INDOSAW
COMMITTED TO EXCELLENCE

THERMAL AND ELECTRICAL CONDUCTIVITY OF METAL

Instruction Manual

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INTRODUCTION:

Thermal conductivity of materials can't be measured directly unlike electrical conductivity. There are two different types of techniques for measurement of thermal conductivity, namely steady-state techniques and transient techniques. In general, steady-state techniques perform a measurement when the temperature of the materials measured does not change with time. This makes signal analysis simple. The transient techniques perform a measurement during the process of heating up and it is not simple. The advantage is that measurements can be made quickly.

In metals, thermal conductivity approximately tracks electrical conductivity according to Wiedmann-Franz law, as freely moving electrons transfer not only electric current but also heat energy. However, the general correlation between electrical and thermal conductivity does not hold for other materials, due to the increased importance of phonon carriers for heat in nonmetals.

OBJECTIVE:

1. Determine the heat capacity of the calorimeter in a mixture experiment as a preliminary test.
2. To begin with, establish a constant temperature gradient in a metal rod with the use of two heat reservoirs (boiling water and ice water).
3. To determine the thermal conductivity of the metal rod (Copper/Aluminium).
4. To determine the electrical conductivity of aluminum and copper by recording a current-voltage characteristic curve.
5. To find out the Lorentz number.

LIST OF ITEMS:

S. No.	ITEM NAME	QTY.
1	Conductivity Rod Al	1
2	Conductivity Rod Cu	1
3	Upper Calorimeter Vessel with Lid	1
4	Lower Calorimeter Vessel with Stirrer	1
5	Laboratory Jack	1
6	Weighing Balance with adaptor	1
7	Immersion Heater	1
8	Digital Thermometer	3
9	Heat Conductive Paste	2
10	Universal Clamp	2
11	Base	1
12	Support Rod	1
13	Bosshead	2
14	Power Supply 0-30V, 20amp	1
15	Multimeter	1
16	Connecting lead 100cm Red and Black Pair	1
17	Connecting lead 50cm Red and Black Pair	1
18	Beaker 500ml	1
19	Gloves (pair)	1
20	Syringe Plastic	1
21	Beaker 2000ml	1
22	Stop Watch	1
23	Power Cord	1

THEORY AND EVALUATION

If a temperature difference exists between different locations of a body, heat conduction occurs. In this experiment there is a one-dimensional temperature gradient along a rod. The quantity of heat dQ transported in time dt is a function of the cross-sectional area A and the temperature gradient $\Delta T/\Delta x$ perpendicular to the surface.

$$\frac{dQ}{dt} = -\lambda A.\frac{\delta T}{\delta x} \qquad \text{-------------1}$$

x is the heat conductivity of the substance.

The temperature distribution in a body is generally a function of location and time and is in accordance with the Boltzmann transport equation

$$\frac{\Delta Q}{\Delta t} = \frac{\lambda}{\rho.c}.\frac{\delta^2 T}{\delta x^2} \text{----------------2}$$

Where ρ is the density and 'c' is the specific heat capacity of the substance.

After a time, a steady state $\frac{\delta T}{\delta x} = 0$ --------------3

is achieved if the two ends of the metal rod having a length l are maintained at constant temperatures T_1 and T_2, respectively, by two heat reservoirs.

On reaching constant temperature gradient (steady state), equation 3 can be considered as having been satisfied by the metal rod. In order to calculate the heat energy transported by the metal rod according to Equation 1, the ambient heat fraction must be subtracted.

That is

$$\frac{dQ_{rod}}{dt} = \frac{dQ_{total}}{dt} - \frac{dQ_{surrounding}}{dt} \qquad \text{--------------4}$$

At room temperature the conduction electrons in metal have a much greater mean free path than the phonons. For this reason heat conduction in metal is primarily due to the electrons.

