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Determination of Thermal Conductivities of Some Metal Materials and Clay

Bello, Rasaq[1*] and Ogundare, Rasheed Toyin[2]

[1]Department of Physics, Federal University of Kashere, Gombe State, Nigeria.
[2]Department of Physics, University of Lagos, Lagos, Nigeria.

Authors' contributions

This work was carried out in collaboration between both authors. Author BR designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author ORT performed the experiment, managed the analyses of the study and managed the literature searches. Both authors read and approved the final manuscript.

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ABSTRACT

This work was carried out to determine the thermal conductivities of some selected metals (copper, brass, steel and aluminium) using silver parameters as standard values to calculate for other four metals. Determination of thermal conductivity of metallic materials is very useful in many engineering applications including electronics, automobiles and civil engineering purposes. The apparatus used in this work include retort stand, metal rods of different materials, burner and thermometers. The thermal conductivity of local material (clay) was also determined after verifying that the method has worked for the materials of known thermal conductivities. This was done by calculating the heat supplied to silver metal rod with a known thermal conductivity of 428 W/m.K. By increasing the temperature at various heat supply (2.5 W, 4.0 W, 6.0 W and 8.0 W), corresponding thermal conductivities were calculated for each metal and the local material. The results showed that with the small range of quantity of heat used in this work (2.5 – 8.0 W), Brass,

**Corresponding author: E-mail: bellorasaq@fukashere.edu.ng;*

Copper and Clay showed a linear increase in thermal conductivity as the quantity of heat increases, while Aluminium and Steel showed a linear decrease in value of thermal conductivity. Also, the thermal conductivity of the local clay was determined to be $9.38\ \frac{W}{m}K$.

Keywords: Conduction; heat; metals; temperature; thermal conductivity.

1. INTRODUCTION

Thermal conductivity is a physical property of materials which is of great importance in physics and engineering. Unlike some physical properties, however, thermal conductivity cannot be directly measured. To determine a material thermal conductivity, intermediate quantities must be determined from which the conductivity may be ultimately calculated [1].

The thermal conductivity is not always constant, and the main factors affecting thermal conductivity are the density of material, moisture of material and ambient temperature. However, increasing density, moisture and temperature the thermal conductivity increases too.

Determination of thermal conductivity is very essential, and various methods have been developed in the recent past for measuring it. The rational design of equipment such as shaft coolers, heaters, and rotary kilns for the heating and cooling of solids requires that the thermal properties of the solids be known. Thermal conductivity (denoted as k, κ or λ) and interfacial thermal conductance play crucial roles in the design of engineering systems where temperature and thermal stress are of concern. To date, a variety of measurement techniques are available for both bulk and thin film solid-state materials with a broad temperature range [2]. Knowledge of thermal conductivity, interfacial thermal conductance and their variation with temperature are critical for the design of thermal systems [3].

In the window building industry "thermal conductivity" is expressed as the U-Factor [4], which measures the rate of heat transfer and inform one how well the window insulates. U-factor values are generally recorded in IP units (Btu/(hr·ft·F)) and usually range from 0.15 to 1.25. The lower the U-factor, the better the window insulates.

The concept of thermal conductivity of solids is not a well understood phenomenon. Transport of heat in solids is governed by the same type of differential equation [5]. Conduction is the most significant means of heat transfer in solids [6]. However, the conduction ability varies from one metal to another [7].

High strength and heat conductivity of metals make them adaptable for different purposes. Determination of thermal conductivity of metallic materials is very useful in many applications from electronics, automobiles and civil engineering purposes [8]. The thermal conductivity of metals must be taken into consideration when determining the area(s) of application.

This work analyzed an experiment used to determine the thermal conductivity of metals. This is to bridge the knowledge gap experienced by some students who have little chance of exploring demonstration or experimentation on the determination of thermal conductivity of materials [9]. This work presents a simple experiment and procedure of analysis in a straightforward manner which students can replicate for other materials. It also provides a general knowledge of thermal conductivity of materials.

