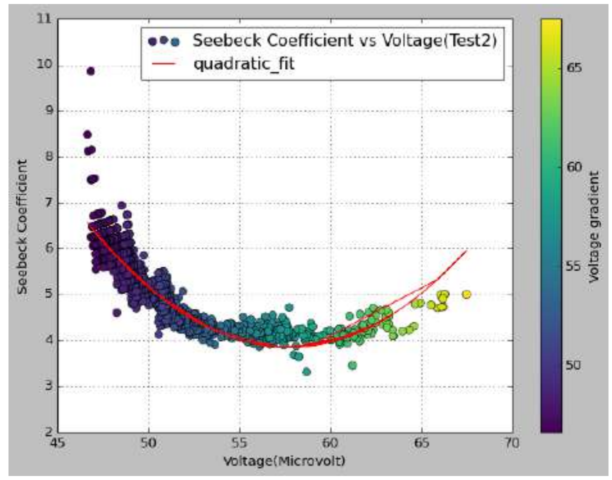
Figure 11. Voltage Versus Temperature Gradient Part 2

Table 5. Curve Fit for Seebeck Effect Versus Voltage

Test Set	**Fit Curve**	**Coefficients**			
		a	**b**	**c**	**d**
1	Logarithmic	-10.01023945	0.09917944	26.30791272	0
2	Quadratic	2.20879698e-02	-2.54994204e+00	7.74425213e+01	0
3	Quadratic	-2.27947187e-01	1.05672529e-03	1.49418850e+01	0
4	Logarithmic	-1.42208282	0.33090073	5.9470875	0

