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DESIGN OF AN INTERFACE TO MEASURE THERMAL CONDUCTIVITY IN AN AUTOMATED FURNACE

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ABSTRACT

This paper takes a sincere attempt to enable advanced research in electric furnace simulation in order to determine thermal conductivity. A simple model was adopted for determining the thermal conductivities of brass, aluminium and copper materials using a system designed, constructed and tested and applying steady state method. C-Sharp program was developed using the standard subroutines to solve the model equations in order to predict the thermal conductivity over a wide range of temperature and process conditions. The furnace was demarcated into heating chamber (made by sandwiching heating coil within thermal insulators), sample holder region and the cold end area. The thermal conductivities of copper, aluminium, and brass were measured using the system and the results obtained were compared statistically with other standards. It was observed that the measured thermal conductivity values were 112.9, 244.4 and 403.2 $Wm^{-1}K^{-1}$ for brass, aluminium and copper respectively. These results compared relatively well with other standard values. Such values are in order 109, 236 and 396 $Wm^{-1}K^{-1}$.

KEYWORDS: Thermal Conductivity, Conduction and Steady State

INTRODUCTION

Thermal conduction is the transfer of heat from one part of a body to another with which it is in contact. Thermal conductivity, k, is defined as ability of material to transmit heat and it is measured in watts per square metre of surface area for a temperature gradient of 1 K per unit thickness of 1 m,(Dewitt, 1990).

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

Important is inner structure of materials. Metals and other dense solid materials tend to have high levels of conductivity, whereas materials with very small amount of solid matter and large proportion of voids (gas or air bubbles, not large enough to carry heat by convection) have the lowest thermal conductivities.

Thermal conductivity is important in material science, research, electronics, building insulation and related fields, especially where high operating temperatures are achieved. High energy generation rates within electronics or turbines require the use of materials with high thermal conductivity such as copper, aluminium, and silver. On the other hand, materials with low thermal conductance, such as polystyrene and alumina, are used in building construction or in furnaces in an effort to slow the flow of heat, i.e. for insulation purposes.

The broad aim of this research work is to design an interface that measures thermal conductivity of a material in an electric furnace.

Thermal Conductivity Measuring Methods

According to Callender (1987), there are a number of possibilities to measure thermal conductivity, each of them suitable for limited range of materials, depending on the thermal properties and the medium temperature. In general there are two basic techniques of measurement:

- The **steady state** technique performs a measurement when material that is analysed is in complete equilibrium. This makes the process of signals analysis very easy (steady state implies constant signals). The disadvantage generally is that it takes a long time to reach the required equilibrium.
- The **non-steady state** techniques perform a measurement during the process of heating up. The advantage is that measurements can be made relatively quickly. Transient methods are usually carried out by needle probes.

Several experimental approaches exist for measuring the thermal conductivity of solids. An early method, called the guarded hot plate technique (ASTM 1997), imposes a measured heat flux across a sample of known thickness. The thermal conductivity is computed from a discrete approximation of Fourier's law

$$k = \frac{qL}{\Delta T} \qquad 2.1$$

In equation (2.1), q is the measured heat flux, L is the sample thickness, and ΔT is the temperature difference across the sample. Another experimental approach is known as the flash diffusivity method (Parker *et al* 1961). In the flash diffusivity method a short duration burst of energy, typically from a laser, heats the surface of a thin specimen approximately 2 cm in diameter. Transient temperature is measured on the face of the specimen opposite the heating. Thermal diffusivity is computed as (Parker *et al* 1961)

$$\propto = \frac{k}{\rho C} = \frac{1.38L^2}{\pi^2 t_{\frac{1}{2}}} \qquad 2.2$$

where L is the specimen thickness and $t_{1/2}$ is the time required for the temperature at the back surface to reach one-half its maximum, the so called half-time (other time intervals may also be used, e.g. $t_{1/3}$, $t_{1/4}$).

For good conductors of heat, Searle's bar method can be used (Callister, 2003), whereas for poor conductors of heat, Lees' disc method can be used (Halliday et al., 1997).