This study aimed at determining the thermal conductivity of five different metals by varying the amount of heat supply and compares it with their standard (Experimental) value. To do so, it is necessary to examine the flow of heat through metal samples. This is done by determining the rate of heat flow through a material and using Silver parameters as a case study with thermal conductivity of 428 W/m.k. This was used to calculate the quantity of heat per time flowing through Silver metal rod to calculate the thermal conductivity of other four metals. The thermal conductivity of local material (clay) with unknown existing value was also determined.

2. MATERIALS AND METHODS

This work was carried out in the laboratory of Physics Department of the Federal University of Agriculture, Abeokuta, Nigeria. The apparatus used in this work include retort stand, metal rods of different materials, burner and thermometers.

The metal rods are silver, brass, aluminium, steel and copper. The rods were purchased at Owode Market, Lagos. The market is an international market for metallic rods, sheets and beams in Nigeria's commercial capital. The metal rods used in this work were selected based on their availability in Nigerian market and their diverse applications in the engineering and construction industries.

The following procedures were employed in this work. A retort stand was placed on a table. A rod was hanged at one end of the retort stand which was insulated to prevent heat transfer from the rod to the retort stand. Heat was applied at one end of the rod using a burner as a heater while the other end was kept at a constant temperature.

Holes were made on the rod at 10 cm interval away from the heating point and the thermometer was inserted on the holes to measure the final and initial temperature. This was repeated four times using different quantities of heat which was calculated for each case. The experiment was repeated for the four other rods.

Let us consider a cubic section of a material whose face A is at a higher temperature Θ_1 (say) and let the opposite parallel face B be a temperature Θ_2. Heat will flow from face A to face B and it will be directly proportional to the area of cross-section, since A is the area of the face of a cube more heat will flow i.e.

$$Q \alpha A \qquad (1)$$

It will be directly proportional to the time of flow of heat, i.e

$$Q \alpha t \qquad (2)$$

It will be directly proportional to the difference of temperature of the two faces of the cube. The more the difference of the temperature (Θ_1- Θ_2), the more rapid is the flow of heat i.e

$$Q \alpha (\Theta_1 - \Theta_2) \qquad (3)$$

It will be inversely proportional to the thickness of the cube i.e

$$Q \alpha 1/d \qquad (4)$$

Combining the above equations we have

$$Q\alpha \frac{A(\theta_1 - \theta_2)}{d}$$

Introducing the proportionality constant *k*, we have,

$$Q = \frac{kA(\theta_1 - \theta_2)}{d} \qquad (5)$$

Where *k* depends on the material in which the heat is flowing.

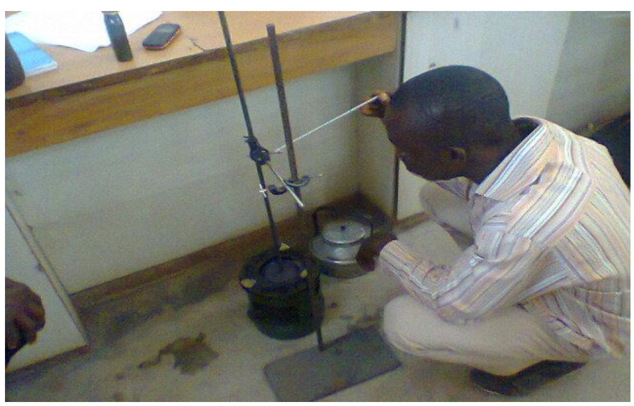

Fig. 1. Experimental setup

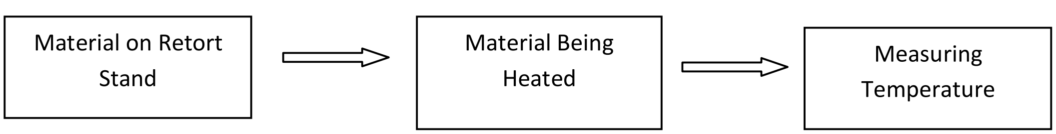

Fig. 2. Block diagram of experimental set up

From equation (5) this constant *k* is known as coefficient of thermal conductivity.

