

DEVELOPMENT AND PERFORMANCE EVALUATION OF A DEVICE FOR THERMAL CONDUCTIVITY MEASUREMENT

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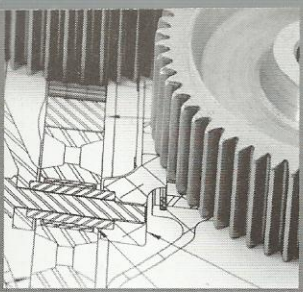
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Abstract

Thermal conductivity (k) of metallic materials as an important parameter with far-reaching applications should be easily determined from any functional laboratory. The design and fabrication of a simple device for thermal conductivity measurements of metals was done to meet the laboratory and research needs. The procedures employed include the design, construction and testing. The device is made up of the sample holder, rod heater, thermometer probe cavity and structural wooden frames. With this device, an experimental test could be made in few hours through the technique of electrical heating of specimen and taking of thermometer readings. This work presents a suitable reproducible device for determining the thermal conductivity of metals in disc form, which would not need either complex arrangements or large quantities of the substances to be examined. The values of k obtained using this device compared favourably with standard values and other research works in the literature.

Keywords: Thermal conductivity, design, construction, testing, electrical heating, measurement





1. Introduction

Thermal conductivity (k) device cannot actually be attributed to any particular time but apparatus in general has its concept in engineering science that began in the 1950s. Its measurements are of considerable interests to many sectors of materials science and engineering [1].

Thermal conductivity otherwise known as heat conduction, of a material is defined as the rate of heat transfer through a unit thickness of material per unit area per unit temperature difference between the faces causing heat flow under a steady state boundary condition [2,3,4,5,6]. The thermal conductivity of a material is a measure of the ability of the material to conduct heat. This implies that heat conduction occurs when a body is exposed to temperature gradient and becomes serious when different parts of a body experience differential temperature ratings [7]. The consequence of this is the initiation of heat flow from the higher temperature region to the lower region. If the material (metal) is uniform (in terms of composition and dimensions) then the temperature along a chosen length decreases uniformly with distance from the relatively hot region to the cold point. And when the temperature at any particular point of a body remains constant with time, a condition of steady state heat flow is assumed to have been established [7].

The thermal conductivity of a material depends on many properties of the material, essentially

upon the following factors [4,5,6,8,9]: material structure, density of the material, moisture content, and the operating conditions (pressure and temperature). Materials with high k -values are good conductors of heat, whereas materials with low k -values are good thermal insulators. Conduction of heat occurs most readily in pure metals, less so in alloys, and much less readily in non-metals [2,3,4]. In metals, thermal conductivity approximately tracks electrical conductivity according to the Wiedemann-Franz law (based on experimental results), as freely moving valence electrons transfer not only electric current but also heat energy [5,6,10] in the outer shell electrons through the crystal lattices.

Generally speaking, there are a number of possibilities to measure thermal conductivity, each of them suitable for a limited range of materials, depending on the thermal properties and the medium temperature. Various relatively new efforts of suitable methods for measuring thermal conductivity have been performed by Battaglia and Leoni [1], Ajimotokan and Ogunsola [2], Owate et al. [2], Ogunsola [6], Srivastava [11], Eyegheleme [12] etc.

This paper presents a suitable reproducible device for determining conductivities of metals in disc form by method of electrical heating, which would not need either complex arrangements or large quantities of the substances to be examined.

2. Design Considerations

In the design of this device, engineering practice that involves utilizing scientific principles to design components and systems that performed reliably, satisfactorily and cost effectively was employed. However, the materials for the fabrication of this device were carefully studied considering strength, suitability and local availability.