The correlation between the thermal conductivity λ and the electrical conductivity σ is established by the Wiedemann-Franz law:

$$\frac{\lambda}{\sigma} = LT \qquad \text{-----------------5}$$

The Lorenz number L, which can be experimentally determined using Equation (5), is established by the theory of electron vapour (for temperatures above the Debye temperature) to be:

$$L = \frac{\pi^2}{3}.\frac{k^2}{e^2} = 2.4x10^{-8}\ \frac{W\Omega}{K^2} \qquad \text{-------------------6}$$

Where k = Boltzmann constant = $1.38x10^{-23}$ J/K,

e = Elementary unit charge = $1.602x10^{-19}$ As

PROCEDURE FOR THERMAL CONDUCTIVITY ESTIMATION:

Heat capacity:- It is the amount of heat required to change its temperature by 1°

Q = cdt

Q = heat supplied (J)

C = heat capacity (JK^{-1})

1) **Measurement of heat capacity of lower calorimeter**

The heat capacity of the calorimeter is obtained from results of the mixing experiment and the following formula:

$$c = c_w.m_w.\frac{T_w - T_m}{T_m - T_R} \qquad \text{------------7}$$

c_w = Specific heat capacity of water, m_W = Mass of the water, T_w = Temperature of the hot water, T_m = Mixing temperature and T_R = Room temperature

Prerequisites:
In this step, we need to determine the heat capacity of the lower calorimeter. For this, at first, we fill the upper calorimeter with water. Now connect the heater (of the upper calorimeter) to the plug socket and allow the temperature of the water to increase to around 60 degree centigrade.

Procedures:
1. Weigh the calorimeter at room temperature.
2. Measure the room temperature (T_r)
3. Note down the temperature of the hot water (T_w).
4. Fill the lower calorimeter with hot water
5. Stir the calorimeter with stirrer. Determine the mixing temperature of water (T_m) with calorimeter.
6. Determine the mass of the water.
7. Calculate the heat capacity of the calorimeter using equation 7.

2) Determination of the heat flow through metal rod thermal conductivity

Equation for the measurement of the thermal conductivity of Aluminium/copper rod is given by

$$\frac{dQ_{rod}}{dt} = \lambda A.\frac{\Delta T}{\Delta x}$$

Fig-1

Prerequisites:

Before starting the experiment, please ensure that you are ready with

A. Computer with Milab software installed.
B. 5-6 kgs of crushed ice
C. At least 2 litres of water maintained at 0 degree centigrade. The water can be maintained at 0 degree centigrade for a long time by adding ice to it from time to time.

Procedures:
1. At first, weigh the empty lower calorimeter.
2. Arrange the experimental set-up as shown in figure 1. Please take note of the following points:

A) Insert the arrow-headed end of the metal rod into the upper calorimeter vessel. To improve the heat transfer, cover the end of the metal rod with heat-conduction paste. Insert the ring into the rod to remove the vacant space between the upper calorimeter and metal rod.
B) Attach the metal rod to the support stand in such a manner that the lower calorimeter can be withdrawn from beneath it.
C) The height of the lower calorimeter can be adjusted with laboratory jack. While doing so, care must be taken to ensure that the non-arrow-headed end of the rod remains completely immersed in the cold water during the experiment.
D) The temperature probes must be positioned as close to the rod as possible. To improve the heat transfer between the rod and the temperature probe, use heat conduction paste.
E) Ensure that the upper calorimeter is well filled with water.

3. Connect power to the heater of the upper calorimeter and allow the water to boil.
4. Fill the lower calorimeter with crushed ice and the remaining portion with cold water.

5. Open the MiLab Software and ensure that all three temperature sensors are detected in the 'Current Set-up Summary'. Deselect all other sensors except those three temperature sensors.
6. Click on Full Setup. Set the "Rate" at "every second" and samples at a suitable value so that duration becomes more than one hour. Click on Minimal Setup.
7. Click on Play button to begin recording data.
8. Wait until a steady state is achieved. A steady state means temperature of the upper and lower portions of the rod (indicated by two temperature sensors inserted into the rod) would not change with time. Keep the water in the lower calorimeter near 0º C (1° to 2° C) with the help of ice. Slowly stir the ice-water mixture with stirrer.
9. When the steady state is reached, remove the additional ice from the lower calorimeter. A decrease in water level should be compensated by cold water at 0 degree centigrade.
10. Continuously stir the water until the temperature of the water (in the lower calorimeter) rises to 6 degree centigrade.
11. Stop data collection and save.
12. Switch off the heater in the upper calorimeter.
13. Determine the mass of the water in the lower calorimeter.
14. Now determine $\frac{dT}{dt}$ and $\frac{dQ_{rod}}{dt}$ as mentioned in page-7 and page-8