If A = 1cm^2, Θ_1- Θ_2 =1°C, t = 1second, d=1cm.

Thus K can be defined as the quantity of heat that flows for one second through a cube whose opposite faces are maintained at a difference of temperature of 1°C[1].

To interpret the recorded data and determine the experimental thermal conductivities, the most stable range of temperature measurements was selected from the recorded values. The averages were determined for each of the thermocouples on each sample rod. From these values and the physical measurements taken during the setup, the rate of heat flow through the silver rod was calculated using the equation

$$\frac{Q}{t} = \frac{k.A(T_{hot} - T_{cold})}{d} \tag{6}$$

In this equation, the ratio $\frac{Q}{t}$ represents the rate of heat flow i.e. power, *K* is the thermal conductivity, *A* is the cross-sectional area of the sample rod, T_{hot} and T_{cold} are the temperatures at two adjacent thermocouples points, and *d* is the separation between these two points.

Also, to determine $\frac{Q}{t}$ for silver, its known thermal conductivity of 428W/mK was used. From this heat flow rate, which for this experiment was assumed to be same for all five materials, the other four thermal conductivity values were calculated from equation (6) [10].

3. RESULTS AND DISCUSSION

3.1 Results

The quantities of heat passed to the rods were calculated using silver of known thermal conductivity of 428W/mK and applying to equation 1. The experiments were therefore repeated for other rods to determine their thermal conductivities. The results of the thermal conductivities determined are presented in Table 1 and plotted in Figs. 3–7.

Table 1. Result of the experiments

	Heat supply (W)	Silver (W/mK)	Brass (W/mK)	Aluminium (W/mK)	Steel (W/mK)	Copper (W/mK)
	Standard value	**428.00**	**109.00**	**235.00**	**14.00**	**401.00**
1	2.5	428.00	106.10±0.03	244.86±0.04	20.00±0.43	397.90±0.01
2	4.0	428.00	107.22±0.02	239.50±0.02	18.90±0.35	402.00±0.003
3	6.0	428.00	108.50±0.01	238.000.01	17.30±0.24	404.00±0.01
4	8.0	428.00	109.80±0.01	237.20±0.01	16.50±0.18	405.20±0.01

