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Experiments for Determining the Thermal Conductivity of Brass and 304 Stainless Steel with Direct Temperature Measurement Techniques Using Lorenz Number as Validation

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ABSTRACT

The quantity of heat transferred through a connecting rod from two sources of different temperatures with time is proportional to the thermal conductivity of the substance. In this study, the experiment was conducted to determine the thermal conductivity of brass and 304 stainless steels by direct temperature measurement. Then the value of thermal conductivity obtained was tested using Wiedemann and Franz's law through the determination of Lorenz number. The experiment was started by determining the rate of heat changes due to environmental influences from a calorimeter filled with cold water. The value obtained is a correction of the environmental influence on the system, which is 1.69 J/s. The value of the heat energy transferred with time by the rod for brass is 0,811 J/s with an average mean absolute percentage error by 19,2% and 304 stainless steel is 0,087 J/s with an average mean absolute percentage error by 9,1%. The result showed that brass thermal conductivity was 146,87 W/m.K and 304 stainless steel was 15,03 W/m.K. Based on Wiedemann-Franz's investigation of the thermal conductivity of several metals at room temperature, it was proportional to the electrical conductivity. After getting the thermal conductivity value, the measurement was continued by determining the electrical conductivity value. The result showed that brass electrical conductivity was σ=1,47x10^7 $(\Omega.m)^{-1}$ and 304 stainless steel was σ=0,14x10^7 $(\Omega.m)^{-1}$. If the measurements were carried out at an average room temperature of 300 K, the Lorenz number for each test rod could be obtained. Lorenz's number of brasses was 2,5x10^{-8} **(**$W.\Omega.K^{-2}$) and 304 stainless steel was 3,5x10^{-8} **(**$W.\Omega.K^{-2}$). When compared to the literature, the result of the Lorenz number shows good agreement, the difference that occurs is due to differences in the temperature. This shows that the experiment to determine the thermal conductivity of brass and 304 stainless steels by direct temperature measurement has been tested well and can be applied to other types of metal materials.

Keywords: *Experiment, Direct Measurement, Thermal Conductivity, Electrical Conductivity, Lorenz Number, Brass, 304 Stainless Steel.*

1. INTRODUCTION

Determination of thermal conductivity of metallic materials such as stainless steel and brass is very useful in many engineering applications purposes. Thermal conductivity is the ability of a material to conduct heat and is one of the parameters needed to identify material in its ability to conduct heat. The thermal conductivity value indicates how fast heat flows in a particular material. The faster a molecule moves, the faster it transports energy [1].

If there is a temperature difference between different locations of objects, heat will flow. If there is a temperature gradient along a cylindrical rod with a small cross-sectional area (considered one-dimensional), the quantity of heat transferred through a connecting rod from two sources of different temperatures with time is proportional to the thermal conductivity of the substance, cross-sectional area A, and temperature gradient. According to the Boltzmann transport equation, the temperature distribution is a function of time and location. After a while the heat flows and a steady-state occurs, the temperature difference between the two points per rod length is the gradient of the temperature distribution equation as a function of location [2]. The better a material conducts heat, the greater the value of its thermal conduction coefficient. Materials with large conduction coefficients are called conductors, this is related to the material's electrical properties. Conductors' materials are good conductors of electricity. Based on this principle, the measurement of thermal conductivity and electrical conductivity with similar materials is carried out and analyzed based on the Lorenz number obtained [3]. Direct temperature measurement requires precision so it can minimize heat transfer from and to outside the environment. Corrections must be applied to the calculation results due to environmental influences on the system [4].

1.1. Related Work

Many methods have been used to determine the value of thermal conductivity, both to determine the thermal conductivity of pure and mixed materials. For thermal characterization of bulk material, hot-wire method, transient plane source (TPS) method the steady-state method, and transient laser flash diffusivity method are most used. For thin-film measurement, the transient thermoreflectance technique including both time-domain and frequency-domain analysis and the 3ω methods are widely employed [5]. The value of thermal conductivity is not fixed but depends on moisture, the density of the material, and ambient temperature [6]. The estimated thermal conductivity of 304 stainless steel was 14,34 W/m.K using parameter estimation techniques [7]. With reference value of 304 stainless steel was 14,9-16,2 W/m.K and the value of the thermal conductivity of brass is 150 W/m.K [8] or in the range of $109-160\ /m.K$ [9].

