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A STUDY ON THE EFFECT OF THERMAL CONDUCTIVITY OF METALS/ALLOY WITH RISE IN TEMPERATURE AT DIFFERENT DISLOCATION

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Abstract

The variation of thermal conductivity due to temperature with respect to displacement in different conducting material metals (iron rod, copper rod) and alloy (stainless steel) has been measured at different dislocations. From our study, we conclude that materials with higher thermal conductivity tend to conduct more heat than materials with lower conductivity for a given temperature at different dislocations. Copper metal exhibit more disparity in thermal conductivity as compared to stainless steel and iron. We also observed that during the cooling process, the material dissipates heat quickly to solidify the conducting materials faster. This study involved the applications of heat in terms of conducting materials that absorb or dissipate the heat from the source to maintain the temperature of the system under study.

1. Introduction

Thermal conductivity is a measure of how well a material transfers heat. Metals are highly important in making electronic devices as they are good conductors of electricity. Copper, aluminium, tin, lead, and magnesium are often used in making parts of phones, laptops, computers, and automotive electronics. Copper is cost-efficient and is used for electrical wiring. Lead is used for cable sheathing and making batteries. Zhu et al. [1] used the guarded-axial heat-flow technique for accurately measuring thermal conductivity between temperatures 78 and 400 °K on small rod samples, and results on a 99.999% pure polycrystalline copper specimen ($\rho 273.16°K/\rho 4.2°K = 9.0 \times 102$) are compared with the results of previous investigators. Tin is used for making solders. S. J. Laredo [2] gave an accurate method of measuring the thermal

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conductivity of tin between 0.2 and 4°K using carbon aqua Dag resistance thermometers and concluded that at low temperatures, the conductivity is mainly due to the lattice. Magnesium alloys are used in the production of new technology because they are light weight. Metals are also important in the engineering industry. Jie-min Zhou et al. [3] used the angstroms method, and an instrument was designed to determine the thermal conductivity of magnesium metal and alloys. Thermal conductivity can then be obtained with relation to thermal diffusivity. Aluminium is often used in making automotive and plane parts and used as an alloy since its pure form is weak. Automobile casting is made of zinc. W. B. Willott [4] measured the thermal and electrical conductivities of several specimens of pure aluminium, which have been measured between 1.2°K and 4.2°K, with an experimental scatter of 0.3% to 0.7%. Iron, steel, and nickel are common metals used in construction and infrastructure. R. W. Powell [5] determined the thermal conductivity of five samples of nickel, two from 323°K to 1100°K and 1300°K, two to 800°K, and one to 600°K. N.G. Bäcklund [6] measured thermal conductivity experimentally at 90–300°K on iron of high purity and dilute alloys of this metal with Mn, Ni, or Si. Stainless steel is an alloy of iron and carbon (and often other elements with different compositions). Thermal conductivity of stainless steel over the temperature range 300 to 550 K, and to perform the measurements, the transient hot-wire technique was employed with a new wire sensor by M. J. Assael and K. Gialou [7]. Increasing the carbon content in steel creates carbon steel, which makes the material stronger but less ductile. Carbon steel is often used in building materials. Brass and bronze (copper alloyed with zinc and tin, respectively) have beneficial surface friction properties and are used for locks and hinges and frames of doors and windows, respectively. Kaiser et al. [8] studied the physical behaviour of thermally affected cast copper, aluminium, bronze, and brass by subjecting them to heating isochronally for one hour at a range of 600°C. Lastly, traditional light bulb filaments for fluorescent light are made of tungsten. However, these are being phased out since only about 5% of the power is converted to light in a light source like this, and the rest of the power is converted to heat. Modern light sources are often based on LED technology and semi-conductors.

1.1 Transfer of Heat

The transfer of heat refers to the process by which thermal energy moves from one object or substance to another due to a temperature difference between them. Thermal energy is transferred between materials in direct contact due to temperature gradients. It occurs as a result of microscopic collisions between particles (atoms, molecules, or ions) within the materials, leading to the transfer of kinetic energy from hotter regions to cooler regions, resulting in a net flow of heat. Materials with higher thermal conductivity allow heat to be conducted more efficiently. There are three mechanisms of heat transfer: conduction, convection, and radiation.

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November 2024, Volume 14, Issue 1

1.2 Thermal Conductivity (K)

Thermal conductivity is a fundamental property of materials that quantifies their ability to conduct heat. It represents the rate at which heat energy is transmitted through a material per unit area, thickness, and temperature gradient. It measures how easily heat flows through a substance. At the microscopic level, thermal conductivity is influenced by the interactions between atoms, molecules, or ions. Materials with closely packed particles and strong bonds between them tend to have higher thermal conductivity because heat can be transferred more efficiently through direct collisions and vibrations. It is an important consideration in various fields, including engineering, physics, and material science. It plays a crucial role in the design and optimisation of thermal management systems, such as heat sinks, insulating materials, and cooling devices. P.G. Klemens and R. K. Williams [9] reviewed the theory of the thermal conductivity of metals and alloys. B. Giordanengo et al. [10] showed that the electrical resistivity and the thermoelectric power can be used to determine the thermal conductivity of metals (liquid aluminium, tin, lead, copper, and metallic alloys) and alloys (Cu-Al, Ag-Ga, Ag-Ge, Cu-Pb, In-Mn, Ga-Ge, and Sn-Bi). Marvin Moss [11] determined the method to calculate the thermal conductivity of a metal with this apparatus for measuring both the axial temperature gradient and the transfer of heat under steady-state conditions in a thermally shielded cylindrical rod of the metal that is heated at one end and cooled at the other.