2.2 DETERMINING OF THERMAL CONDUCTIVITY IN STEADY STATE

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 that 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 (Cairns et al,2003). Callender (1987) stated that 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 established.

Thermal conductivity k in steady state is given by formula:

$$k = \frac{QL}{A(T_1 - T_2)} \qquad 2.3$$

Where,

$\dot{Q}$ = Quantity of electrical energy delivered per second as calibrated in the heater (W)

L = Distance between T_1 and T_2 (meter).

T_2 = Temperature of hot point (^oC)

T_1 = Temperature of cold point (^oC)

A = Cross al area of specimen (per square meter).

MATERIALS AND APPARATUS

The materials used in this project work are Control interface box, Data acquisition board, a Personal Computer (PC), two type C thermocouples, a variable resistor (varactor), a voltmeter, a clamp meter, resistance heating furnace, the monitoring software and foundry controller which are written in C-sharp and C+ programming languages respectively and the test samples; copper, brass and aluminium of known length, breadth and thickness are used.

Method

The system of thermal conductivity measurement used in this project work is the modified form of steady state method of Smith's thermal conductivity apparatus. The procedures employed include the design stage, construction and testing (estimation of thermal conductivities of copper, aluminium and brass).

Design Stage

The system consists of three parts namely; computer hardware parts, computer software and the electric resistance furnace design.

Computer Hardware

The computer hardware which comprises of Control interface box, Data acquisition board, a Personal Computer (PC), two type C thermocouples and resistance heating furnace were designed such that they are interactive and can be easily modified with respect to other parts (i.e. the software and the electric resistance furnace design). The thermocouple which is of $50\mu V/^oC$ Seeback coefficient was powered by 5V DC microcontroller and connected to the connectors and then amplified and filtered by the amplifier. The bluetooth connector on the printed circuit board (PCB) houses the bluetooth device which helps to relay the sensed temperature by the thermocouple wirelessly. The push buttons and indicators were connected to the three-phase contactor and the circuit breaker through which the heating wire is connected. The heating wire connects the vareactor, clamp meter and voltmeter to the heating coil and control interface box as shown in figure 3.1.

Computer Software

The second part is the software which includes the monitoring software and foundry controller which are written in C-sharp and C+ programming languages respectively. The circuit design was coupled with the foundry; serving as the foundry controller. The control board monitors the temperature of the foundry.

1. Vareactor. 2. Clamp meter. 3. Volt meter. 4. Variable resistor.

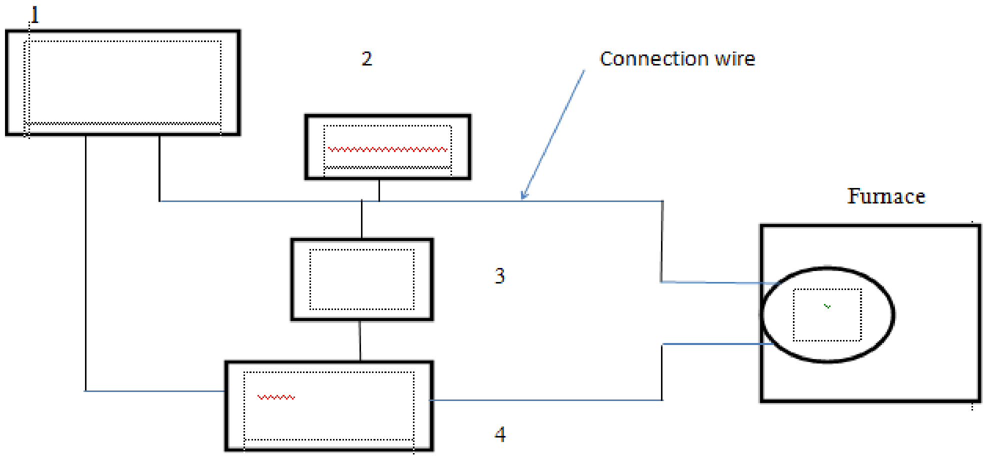

Figure 3.1 : Diagram Showing The Connection of the Various Components of the Hardware

This information is relayed wirelessly using bluetooth connection which will allow basic commands to be issued to the PC; control foundry temperature, control the starting and stopping of the heating process at a distance of up to ten meters (10m) between the control interface box and the PC, on which the monitor software is running. The software receives this information and uses these to draw graphs showing the parameter trends in the foundry.