1.2. Our Contribution

This experiment was conducted to determine the thermal conductivity of brass and 304 stainless steel by direct temperature measurement. Then the value of thermal conductivity obtained is tested using Wiedemann and Franz's law through the determination of Lorenz number. Based on Wiedemann and Franz's observation, the conductivities of metal for heat and electricity are relatively close to each other and are probably both function of the same quantity [10]. So it is also necessary to measure the value of the electrical conductivity of the material being tested, namely by measuring the value of its resistivity [11]. The direct temperature measurement technique in this experiment is set so that it can be applied in determining the thermal conductivity of other metals.

2. BACKGROUND

When a temperature gradient exists in a body, experience has shown that there is an energy transfer from the high-temperature region to the low-temperature region. In this study, two calorimeters in which each filled with hot and cold water connected to a metal rod which thermal conductivity value will be determined. The quantity of heat energy transferred per unit of time is equivalent to the temperature gradient, that is the rate of change of temperature per unit length of the path. The quantitative expression of the relationship between the one-dimensional heat transfer rate in the x-direction, with the temperature gradient and the properties of the conducting medium, is expressed in the Fourier equation [4].

$$\frac{dQ}{dt} = -kA\frac{dT}{dx} \tag{1}$$

Under the *steady-state conditions* where the temperature distribution is *linear*, the temperature gradient expressed as [12]:

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} \tag{2}$$

Based on Wiedemann-Franz's investigation of the thermal conductivity of several metals at room temperature, it was proportional to the electrical conductivity. Lorenz has added that the ratio of the thermal conductivity of a material to its electrical conductivity is directly relative to temperature [10]. Thus, the Wiedemann-Franz law is stated as follows:

$$\frac{\kappa}{\sigma} = LT \tag{3}$$

Where L is Lorenz's number with $L_0 = \frac{\pi^2 (K_B)^2}{3\, e^2} = 2{,}44\, x\, 10^{-8}\, W.\Omega.K^{-2}$. L_0 is called the Sommerfeld value of the Lorenz number [13], it is not a universal number, there is some deviation of the L number depending on the ratio of the mean free part of electrons between the thermal and electrical conductivity, also depending on the type of metal and temperature. The value of L will be equal to L_0 if the electron means the free path is the same as thermal and electrical conductivities.

Meanwhile, to get the value of electrical conductivity can be done by determining the value of electrical resistivity. The relationship between the two quantities is as shown in the following equation [11]:

$$\sigma = \frac{1}{\rho} \tag{4}$$

The resistivity value of the material can be obtained through the equation below by directly measuring the resistance of the conductor (R), the length of the conductor (*l*), and the diameter/cross section of the conductor (A) [11].

$$R = \rho\frac{l}{A} \tag{5}$$

3. METHODOLOGY

The equipment used in this experiment includes two calorimeters each filled with hot and cold water, a metal rod which thermal conductivity value will be determined, thermometers, and statives. The metal rods were covered by aluminum foil to prevent heat from escaping to the environment. The experiment was started by determining the rate of heat change due to environmental influences from a calorimeter filled with cold water. The value obtained is a correction of the environmental influence on the system. The experimental apparatus was set up as shown in Figure 1. The amount of heat change in the cold calorimeter was the same as the amount of heat flow in the rod (which will be calculated for its thermal conductivity) connecting the two hot and cold calorimeters. The temperatures in the cold and hot calorimeters were kept close to 273K and 373K, respectively.