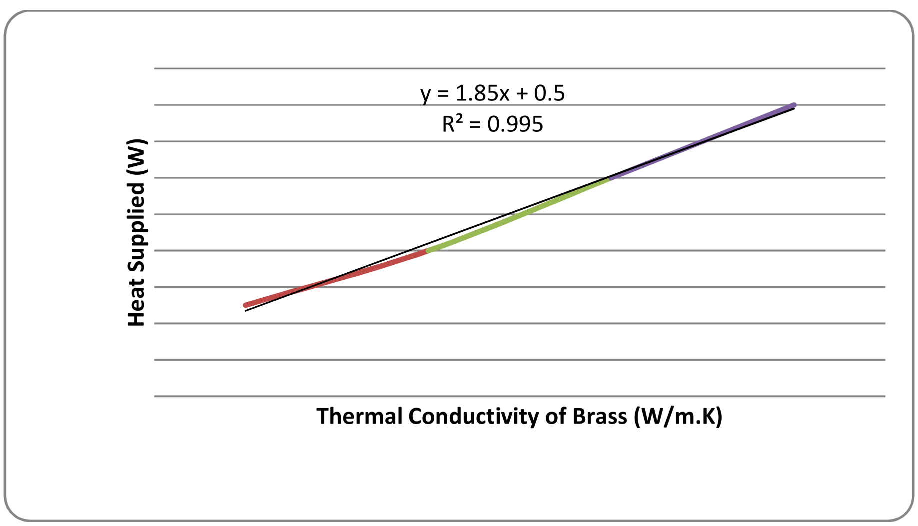

Fig. 3. Graph of heat supplied against thermal conductivity of brass

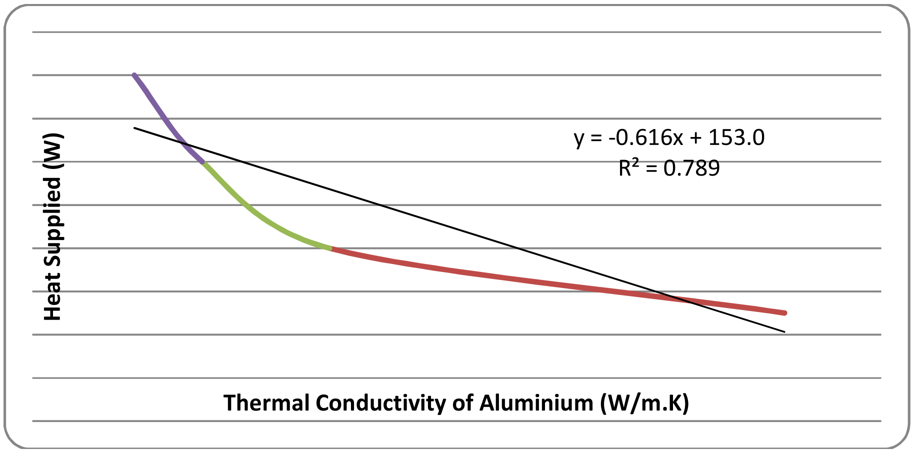

Fig. 4. Graph of heat supplied against thermal conductivity of aluminium

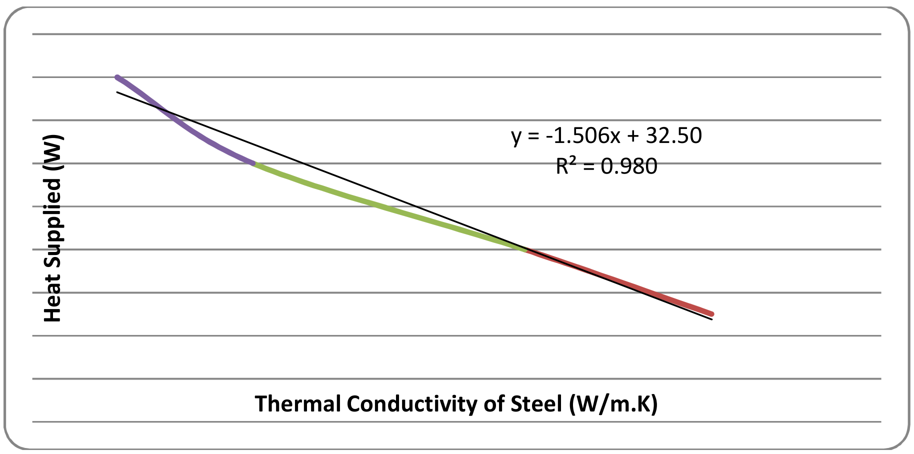

Fig. 5. Graph of heat supplied against thermal conductivity of steel

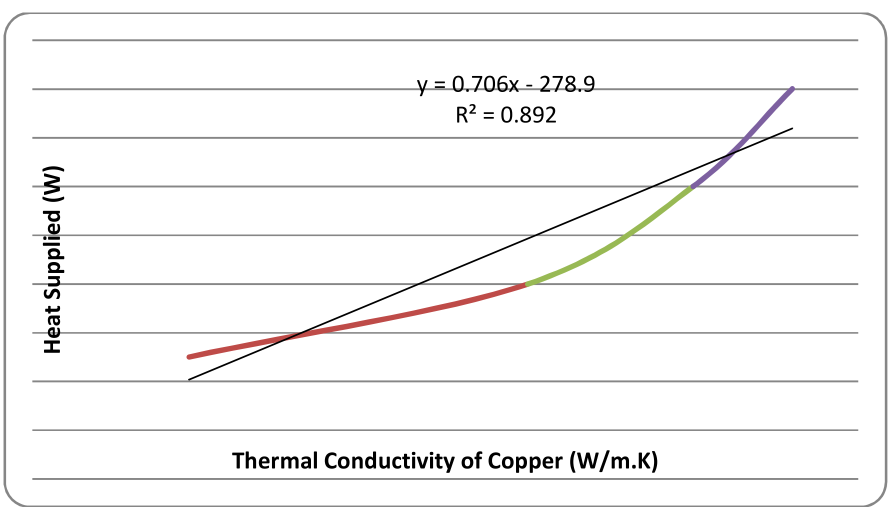

Fig. 6. Graph of heat supplied against thermal conductivity of copper

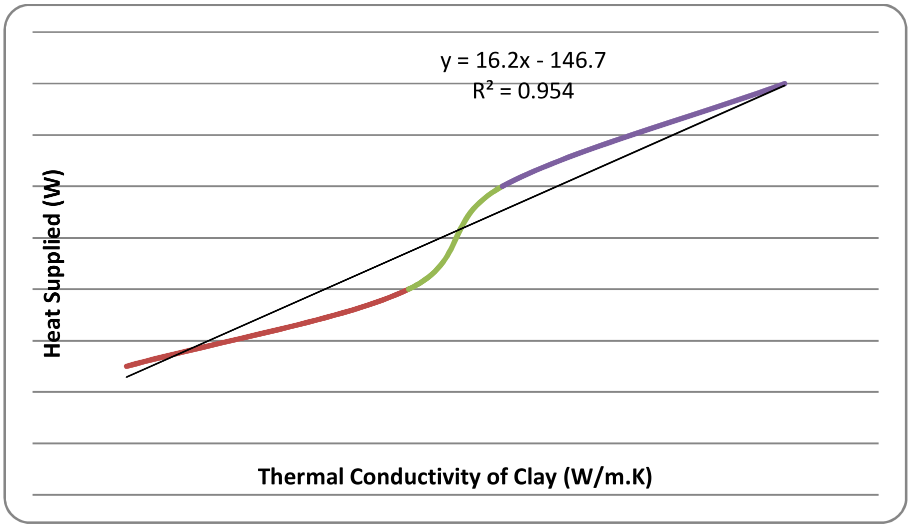

Fig. 7. Graph of heat supplied against thermal conductivity of clay

3.2 Determination of Thermal Conductivity of Clay

Having determined the thermal conductivities of the different metals stated in Table 1 and found that the results obtained were in agreement with standard values obtained from textbooks, the method was now applied to determine the thermal conductivity of local clay obtained within the premises of College of Natural Sciences, Federal University of Agriculture, Abeokuta, Nigeria.

The experiment was set up as described in section 3.0. Clayey soil was moulded in form of rod and it was dried up for a period of two (2) hours. The same quantities of heat used for the other metals were used for the clay rod. The diameter of the clay rod was also 10 cm. The thermal conductivity of clay was calculated using equation 1 as was done previously. Table 2 shows the results obtained.

Table 2. Thermal conductivity of clay

Heat Supplied (W)	Thermal Conductivity (W/mK)
2.5	9.20
4.0	9.35
6.0	9.40
8.0	9.55

From Table 2, average thermal conductivity of clay was obtained as 9.38 W/mK.

3.3 Discussion

Thermal conductivity depends on many properties of a material, notably its structure and temperature. For instance, pure crystalline substances exhibit very different thermal conductivities along different crystal axes, due to differences in phonon coupling along a given crystal axis. Sapphire is a notable example of variable thermal conductivity based on orientation and temperature, with 35 W/(m·K) along the c-axis and 32 W/(m·K) along the a-axis [11].

The values of thermal conductivities of different metal obtained in this work were in agreement with the standard values, this gave the confidence to apply this method to determine the thermal conductivity of local clay. Average value of thermal conductivity of local clay was obtained as 9.38 W/mk. This value is also in agreement with standard value of thermal conductivity of clay with the value of 9.3±0.3W/mk.