Electric Resistance Furnace Design

This system consists of three parts namely; the heating chamber, sample holder chamber and the cold-end chamber. The heating chamber has an embedded heating coil (heater) with an electrically power supply system. The chamber was generally lagged with thermal insulators for the purpose of controlling and conserving much of the heat generated by the heater. Part of the test specimen was allowed to extend into this in order to create a temperature gradient along the test sample. This allows one to measure the temperature difference along the samples. The specimen chamber was designed to hold either the cylindrical or rectangular specimen. Two circular openings (of known diameter) were drilled through the specimen surface for the insertion of thermocouples during temperature measurements. This chamber was equally insulated from much heat losses by adapting lagging process. The cold-end consists of a chamber for ice-block storage and provision for water drain-out. The other end of the specimen also spills into this thereby creating the thermal gradient required for heat flow.

Theory

The description of the design implies that the expression for thermal conductivity is given by **k** as derived by Fourier law of conduction

$$\dot{Q} = \frac{Q}{t} = -kA\left(\frac{dT}{dx}\right) = kA\left(\frac{T_1 - T_2}{L}\right) \tag{3.1}$$

$$k = \frac{\dot{Q}L}{A(T_1 - T_2)} \tag{3.2}$$

$$k = \frac{QL}{At\,(T_1 - T_2)} \tag{3.3}$$

Where,

$\dot{Q}$ = Quantity of electrical energy delivered per second as calibrated in the heater (W)

Q = Quantity of heat supplied by the heater (J)

L = Distance between T_1 and T_2 (meter).

T_2 = Temperature of hot point (^oC)

T_1 = Temperature of cold point (^oC)

A = Cross al area of specimen

(per square meter).

t = time taken to reach steady state (seconds)

The thermal conductivity k is calculated from the expression given above where, the solid specimens used were cylindrical or rectangular in shape and the cross-al area A, employed in equation 3.3 was given by

$$A = L \times B \tag{3.4}$$

(Rectangular shape test sample)

$$A = \pi\frac{d^2}{4} \tag{3.5}$$

(Circular shape test sample)

Where, L= length of the test sample (m), B= breadth of the test sample (m) and

d = diameter of the cylinder (m).

Consequently, the current (power produced) was regulated by the electrical system of the heater. This implies that by regulating the allowed current through the resistance coil of the heater, the power of the heating wire rises accordingly.

$$Q = I \times V \tag{3.6}$$

Where, I= current (Amperes) and

V= voltage (volts)

Testing and Calibration of the Measurement System

The measurement equipment proper consisted of two s of electrical circuits, namely a power supply and a temperature measurement. Connected to this measurement equipment proper were a resistance heating furnace for measurements at high temperatures, a 240V AC power source unit, and an interface unit for automatic measurement, calculation and control, and a PC. Firstly, the system was connected to an electrical power supply unit of 240 volts and allowed to be connected through Bluetooth to the computer interface. The furnace was allowed to be thermally stable, at such the sensed temperature of the two thermocouples are equal. A specimen of known dimensions (which will be stated later for aluminium, copper and brass) which was machined to fine finish and washed in de-ionized water, and dried in open air was used for the measurement. At this temperature, the specimen was individually placed in the sample holder. The thermocouple 1 was inserted in the drilled hole on the specimen close to the heater (in the heating chamber) and the thermocouple 2 was inserted in that close to the ice cubes (in the cooling chamber) and temperature T_1 and T_2 were recorded for each of the respective thermocouples. The heater is on (as indicated by the green light on the control interface box), and corresponding temperatures at point 1 and point 2 were recorded over a log period of one minute, automatically by the control system. Measurements were obtained when the temperature was fairly stable and, the measured temperature gradient was applied to equation 3.3 in obtaining the values of the thermal conductivities for the samples. Similarly, the thermal conductivities for each sample were determined at increasing power supply (temperature). This was achieved by increasing the electrical power supply through the adjustable control knob

Plate 3.1: The Arrangement of the System

RESULTS

The thermal conductivities, k, heat supplied, Q, time to reach steady state, t, and their corresponding temperatures, T_1 and T_2, for copper, aluminium and brass were presented in Table 4.1 below.