1. Electrical conductivity theory:

A) Ohm's Law $V \alpha I$ So $R = \frac{V}{I}$

and

$$\left.\begin{aligned} R &= \frac{\rho L}{A} = \frac{1}{\sigma}\frac{L}{A} \\ \sigma &= \frac{L}{AR} \end{aligned}\right\}$$

ρ =Resistivity of material

σ =Conductivity

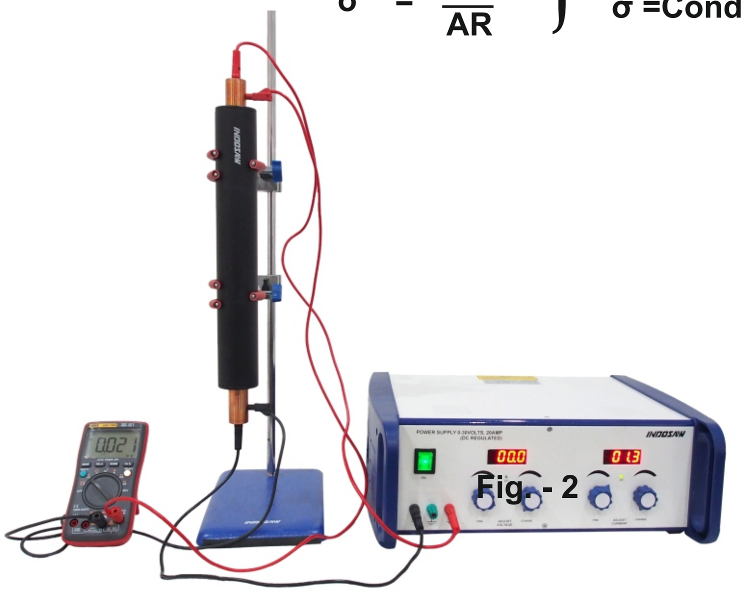


Fig. - 2

B. Measurement of the electrical conductivity.

a. Perform the experimental set-up according to the circuit diagram in Fig. 2 (set-up in accordance with a 4-conductor measuring method).

b. Connect the multimeter and set it to mV range.

c. Slowly increase the current value through high current power supply.

d. Record the values of current I and voltage V

e. Calculate R = V/I (slope of V-I graph)

f. Calculate electrical conductivity using $\sigma = \frac{L}{AR}$

Where,

L = 39.5 cm = length of rod between to probes.

Dia, D = 25 mm, r = 12.5 mm

$A = \frac{\pi D^2}{4} = \pi r^2$ = Area of crossection of hot end.

From the graph of V - I slope will give us R

So electrical conductivity $\sigma = \frac{L}{AR}$

L = length of rod between to probes.
A = πr^2 area of crossection of hot end.

Relation between electrical and thermal conductivity

Wiedemann-Franz law
At a given temperature the thermal and electrical conductivity of metals are proportional, but raising the temperature increase the thermal conductivity while decreasing the electrical conductivity.
This behavior is quantified in the Wiedemann-Franz law.

$$\frac{\lambda}{\sigma} = LT \quad \text{or} \quad L = \frac{\lambda}{\sigma T}$$

Theoretical value is given in eq 6

PRECAUTIONS:

A. The mixing temperature is close to the temperature of hot water, so one has to be prompt in reading the fall in temperature versus time.

B. Care should be taken to ensure the immersion heater used is not exposed to air for long.

C. Handle temperature probes with care. Bending front portion too much may damage the sensor.

QUESTIONS:

A. What is the difference between specific heat and heat capacity? Which one of them is an extensive variable?

B. What is the necessity of maintaining steady state for thermal conductivity measurement?

C. What is the necessity of thermal conducting paste? What is thermal contact resistance?

Calculated values for electrical conductivity are close to the literature values of the material but for the thermal conductivity it is significantly different, because.