2.1 Theoretical Considerations

Thermal conductivity k as an intensive property of a material depicts the ability to conduct heat within and through such material. Generally, the quantity of heat, Q per unit time (in watts), in a given perpendicular direction to the surface area A (in m^2), the temperature difference ΔT (in $^{\circ}C$ or K) and the thickness of conducting surface separating the two temperatures L (in m), under steady state boundary condition as given by Ajimotokan and Ogunsola [2], Rajput [4], Yunusa [5], Ogunsola [6] and Meadan [7] is:



$$k = \frac{QL}{A\Delta T} \quad (1)$$

where Q = Quantity of electrical energy absorbed per second, L = Thickness of the specimen, ΔT = Change in temperature of specimen when heated for t sec, A = Cross sectional area of specimen. Mathematically, the observed design implies that the expression for thermal conductivity k is given as

$$k = \frac{QL}{A(T_2 - T_1)} \quad (2)$$

Source: Meadan [7]

where Q = Quantity of electrical energy absorbed per second, L = Thickness of the specimen, T_2 = Temperature of specimen when heated for t seconds, T_1 = Temperature of specimen before heating.

$$Q = VI \quad (3)$$

Source: Sachdeva, [13]

where V = Voltage per second and I = Current delivered
For a cylindrical specimen, the area of the specimen A (in mm^2) is given as

$$A = \frac{\pi d^2}{4} \quad (4)$$

where d = diameter of the specimen.

The thermal conductivity (k) can be calculated from equation (2) as given.

2.2 Design Calculations

For a mild steel specimen holder of 14mm diameter and 200mm long under steady loading;

$$\begin{aligned} \text{The area of the rod, } a &= \frac{\pi d^2}{4} \\ &= \frac{\pi \times 14^2}{4} = 154 \text{mm}^2 \end{aligned}$$

Weight of 1kg of specimen = $1 \text{kg} \times 9.8 = 9.8 \text{N}$

Thus, weight of three specimens of aluminium, brass and mild steel is 29.4N

For a disc specimen of diameter 95mm by 25mm thickness,

$$\text{Area of a disc, } A = \frac{\pi d^2}{4} = \frac{\pi \times 95^2}{4} = 7.09 \text{mm}^2$$



Thus, the area of the three disc specimens = $7.09 \times 3 = 21.27 \text{ mm}^2$

Therefore, normal stress

$$\sigma = \frac{\text{Load}}{\text{Area}} \quad (5)$$

Source: Patnaik and Hopkins [14]

$$\text{Yield stress} = \frac{29.4}{21.27} = 38 \text{ N/mm}^2$$

$$\text{Design stress} = \frac{29.4}{154} = 0.19 \text{ N/mm}^2$$

It is common practice to size machine elements, so that the maximum design stress is below the Ultimate Tensile Stress (UTS) or yield stress by an appropriate factor - the Factor of Safety (or Safety Factor), based on UTS or Yield Strength [15].

2.3 Principle of Thermal Conductivity Measuring Device Operation

The working principle of the device is based on the principle that heat conduction occurs in a metallic material as a result of the initiation of heat flow from the higher temperature region to the lower region.

2.4 Operation Mechanism

With the device main's connected to power source, heat is generated and the rod heater gains heat; and resultant conduction by the specimens. The heated specimens and their rate of heat conduction are measured by taking the thermometers readings.

3. Materials and Methods

A device for determining k -values for metals in disc form was designed and fabricated. The procedures employed include the design, construction and testing (estimation of thermal conductivities of aluminium, brass and mild steel) stages. The materials used were wooden frames, thermal insulators (alumina-ceramics bushings), heating system, and mercury in glass thermometers.

3.1 Equipment Description

The system is made up of the following parts namely: specimen holder, rod heater, thermometer probe cavity and structural wooden frames as depicted in Plate 1.