Table 4.1: Measured Thermal Conductivities ($Wm^{-1o}C^{-1}$) for Copper, Aluminium and Brass at Different Q

S/N	Q (J)	k_{brass}	$k_{aluminium}$	k_{copper}
1	288	114.851	238.095	409.132
2	330	107.770	282.922	350.997
3	385	108.821	237.654	422.497
4	486	113.369	232.843	347.586
5	520	117.226	273.569	385.185
6	574	116.569	233.106	432.916
7	660	116.850	242.504	465.608
8	736	107.863	245.725	405.988
9	850	106.104	231.481	391.770
10	936	119.556	225.694	420.20
Mean		112.90	244.36	403.19

Graph of t, k, T_1 and T_2 against Q for each of the test samples

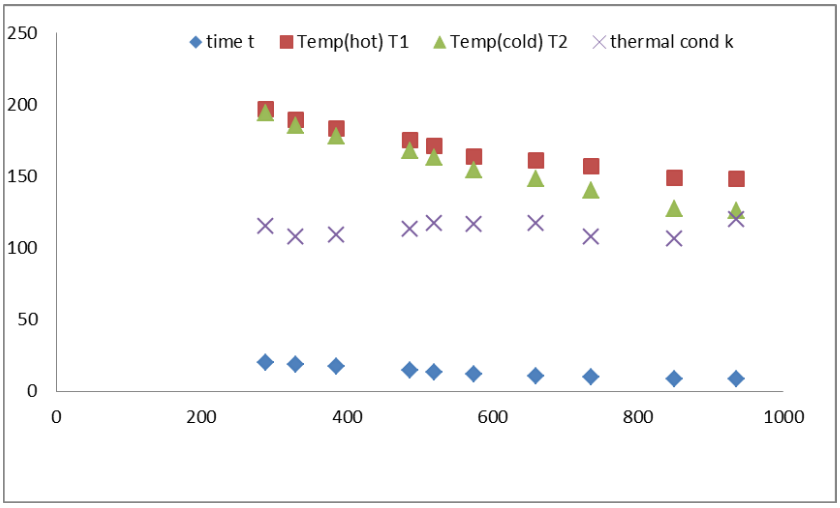

Figure 4.1: Graph of t, k, T_1 and T_2 against Q for brass

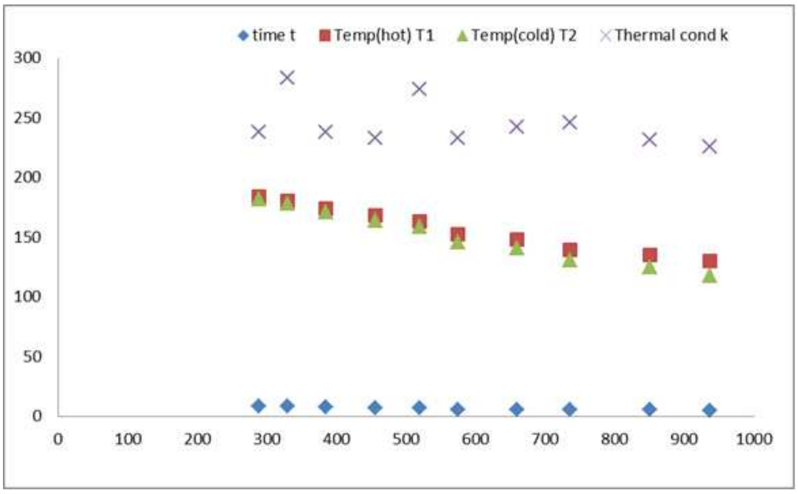

Figure 4.2: Graph of t, k, T_1 and T_2 against Q for aluminium

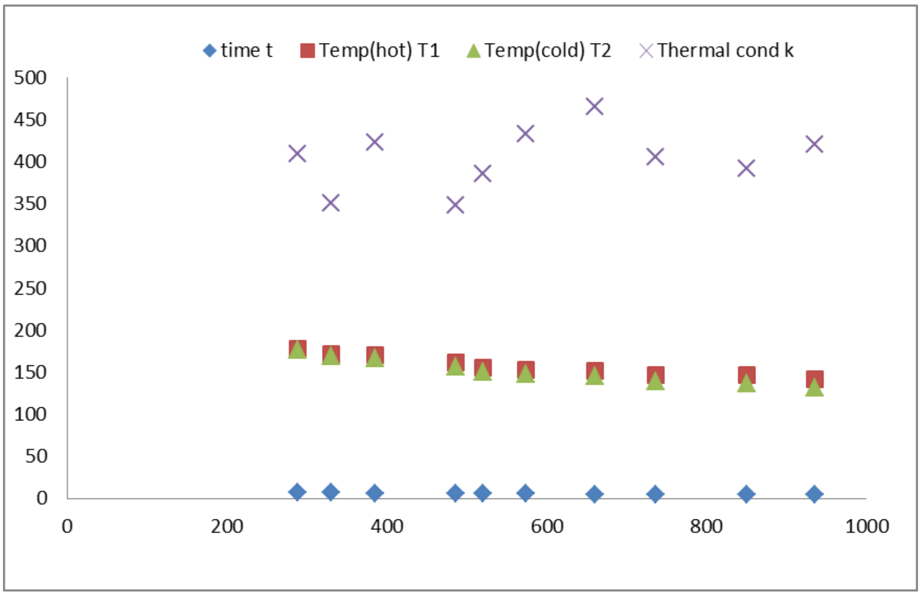