1. It is very difficult to obtain constant temperature gradient since we have to keep both the calorimeter at fixed temperatures.
2. Even though after coming to steady state the system will get disturbed, as no insulator and conductor is perfect.

TEST REPORT OF THERMAL AND ELECTRICAL CONDUCTIVITY OF COPPER

THERMAL CONDUCTIVITY OF COPPER

HEAT CAPACITY OF LOWER CALORIMETER

Weight of calorimeter with stirrer = 1.498 kg

Formula Used

$$C = C_w M_w \frac{T_w - T_m}{T_m - T_r}$$

Specific Heat of Water (C_w) in Joule Kg^{-1} K^{-1}	Mass of Water (M_w) in Kg	Temperature of hot Water (T_w) in Centigrade	Mixing Temperature (T_m) in Centigarde	Room Temperature (T_r) in Centigrade	Heat Capacity (C) in Joule / Kelvin
4200	0.472	58.61	53.71	30.18	412

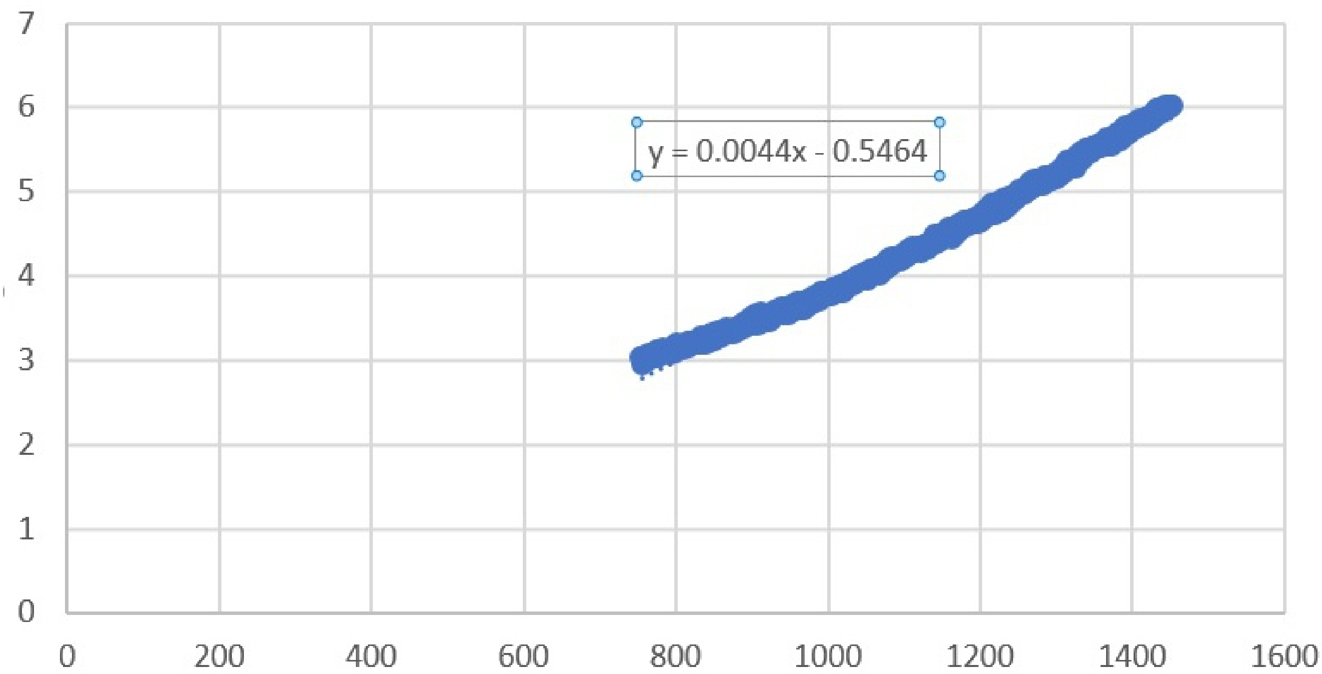
DETERMINATION OF dT/dt

In order to obtain the slope of the graph – temperature of the lower calorimeter as a function of time, we need to use excel or similar tool. For this at first we need to export the data in .csv format.