Results from Table 1 also indicated that the increase in the value of the quantity of heat supplied has no significant effect on the thermal conductivities of these metals. Theory of thermal conductivity of materials indicated that temperature affects thermal conductivity of materials. However, in this work, this is not so because the range of temperature here is very small. A significant increase in thermal conductivities of materials could only be noticeable over a wider range of temperature. It is well known that thermal conductivity is the ability of materials to conduct heat. In the present work, thermal conductivity has been determined for some metals. Results showed that with the small range of quantity of heat used in this work (2.5 – 8.0 W), Brass, Copper and Clay showed linear increase in thermal conductivity as the quantity of heat increases, while Aluminium and Steel showed a linear decrease in value of thermal conductivity.

Fig. 3 showed a graph of quantity of heat supplied against thermal conductivity of brass. The graph showed a linear graph with values of thermal conductivity of brass increasing with increase in quantity of heat supplied. The graph has a regression equation of

$$Y = 1.85x + 0.5 \quad (7)$$

and R – squared value of 0.995. This shows that equation (7) will give 99.5% prediction accuracy.

Fig. 4 showed a graph of quantity of heat supplied against thermal conductivity of aluminium. The graph showed a decrease in the value of thermal conductivity of aluminium with an increase in quantity of heat supplied. The graph has a regression equation of

$$Y = -0.616x + 153.0 \quad (8)$$

and R – squared value of 0.789. This shows that equation (8) will give 78.9% prediction accuracy.

Fig. 5 showed a graph of quantity of heat against thermal conductivity of steel. The graph showed a decrease in the value of thermal conductivity of steel with increase in quantity of heat supplied. The graph has a regression equation of

$$Y = -1.506x + 32.50 \quad (9)$$

and R – squared value of 0.980. This shows that equation (9) will give 98.0% prediction accuracy.

Fig. 6 showed a graph of quantity of heat supplied against thermal conductivity of copper. The graph showed an increase in the value of thermal conductivity of copper with increase in quantity of heat supplied. The graph as a regression equation of

$$Y = 0.706x – 278.9 \quad (10)$$

and R – squared value of 0.892. This shows that equation (10) will give 89.2% prediction accuracy.

Fig. 7 showed a graph of quantity of heat supplied against thermal conductivity of clay. The graph showed a linear increase in the value of thermal conductivity of clay with increase in quantity of heat supplied. The graph has regression equation of

$$Y = 16.2x – 146.7 \quad (11)$$

and R – squared value of 0.954. This shows that equation (11) will give 95.4% prediction accuracy.

4. CONCLUSIONS

From this work, the thermal conductivity of clay was determined which was confirmed by calculating the thermal conductivity of some selected metals (Copper, Aluminium, Brass and Steel) using Silver parameters and the values obtained were compared with the textbook values which showed no significant difference. The values of thermal conductivity of metals determined in this work ranged from 106.10 – 109.80 W/mK for brass, 237.20 – 244.86 W/mK for aluminium, 16.50 – 20.00 W/mK for steel and 397.90 – 405.20 W/mK for copper, all in close agreement with standard values of 109.00 W/mK, 235.00 W/mK, 14.00 W/mK and 401.00 W/mK respectively.

In this study, thermal conductivity has been determined for some metals. Results showed that with the small range of quantity of heat used in this work (2.5 – 8.0 W), Brass, Copper and Clay showed linear increase in thermal conductivity as the quantity of heat increases, while Aluminium and Steel showed a linear decrease in value of thermal conductivity. Thermal conductivity of clay was determined to be 9.38 W/m.K. It was noted that, clay has an experimental thermal conductivity value of 9.3±0.3 W/mk.

Clay is of great importance for commercial use. It is used in bakery in order to prevent heat loss because it absorbs heat. Clay is found in most part of Nigeria with long history of existence. It was used in ancient times in building of huts and even in modern day Nigeria, it is still being used in building construction.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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