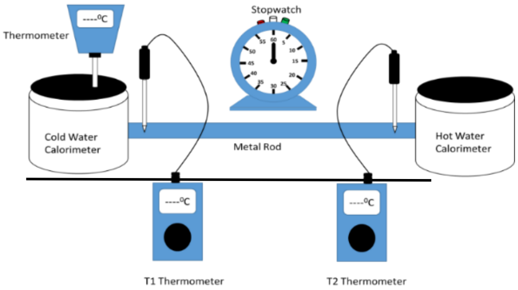


Figure 1 Experimental diagram for determining thermal conductivity

After getting the thermal conductivity value, the measurement was continued by determining the electrical conductivity value. Figure 2 shows the setting of the electrical conductivity measurement equipment. A cylindrical metal rod is connected to a voltage source, then the current and voltage are measured in the cylindrical rod. By using the linear regression method, the resistance value can be calculated. And by knowing the length and cross-sectional area of the cylindrical rod, the resistivity (ρ) value can be determined, and using the relationship in equation 4, we can get the value of electrical conductivity.

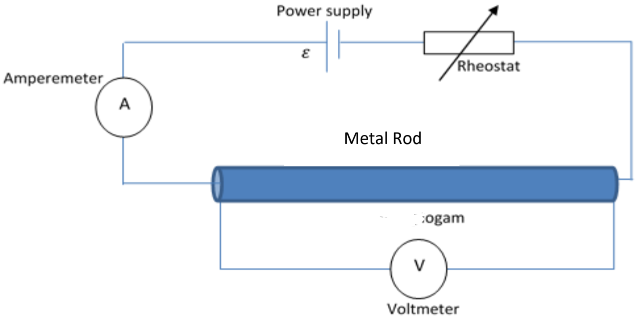
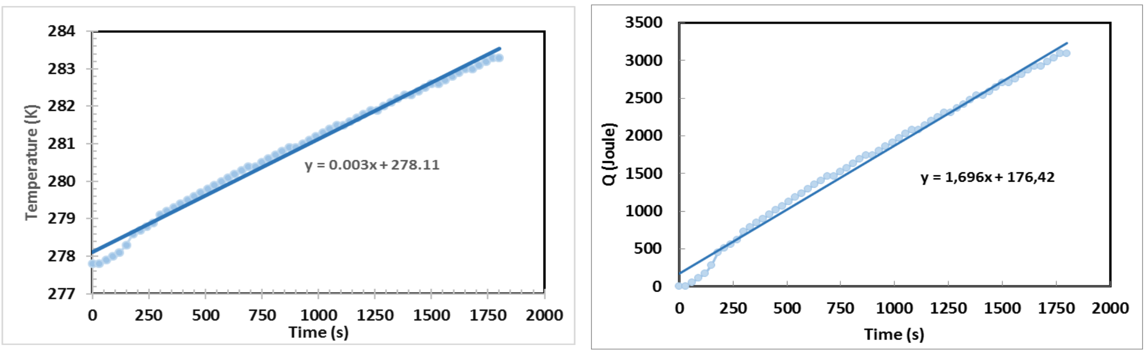


Figure 2 Experimental diagram for determining the electrical conductivity

4. RESULTS

In Figure 3, graph (a) changes the heat in the cold calorimeter from time to time. This shows the addition of heat from the surrounding environment. The graph gradient (b) is the rate of heat change due to environmental influences from the cold calorimeter. The value obtained is a correction of the environmental effect on the system, which is 1.69 J/s.



(a) (b)