To do this, use the Export tool from the graph toolbar at the bottom of the graph window. Click on the export toolbar. Type a name in the file name box and click on save. By default, it will be saved in the Multilab folder in the Documents (or My Documents) location.

Go to Documents → Multilab folder. Open the file (which was just saved) with excel. Plot a graph of the temperature of the lower calorimeter as a function of time for the region where the temperature increases linearly with time. You may choose the region by observing the plot in Milab interface.

When the graph is obtained in the excel, determine the slope using linear fit.



DETERMINATION OF dQ_{rod} /dt

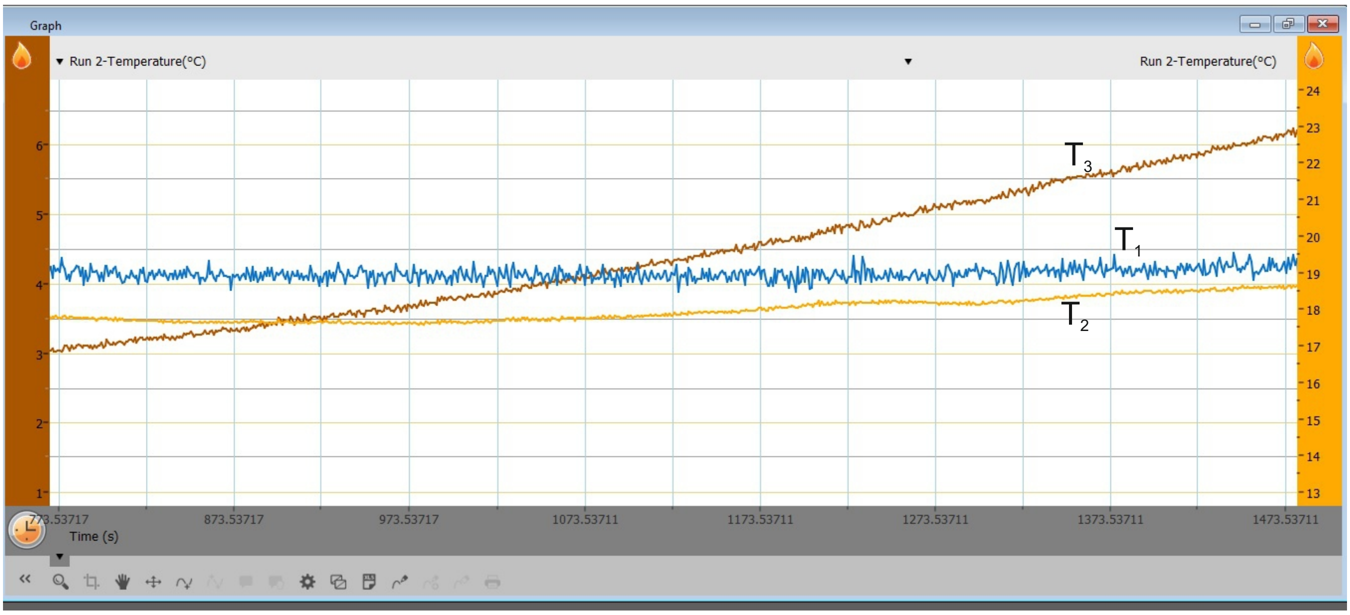
Weight of calorimeter with stirrer = 1.498 kg