Figure 4.3: Graph of t, k, T_1 and T_2 against Q for copper

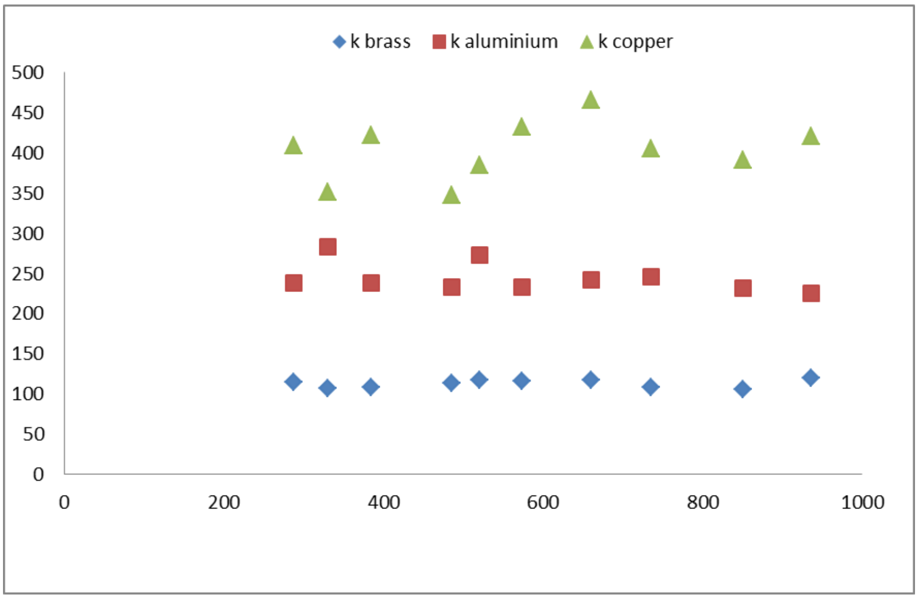

Figure 4.4: Graph of k against Q for brass, aluminium and copper

Discussion of the Results and Graphs

Figure 4.1 shows graph of t, k, T_1 and T_2 against Q. From this figure, it takes 20.2 minutes for the brass sample to reach steady state at 288J of heat supplied. This time decreases significantly to 8.6 minutes when a quantity of 936J of heat was supplied. This shows that the heat supplied increases with decrease in the time required to reach steady state, this fits perfectly with the relationship as indicated in equation 3.1. Over the various quantity of heat supplied, it could be seen that there is little difference between the temperature difference (T_1- T_2) as the heat supplied increases.