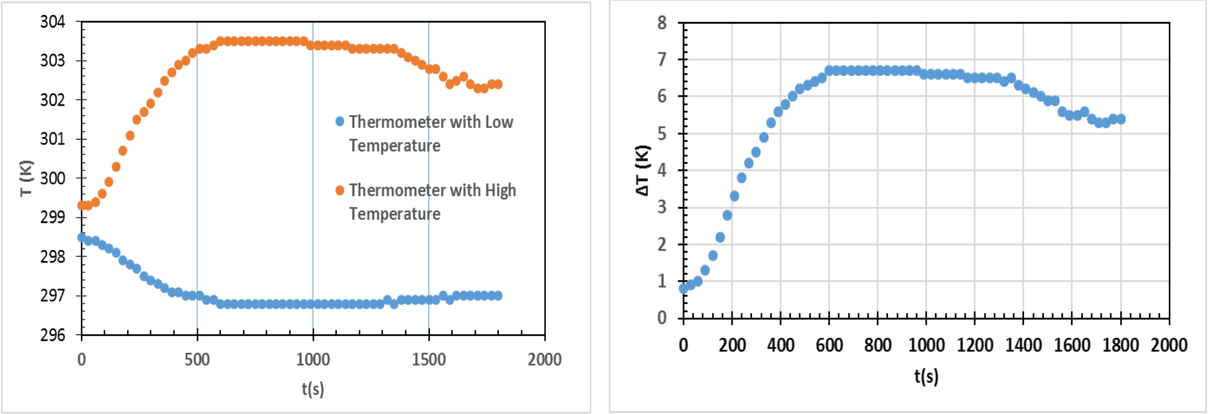
Figure 3 (a) Changes in temperature (b) rate of heat changing in the cold calorimeter

After the equipment is set up as shown in Figure 1 and the calorimeter has been filled with hot and cold water, data collection on the transport of the heat energy in the metal rod begins after a stable constant temperature occurs between the two thermometers. Each thermometers are placed at the ends of the rods approaching the calorimeter at a distance l from each other. Table 1 is the other quantities required for calculation.

Table 1. Quantities for calculations

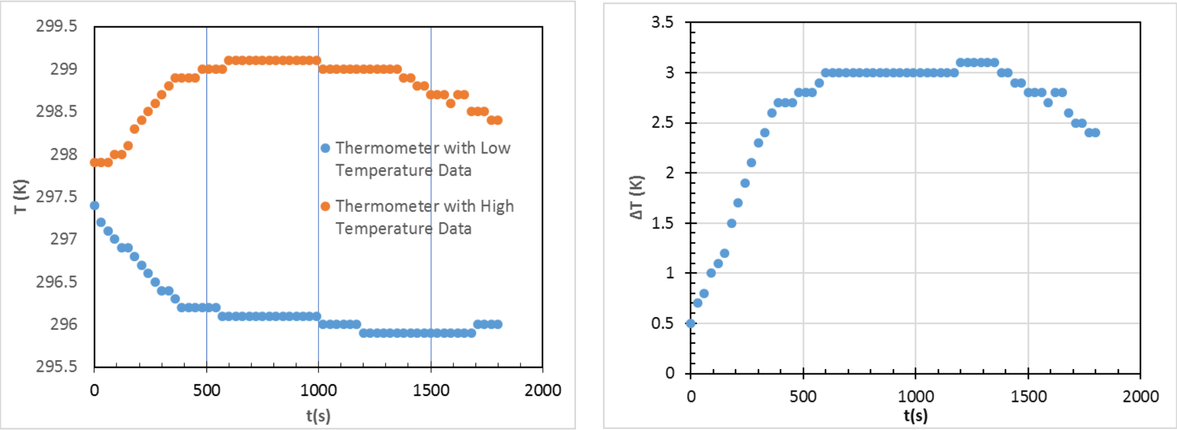
Quantity (Unit)	Magnitude
Metal rod diameter (d)	0,005 m
Rod length (l)	0,8 m
Heat capacity of the calorimeter (C)	62,87 J/g
Specific heat of water (c)	4,2 J/g.C

Figures 4 and 5 (a) show the results of temperature readings on each of the brass and stainless steel rods in both thermometers T_1 and T_2 to determine the time at which the steady-state occurs, $\frac{dT}{dt} = 0$. Figures 4 and 5 (b) show the steady-state with the stable ΔT between T_1 and T_2 achieved at the 600th second to about the 1200 second.