Total mass of lower calorimeter with ice water = 2.35 kg

Mass of water = (2.35 - 1.498) kg = 0.852 kg

Formula Used $$\frac{dQ_{rod}}{dt} = (C + C_w M_w)\frac{dT}{dt}$$

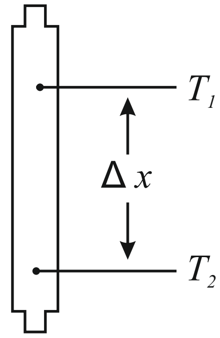
Heat Capacity (C) in Joule / Kelvin	Mass of Water (M_w) in Kg	Specific Heat of Water (C_w) in Joule Kg^{-1} K^{-1}	dT/dt from graph in Kelvin / second	dQ_{rod} /dt in Joule/second
412	0.852	4200	44×10^{-4}	17.7



Temperature 3 showing the temperature of the lower calorimeter (T_3)
Temperature 2 showing the temperature of the lower end of the rod (T_2)
Temperature 1 showing the temperature of the upper end of the rod (T_1)

DETERMINATION OF DIFFERENCE IN TEMPERATURE OF UPPER AND LOWER END OF THE COPPER ROD

Formula Used



$$\Delta T = T_1 - T_2$$

$= (\ 53.1 - 18.6\ )$ ºC

$= 34.5$ ºC

where, T_1 = Mean Temperature of the Upper end of the rod;
and T_2 = Mean Temperature of the Lower end of the rod.

That temperature gradient was obtained at a **distance, Δx = 0.315 meter**.

DETERMINATION OF THERMAL CONDUCTIVITY OF COPPER ROD

Formula Used

$$\frac{dQ_{rod}}{dt} = -\lambda A \frac{\Delta T}{\Delta x} = \lambda A \frac{\Delta T}{\Delta x}$$

$$\lambda = \frac{dQ_{rod}}{dt} \times \frac{\Delta x}{A \Delta T}$$

The negative sign expresses only the fact that the temperature diminishes as Δx increases.

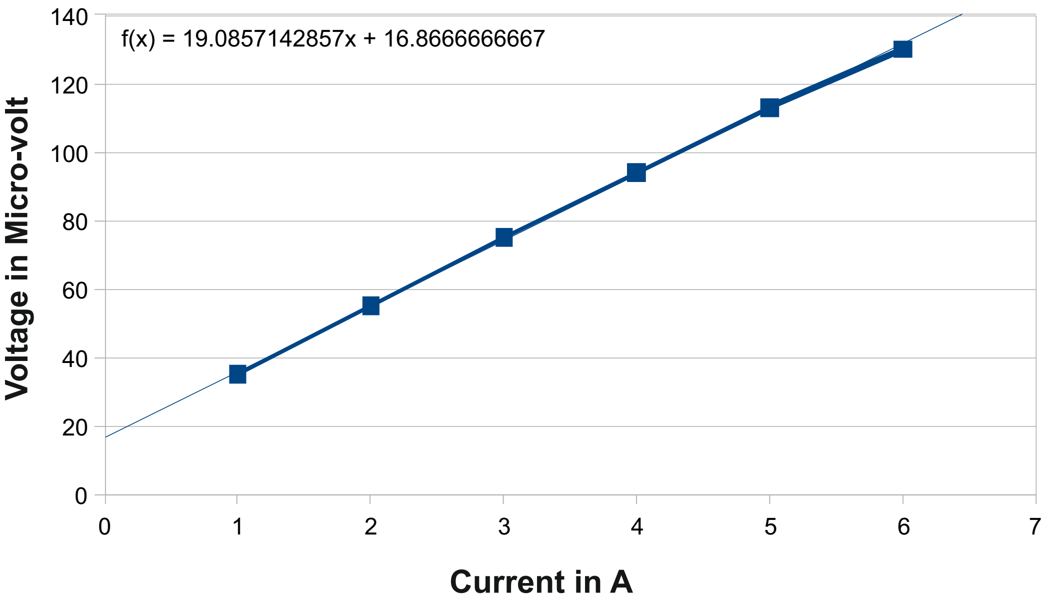
Radius of the Rod, R in m	Area of cross – section, A = πR^2 in m^2	ΔT in Kelvin	Δx in m	**dQ_{rod}/dt** in Joule /S	λ in Watt meter $^{-1}$ Kelvin $^{-1}$
1.25×10^{-2}	490.6×10^{-6}	34.5	0.315	17.7	329.2