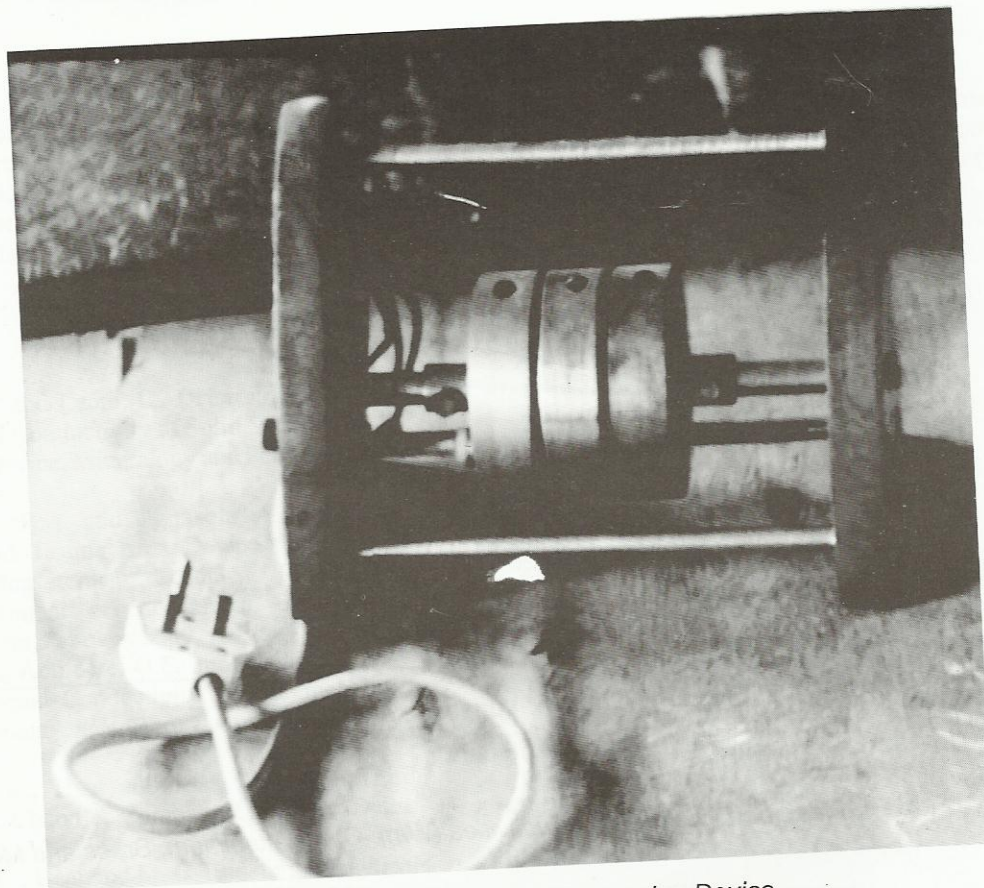


Plate 1: Thermal Conductivity Measuring Device

Legend: A-Specimen holder, B-Rod Heater, C-Thermometer probe cavity, D-Structural wooden frame, E-Specimen

The sample holder was designed to hold three disc specimens of diameter 95mm by 25mm thickness each; the heating cavity (a horizontal circular eccentric opening of 17mm diameter on the test specimen) to accommodate the rod heater with an electrical power supply system. This cavity was lagged with thermal insulators for the purpose of conserving the heat generated by the heater and to create a temperature gradient along the test

specimens. This allows one to measure the temperature difference along the specimen only. Vertical eccentric holes of 8mm diameter by 80mm depth were drilled through the specimen surface to allow for the insertion of thermometer for temperature measurements. This cavity was equally insulated for heat losses to be minimized by adapting lagging process.

4. Results and Discussion

The observed temperature curves for aluminum, brass and mild steel at different time intervals are depicted in Figure 1. The temperature gradient values deduced from Figure 1 consequently were used to determine the thermal conductivity values for aluminium, brass and mild steel as presented in Table 1 with their mean values and percentage errors.