(a) (b)

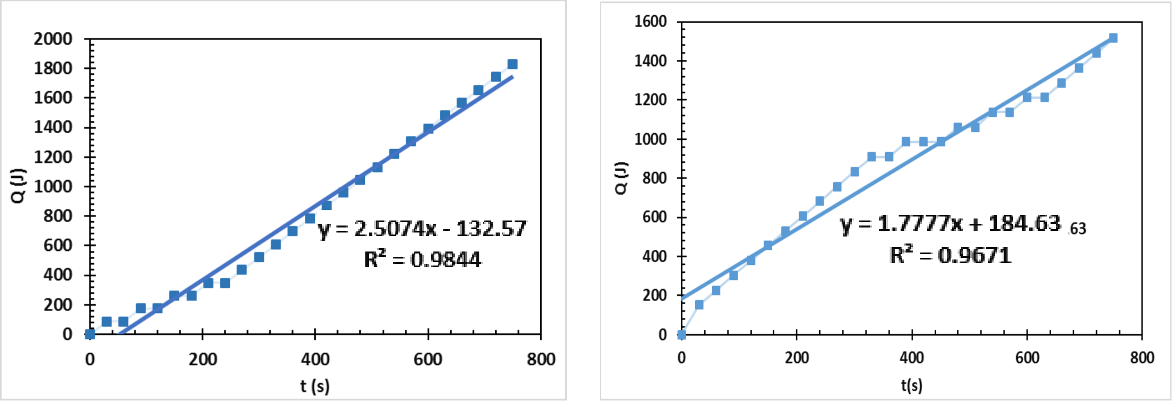
Figure 4 Brass rod (a) change in temperature (b) the stable of ΔT between T_1 & T_2



(a) (b)

Figure 5 Stainless steel rod (a) change in temperature (b) the stable of ΔT between T_1 & T_2

Figure 6 (a) and (b) shows the heat changing in a cold calorimeter with time at a steady state in brass and stainless steel rods, respectively. The gradient of the graph is the value of $\frac{dQ_{system}}{dt}$, after subtracted by $\frac{dQ_{env}}{dt}$, then it will be obtained $\frac{dQ_{rod}}{dt}$, the heat energy dQ transferred with time dt at the rod.

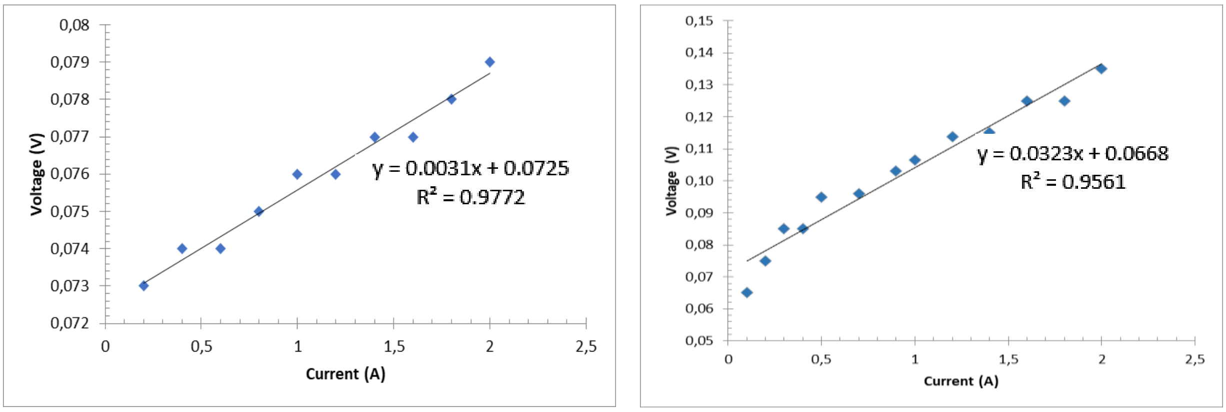


(a) (b)

Figure 6 The heat changing in a cold calorimeter at the steady-state (a) brass rod (b) stainless steel rod

By knowing $\frac{dQ_{rod}}{dt}$ value, the thermal conductivity value of each test material can be determined. The value of the heat energy transferred with time by the rod for brass is 0.811 J/s with an average mean absolute percentage error is 19,2% and coefficient of determination (R^2) 0,98. It shows the magnitude of the effect of the time variable simultaneously on the heat change variable. The value of the heat energy transferred with time by the rod for 304 stainless steel is 0.087 J/s with an average mean absolute percentage error is 9,1% and coefficient of determination (R^2) 0,96. The result showed that brass thermal conductivity is 146,87 W/m.K and 304 stainless steel thermal conductivity is 15,03 W/m.K.