Test report of electrical conductivity of Copper

Electrical conductivity (Cu-rod)
D = 25 mm R = 12.5 mm $A = \pi R^2 = 490.6 \times 10^{-6}\ m^2$
l = 39.5 cm
Table - Cu

Current I	Voltage drop ΔV		Slope from graph $R = \frac{(\Delta V)}{(\Delta I)} (ohm)$	$\sigma = \frac{l}{R\,A} ohm^{1-} m^{1-}$
	mV	uV		
1	.0.35	35	19.08×10^{-6}	4.3×10^{-7}
2	.055	55		
3	.075	75		
4	.094	94		
5	.0113	113		
6	.0130	130		

Voltage Vs Current Plot



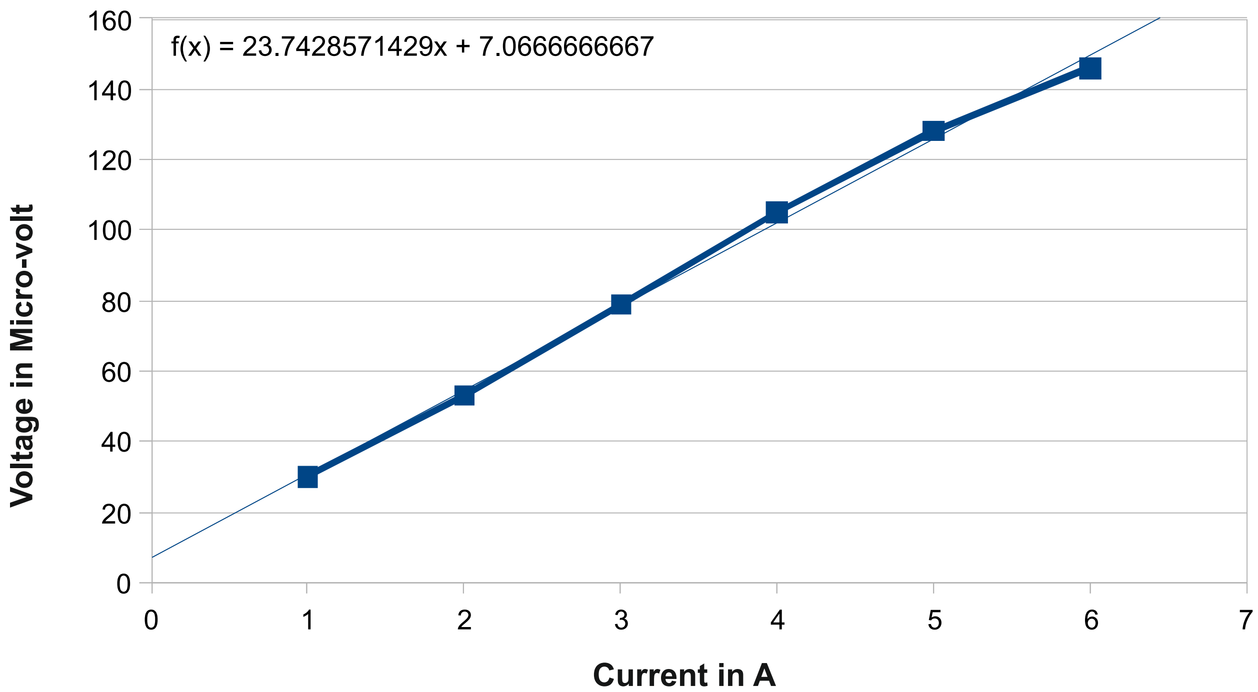
The slope of the graph gives the the resistance of the Cu bar.

Resistance, $R = 19.08 \times 10^{-6}$ Ohm

Test report of electrical conductivity of Aluminium

Table – 2 – Al

Current I A	Voltage drop ΔV		Slope from graph $R=\frac{(\Delta V)}{(\Delta I)}(ohm)$	$\sigma = \frac{l}{R A} ohm^{1-} m^{1-}$
	mV	uV		
1	.0.28	28	23.07×10^{-6}	3.39×10^{-7}
2	.053	53		
3	.079	79		
4	.0105	105		
5	.0128	128		
6	.0146	146		



The slope of the graph gives the the resistance of the Al bar.