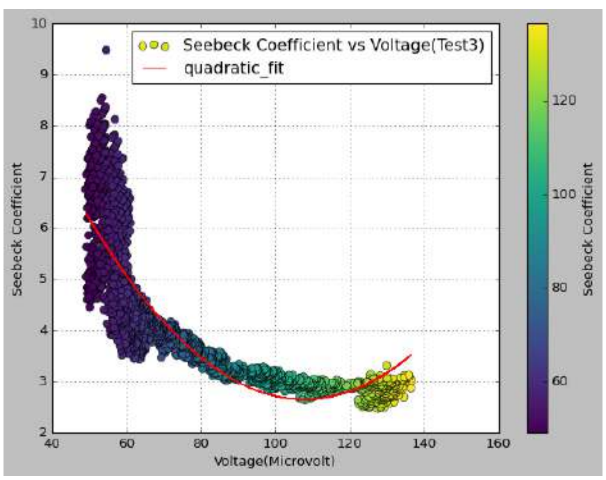


(a) Test 1

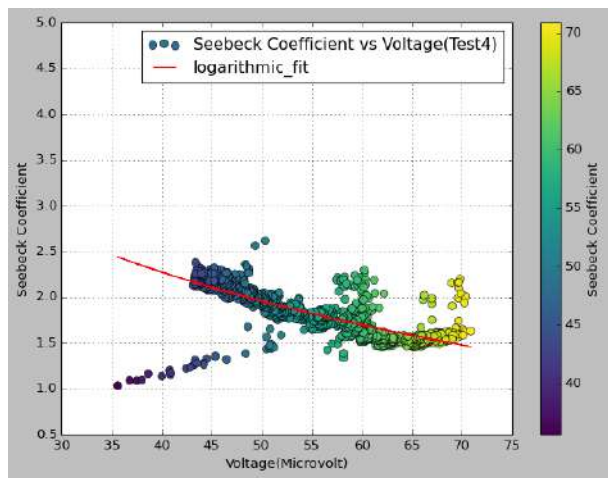


(b) Test 2

Figure 12. Voltage Versus Seebeck Coefficient Part 1



(a) Test3

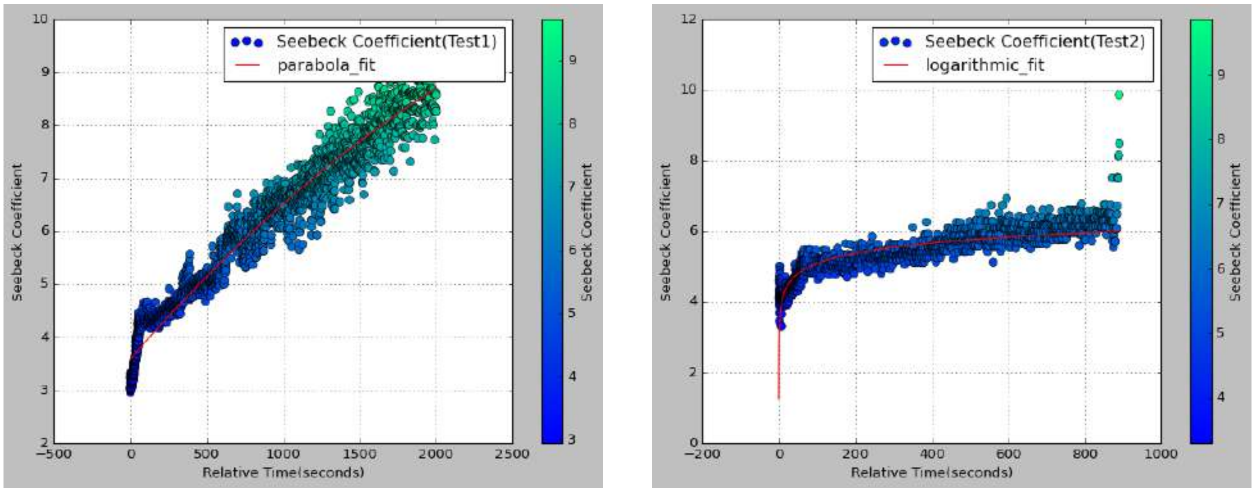


(b) Test4

Figure 13. Voltage Versus Seebeck Coefficient Part 2

Table 6. Curve Fit for Seebeck Coefficient Versus Time

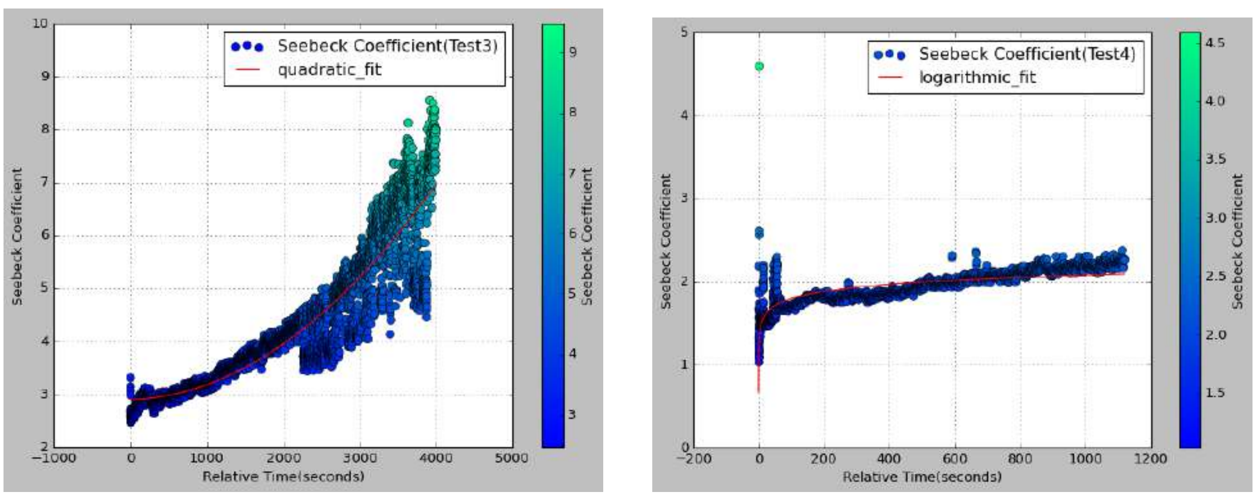
Test Set	**Fit Curve**	**Coefficients**			
		a	**b**	**c**	**d**
1	Quadratic	3.30372036e-03	-3.73256838e-07	3.58421874e+00	0
2	Logarithmic	0.41682691	2.57613635	2.77103584	0
3	Quadratic	3.22532947e-05	2.46866288e-07	2.89813771e+00	0
4	Logarithmic	0.12228174	0.15458458	1.46251749	0