Figure 7 shows the relationship between the rated voltage and current flowing through the test rods (a) brass and (b) stainless steel. The next step is to determine the gradient of the graph which is the resistance value (R) of the bar so that the resistivity value of the rod (ρ) can be determined. Furthermore, by following equation 4, it can be determined the value of the electrical conductivity of brass and stainless steel rods,



(a) (b)

Figure 7 Relationship between voltage and current in (a) brass rods (b) stainless steel rods

In Figure 7(a), the resistivity value of the brass rod is $\rho = 0{,}681\ x\ 10^{-7}$ Ω.m with average mean absolute percentage error is 0,31% and coefficient of determination (R^2) 0,97. It shows the magnitude of the effect of the current variable simultaneously on the voltage variable. The resistivity value of brass material based on literature is 0,63 x 10^{-7} Ω.m [8]. So the value of the electrical conductivity of the test results for the brass rod is σ=1,47 x 10^7 $(\Omega.m)^{-1}$ (Literature: electrical conductivity of brass material 1,59 x 10^7 $(\Omega.m)^{-1}$ [8]).

Figure 7(b) shows the resistivity value of stainlesssteel rod is $\rho = 7{,}1\ x\ 10^{-7}$ Ω.m with average mean absolute percentage error is 4,0% and coefficient of determination (R^2) 0,95. The resistivity value of 304 stainless steel material based on literature is 7,3 x 10^{-7} Ω.m). So that the value of the electrical conductivity of the test results for stainless steel rods is σ = 0,14 x 10^7 $(\Omega.m)^{-1}$ (Literature: electrical conductivity value of stainless steel material 0,137 x 10^7 $(\Omega.m)^{-1}$) [8]. Lorenz number can be determined experimentally using equation (4) Wiedemann-Franz law. If the measurements are carried out at an average room temperature of 300 K, the Lorenz number for each test rod can be obtained as shown in table 2 below.

Table 2. Lorenz Number Determination

Material	σ (x 10^7 $(\Omega.m)^{-1}$)	κ (W/m.K)	L x 10^{-8} (W.Ω.K^{-2})	L x 10^{-8} (W.Ω.K^{-2}) (NIST)	Relativeuncertainty (%) to L_0
Brass	1,47	146,87	2,5	2,61 (at 90 K)	3,2
Stainless steel	0,14	15,03	3,5	5,4 (at 78,77 K)	44,8

Table 2 shows the deviation of Lorenz number between the research results and the L_0 number (the degenerate limit). The value of the L number is greater than L_0 number. However, it is lower than the L number at temperature 90 K for brass and at temperature 78.77 K for stainless steel [14]. Significant deviations from the degenerate limit approximately can reach up to 40% or more based on several metal samples at different temperature ranges [10]. Deviation can be caused by a variety of reasons. At low temperatures, in metals, the deviation is caused by the inelastic nature of electron-phonon interactions. The higher Lorenz number can be caused by the presence of impurities in the material and the contribution of phonons to the thermal conductivity and is inversely proportional to temperature. Lorenz number at higher temperature has also been investigated and found to deviate from the Sommerfeld value [10]. The increase in L number is correlated with a decrease in thermopower (absolute value of Seebeck coefficient) [15].

5. CONCLUSION

The measurement of thermal conductivity through experiments with direct temperature measurement techniques can be carried out. The important thing that must be considered is the correction factor by determining the rate of heat change due to environmental influences on the calorimeter. As well as the use of aluminum foil as a blanket to protect the metal rod from interacting openly with the outside environment. When compared to data from the National Institute of Standards and Technology (NIST), the Lorenz number in the result of this research has shown a good agreement, the difference that occurs is due to differences in the temperature of the rods when measuring.

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