Resistance, R = 23.74×10^{-6} Ohm

where,
l = distance between the two points on the Cu – bar between which potential difference is measured = 39.5 cm,

R = Resistance between those two points mentioned above
For Cu, R= 19.08 X 10^{-6} ohm,

For Al, R = 23.74 X 10^{-6} ohm,

A = Area of Cross-section of the Cu – bar = 490.6 X 10^{-6} m^2.

Results

Heat capacity of calorimeter = 412 J/k
Electrical conductivity of Al= 3.4 x 10^7 $\Omega^{-1}m^{-1}$
Literature value = 3.75 x 10^7 $\Omega^{-1}m^{-1}$
Electrical conductivity of Cu =4.3 x 10^7 $\Omega^{-1}m^{-1}$

Literature value = 5.882 x 10^7 $\Omega^{-1}m^{-1}$

Thermal conductivity of Cu= 329.2 $wm^{-1}K^{-1}$
Literature value = 386 $wm^{-1}k^{-1}$

LORENTZ NUMBER CALCULATION

Thermal Conductivity of Cu, λ = 329.2 Watt $meter^{-1}$ $Kelvin^{-1}$
Electrical Conductivity of Cu σ = 4.3 X 10^7 ohm^{-1} $meter^{-1}$
Room Temperature, T = 300 K
Lorentz Number, $L = \frac{\lambda}{\sigma T}$ = 2.55 X 10^{-8} Watt ohm K^{-2}
Literature value L = 2.4 x 10^{-8} Watt ohm K^{-2}

APPENDIX-1

Determination of the influence of the surroundings

The addition of heat from the surroundings is calculated from the temperature increase (Temperature (T) rise of the cold water in the calorimeter)

$$Q = (c_w.m_w + c).(T - T_0)$$

$$\textbf{Or,}\quad \frac{dQ}{dt} = (c_w m_w + c)\frac{dT}{dt} \quad \text{-----------------8}$$

Where T_0 = Temperature at time t = 0 sec.
*By plotting a graph between increase of temperature versus time, heat energy supplied by surroundings with time **(dQsurr/dt)** can be estimated.*

Method:
1. Weigh the empty lower calorimeter.
2. Add ice to the lower calorimeter till the temperature reaches to 0°C.
3. Then remove the ice and take the temperature readings in 1 min interval till the temperature rises to 12°C.
4. Reweigh the calorimeter to determine the mass of the water that it contains.

Table for calefaction of cold water using eq^n - 8

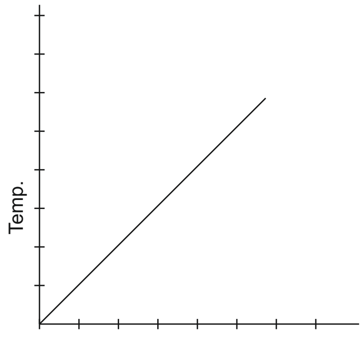
Time (m)	Temp. °C

Slope of the graph give us $\frac{dT}{dt}$

use eq^n- 8 to calculate $\left(\frac{dQ}{dt}\right)_{Surr}$

Then rate of flow of heat through rod.

$$\left(\frac{dQ}{dt}\right)_{rod} = \left(\frac{dQ}{dt}\right)_{total} - \left(\frac{dQ}{dt}\right)_{surr}$$



DETERMINATION OF CALCIFICATION

Formula Used

Heat Capacity (C) in Joule / Kelvin	Mass of Water (M_w) in Kg	Specific Heat of Water (C_w) in Joule Kg^{-1} K^{-1}	dT/dt from graph in Kelvin / second	$dQ_{surroundings}/dt$ in Joule/second $\frac{dQ_{su}}{dt} = (C + C_w M_w)\frac{dT}{dt}$

However, the effect of surrounding due to specially designed Calorimeter is very small and so can be neglected.