The corresponding plots of variations of temperature as a function of time are shown in Figure 1. Rate of heat conduction are shown to be highest in aluminum followed by mild steel then brass. Primarily, the rate of heat conduction of brass was higher than that of mild steel. This implies that heat conduction occurs when a body is exposed to temperature gradient

and becomes serious when different parts of a body experience differential temperature ratings. The consequence of this is the initiation of heat flow from the higher temperature region to the lower region [3]. If the material (metal) is uniform (in terms of composition and dimensions) then the temperature along a chosen length decreases uniformly with distance from the relatively hot region to the cold point. This simple device, which would not need either complex arrangements or large quantities of the substances to be examined, demonstrates that the measurement of thermal conductivities of metals and alloys with far-reaching applications can easily be determined to a great extent of accuracy.

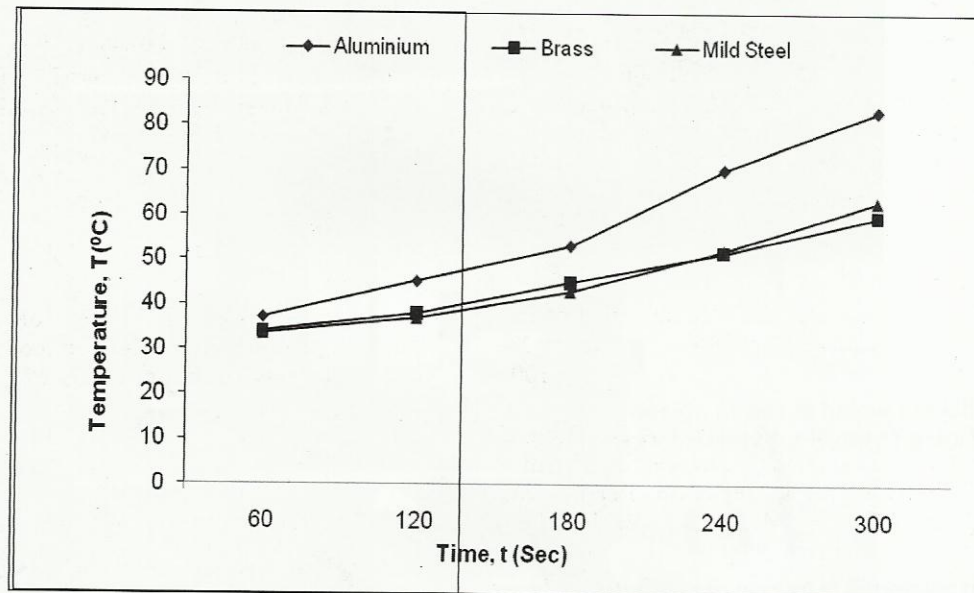
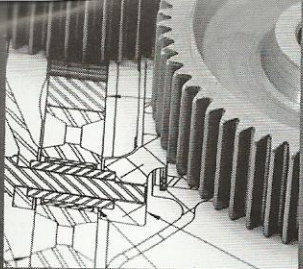


Figure 1: Graph of Variations of Temperature with Time

Table 1: Measured Thermal Conductivities ($W/m^{\circ}C$) for Aluminium, Brass and Mild Steel

No. of Measurement s	Aluminium	Brass	Mild Steel
1	236	104	246
2	240	108	251
3	241	111	248
4	236	109	245
5	234	106	242
Mean	237.4	107.6	246.4
Std Values	236±1	106±1	245±2
% Error	0.59	1.51	0.57

5. Conclusions

A device for determining k-values for metals in disc form was designed and constructed. Results obtained compared favourably with standard and other research works despite differences in design and the instrumentation systems. The variations of percentage error was between 0.57 to 1.51% as depicted in table 1, relative to

standard values of k of aluminium ($236 \pm 1 W/m^{\circ}C$), brass ($106 \pm 1 W/m^{\circ}C$) and mild steel ($245 \pm 2 W/m^{\circ}C$) [3,5,7,8]. Thus, the values of k obtained were within standard values and compared favourably with other research works in the literature, which is an indication that the device can be used for the measurement of k.



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