Considering figure 4.2, the same quantity of heat was supplied as that used for brass. Here, it takes 8.4 minutes for the aluminium sample to reach steady state at 288J of heat supplied. This time decreases significantly to 4.8 minutes when a quantity of 936J of heat was supplied. This shows that the aluminium test specimen attained steady state faster compared to the brass and also the former has higher thermal conductivity. It could also be deduced that increase in the quantity of heat supplied leads to increase in the temperature difference.

Furthermore, figure 4.3 shows that the copper test specimen attained steady state faster and has higher thermal conductivity compared to the brass and aluminium at the same quantity of heat supplied. Here, it takes 7.3 minutes for the copper sample to reach steady state at 288J of heat supplied. This time decreases significantly to 4.2 minutes when a quantity of 936J of heat was supplied. Also, it could be deduced that increase in the quantity of heat supplied leads to increase in the temperature difference.

The measured thermal conductivities for copper, aluminium and brass are presented in Table 1 with their mean values. It was observed that copper has the highest value of thermal conductivity followed by aluminium and the least is brass.

CONCLUSIONS

From the results, it was discovered that the quantity of heat supplied affected the time taken to reach steady state, which is showed an inverse proportionality relationship. Brass which has the lowest thermal conductivity of 112.9 $Wm^{-1o}C^{-1}$

has the highest time to reach steady state and copper which has the highest thermal conductivity has the lowest time to reach steady state. Hence, it can be concluded that the quantity of heat supplied and the microstructure of the test samples greatly influenced the time taken to reach steady state.

Additionally, the temperature difference between the temperature sensed by thermocouple 1 in the hot chamber (T_1) and that of thermocouple 2 (T_2) in the cold chamber increases with the increase in the quantity of heat supplied. Also, at high conduction time, the temperatures are very high; this was due to the continuous heating of the test sample before it reaching steady state was reached. In summary, the lower the quantity of heat supplied, the higher the time taken to reach steady state , the higher the temperature and the lower the temperature difference and vice versa.

This experiment demonstrates that the measurement of thermal conductivities of some metals and alloys can be achieved to great extent of accuracy by employing the simple and reproducible design presented. The values of thermal conductivities obtained were relatively within standard value despite some heat sinks process.

REFERENCES

1. Blanpied WA (1983). Thermal Conductivities of Metals and Alloys of Low Temperature. John Wiley and Sons Inc. New York.
2. Buschow, K. H. J(2001).*Encyclopedia of materials : science and technology*, Elsevier, 2001 ISBN 0-08-043152-6, p. 5021 table 1
3. Callender JP (1987). Methods of Measuring Thermal Conductivity of Materials. McGraw Hill, New York.
4. Callister, William (2003). “Appendix B” Materials Science and Engineering. An introduction. John Wiley & Sons, INC 757. ISBN 0- 471-22471-5.
5. Dewitt DD (1990). Fundamentals of Heat and Mass Transfer 3rd ed. McGraw Hill, New York.
6. http://en.wikipedia.org/wiki/Thermal_conductivity
7. Gee MG (1980). Electrical Properties of useful Conducting Materials. Heinemann, London.
8. Grimval G (1986). Thermophysical Properties of Materials, Student Edition, Wohlforth, India.
9. http://www.engineeringtodbox.com/thermal-conductivity429.html 2/22/2007
10. Meadan CT (1990). Thermal Conductivity of materials Southampton Technical College Press, Southampton, UK. pp. 15-16.
11. I.O. Owate, O. E. Abumere and G.O. Avwiri (2007), A device for thermal conductivity measurement in a developing economy, Scientific Research and Essay Vol. 2 (4), pp. 122-126
12. http://tpm.fsv.cvut.cz/student/documents/files/BUM1/Chapter16.pdf
13. Zemansky MW, Dittman RH (1993). Fundamental Concept of Heat Flow, 6th Ed. McGraw Hill, London.