(a) Test 1

(b) Test 2

Figure 14. Time Versus Seebeck Coefficient Part 1



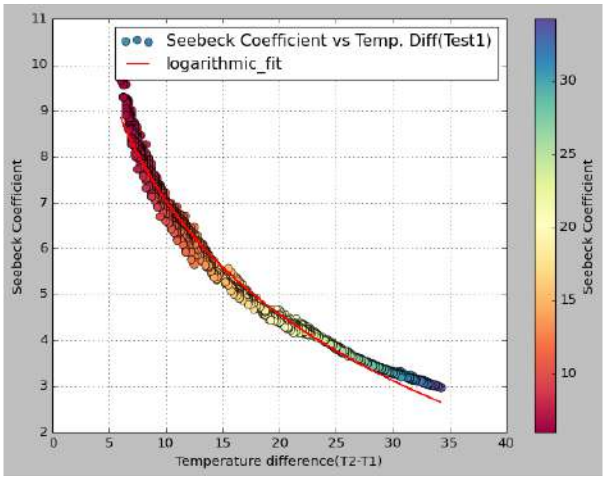
(a) Test3

(b) Test4

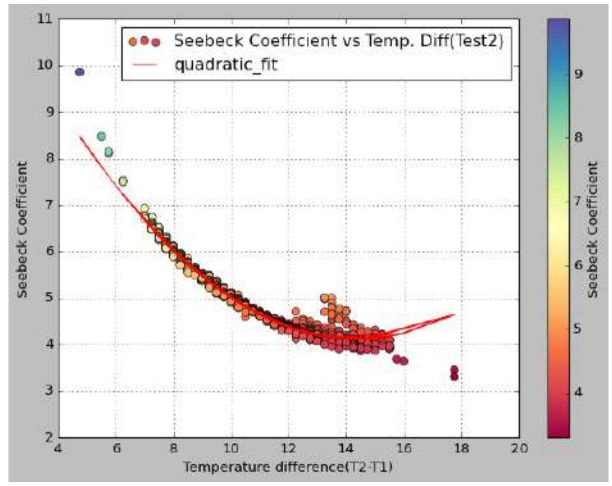
Figure 15. Time Versus Seebeck Coefficient Part 2

Table 7. Curve Fit for Seebeck Coefficient Versus Temperature Gradient

Test Set	Fit Curve	Coefficients			
		a	b	c	d
1	Logarithmic	-3.57121902	6.9418079	22.18444586	0
2	Quadratic	0.04707276	-1.35400358	13.84655497	0
3	Cubic	-2.42768447e-04	2.39811432e-02	-7.77383088e-01	1.13874600e+01
4	Logarithmic	-0.92754342	1.05356474	5.03421257	0

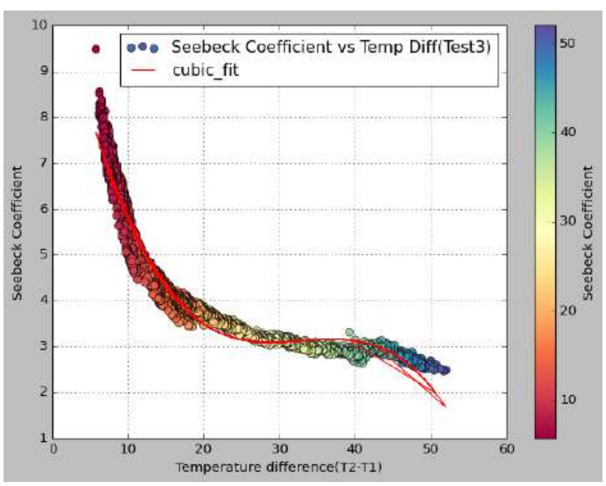


(a) Test 1

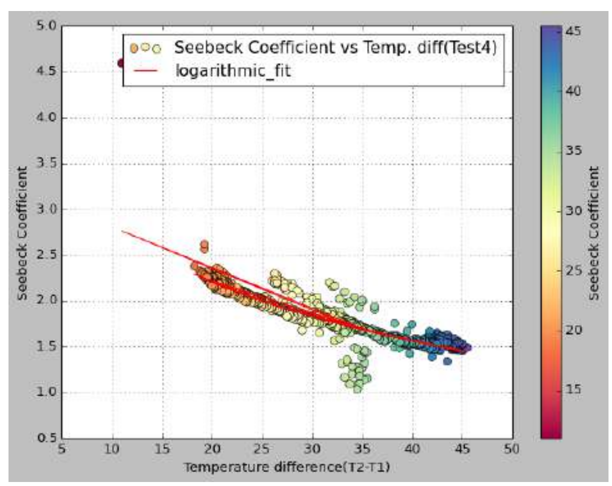


(b) Test 2

Figure 16. Temperature Gradient Versus Seebeck Coefficient Part 1



(a) Test3



(b) Test4

Figure 17. Temperature Gradient Versus Seebeck Coefficient Part 2

RESULTS

From the graphs and tables plotted above these are the results drawn for each of the resulting correlation curves between variables:

- Voltage Versus Time Correlation
  - The voltage versus time graph follows a logarithmic decay or an exponential delay pattern as clearly visible in Fig. 6 and Fig. 7 along with Table 2. As the temperature difference decreases, the rate of heat transfer also decreases, leading to a slower change in voltage over time. Eventually, the temperature difference approaches equilibrium, and the voltage output becomes negligible.
- Temperature Versus Time Correlation
  - As the thermocouple cools down, the temperature difference between the hot and cold junctions decreases. This reduction in the temperature gradient leads to a slower rate of heat transfer. The rate of temperature change becomes less pronounced over time, resulting in a logarithmic decay.
  - As it is clearly visible from Fig. 8 and Fig. 9 along with Table. 3 the curves follow a logarithmic decay pattern. The logarithmic decay occurs because the cooling process approaches an equilibrium state. As the temperature gradient decreases, the cooling rate diminishes, and the temperature gradient asymptotically approaches zero.
  - Therefore, the temperature gradient versus time graph for a cooling thermocouple is expected to display a logarithmic decay pattern rather than an exponential decay.
- Temperature Versus Voltage Correlation
  - The Temperature versus Voltage Correlation graph is a linear fit as the slope of this graph relates to the Seebeck Coefficient.

- Therefore, as observed in Fig. 10 and Fig. 11 along with Table 4the curve between temperature gradient and induced voltage for a thermocouple is generally a straight line. As the temperature gradient increases, the induced voltage also increases linearly. Conversely, as the temperature gradient decreases, the induced voltage decreases linearly

- Seebeck Coefficient Versus Time
  - The Seebeck coefficient remains constant with respect to time as expected. Even though the fit curves tend to be logarithmic or quadratic in nature from Fig. 13, Fig. 14, and Table 5, we can see that the underlying nature of these curves is linear and because of the errors at the lower values, the best fit curves tend to be logarithmic or quadratic in nature.

- Seebeck Coefficient Versus Voltage
  - The Seebeck coefficient should remain constant with time which is as observed from the data in Fig. 15, Fig. 16, and Table 6 apart from the test 1 graph which is linearly changing, those changes are induced because of the environmental factors and humidity changes near the temperature measuring thermocouple (since the thermocouple for test 1 was left open in the air to measure the room temperature and was not connected to the other end of the thermocouple, which was not the case in the subsequent tests.)

- Seebeck Coefficient Versus Temperature Gradient
  - From Fig. 16, Fig. 17 and Table 7With respect to temperature the coefficient remains constant at higher temperature gradient values whereas, at lower temperature gradient values we can see multiple Seebeck coefficient values, this is attributable to the fact that the thermocouples are not as accurate to justify the smaller temperature measurements hence giving a glance at the higher temperature gradient values one can verify the theory predictions as they do not vary with change in temperature.

– Specifically test2 shows somewhat of a parabolic behaviour, the reason for which might be attributable to other environmental factors since the experiments were carried over a long span of 2.5 hrs and there were significant environmental factors such as temperature, precipitation, humidity, and background noises constantly fluctuating

CONCLUSION

In conclusion, the experimental investigation of an Aluminum Copper thermocouple provided valuable insights into the Seebeck Coefficient and the correlations depicted by the Induced Voltage versus Temperature cooling curves. Despite potential error factors affecting certain results, the overall findings contribute to our understanding of thermoelectric principles.

The experiment confirmed the significant role of the Seebeck Coefficient in determining the induced voltage generated by the thermocouple. The observed linear relationship between the temperature gradient and induced voltage, as governed by the Seebeck effect, highlights the proportional nature of these variables.

Acknowledging the limitations and potential sources of error, this study emphasizes the importance of meticulous experimental design and measurement techniques in thermoelectric research. The obtained insights contribute to the broader field of thermoelectric materials and devices, paving the way for further advancements and improvements.

In summary, while considering the impact of error factors, the experiment provided valuable information about the Seebeck Coefficient and the relationships depicted by the Induced Voltage versus Temperature cooling curves for an Aluminum Copper thermocouple. These findings enhance our understanding of thermoelectric principles and underscore the significance of accurate experimentation and analysis in advancing the field of thermoelectricity.

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