1.3 Searle's Bar Method for K

Searle's bar method is a laboratory technique used to measure the thermal conductivity (k) of materials, particularly solids. The method involves measuring the temperature difference across a sample of known dimensions and applying a known heat flux to one end of the sample. By monitoring the temperature change along the sample's length, the thermal conductivity can be calculated using Fourier's Law of heat conduction. A material that is a good conductor of heat is also a good conductor of electricity. In 1853, Wiedmann and Franz [12] established a relationship between thermal conductivity (K) and electrical conductivity. It is given as the ratio of thermal and electrical conductivities is the same for the metals at a particular temperature and is proportional to the absolute temperature of the metal.

$$\frac{K}{\sigma} = T$$

Here, K is thermal conductivity, σ is electrical conductivity, and T is absolute temperature.

D. J. Radcliffe and H. M. Rosenberg [13] calculated the thermal conductivity of one type of glass-fibre/epoxy and three types of carbon-fibre/epoxy composites from 2 to 80 K by Searle's bar method. S. A. Srinivasan et al. [14] calculated the thermal conductivity of Metal Matrix Nano Composites (MMNC's) by Searle's bar method and developed MMNC's to meet the demand for lighter materials with significant improvements in mechanical and physical properties like high strength, excellent wear resistance, good thermal conductivity, and low thermal expansion coefficient. J. E. Lorrimer et al. [15]

COMMUNIQUE

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reconsidered Searle's method for the determination of the thermal conductivity of solids for the physics of solids course, and a miniaturised version of the apparatus was described based on its advantages over the traditional design.

In inference, the thermal conductivity of metals is very important for designing any structure. It is integral to safety, efficiency, and new innovations within industries. The movement of electrons in the conductor is the mechanism behind the high conductivity of metals in comparison to non-metal materials. However, the thermal conductivity value (K) can vary greatly among metals due to temperature with respect to displacement.

2. Method of measurement

2.1 Experimental Setup

The sample of materials (iron, copper, and stainless steel) is typically a solid bar rod of uniform composition and dimensions for the study of thermal conductivity. The length, breadth, and thickness of each sample material are 30 cm, 2.5 cm, and 0.5 cm, respectively. Holes in the bar rods were drilled carefully, with a depth of 0.25 cm at equal positions of 6 cm, to place thermometers in each drilled hole. The hole depth of the sample was carefully prepared to ensure good thermal contact with the heating or cooling elements. The complete experimental setups for each material are shown in figures 1, 2, and 3, respectively.

Fig. 1 **Fig. 2**

Fig. 3

2.2 Measurement of Temperature at Different Holes of Bar Rods

Thermometers are placed at equal distances (each having a 6 cm difference) in the holes drilled in the bar rods to measure the temperature at various points. The temperature at each hole is noted when heat is provided at one end of the rod.

2.3 Measurement of Thermal Conductivity

Thermal conductivity is a measure of the ability of a substance to conduct heat, determined by the rate of heat flow normally through an area of the substance divided by the area by the component of the temperature gradient in the direction of flow with a negative sign. It can be measured in watts per metre Kelvin (W/Mk) and is denoted as K, called thermal conductivity, given as:

$$Q = -KA\frac{dT}{dx} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Or

$$Q = K\frac{A(\theta_1 - \theta_2)t}{d}$$

Here, Q is the heat flow (by conduction) rate through the material A.

A is the section through which heat flows by conduction.

$\frac{dT}{dx}$ is the temperature gradient at the

COMMUNIQUE

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section.

The proportionality constant K is a transport property known as thermal conductivity (W/MK) and is a characteristic of the material. It provided an indication of the rate at which energy is transferred by the diffusion process. Using Fourier's Law of heat conduction (Q), and knowing the heat flux, cross-sectional area (A), length (L), and temperature gradient (ΔT/Δx), the thermal conductivity (K) of the sample can be calculated.

2.4 Measurement of K by Searle's Bar Method

Searle's method is a laboratory technique used to measure the thermal conductivity (K) of metals and alloys. Thermal conductivity (K) is calculated by the below formula.

$$K = \frac{m\,(T_4 - T_3)d}{A(T_1 - T_2)t}$$

Here, A = area of cross section of the rod.
T_1 and T_2 = Steady temperature at the two fixed points of the rod in steady state
T_3 and T_4 = Steady temperature of the rods
d = Distance between two thermometers T_1 and T_2
m = The mass of the rods per unit area
t = Time, respectively.

3. Results and Discussion

The thermal conductivity of heat is a major property of an object. According to the modern electronic theory of thermal conduction, the flow of heat in a body from the hotter part to the cooler part is due to the motion of free electrons. These electrons in the outermost orbit of metals are loosely bound to the nucleus. When a metallic rod is heated at one end, the atoms acquire greater kinetic energy, and their amplitude of vibrations increases. A part of this energy is gained by the electrons in the outermost orbit. These electrons drift away from the atoms and move towards the cooler portion of the rod. These energetic electrons collide against atoms in the cooler portion of the rod and are freed. Thus, the heat energy is transported from the hotter parts to the cooler parts by the motion of free electrons. Iron and stainless steel have the lowest conductivity of heat, and copper has the highest conductivity of heat among the given set of metals and alloys. It is because metallic materials with good thermal conductivity can conduct heat very quickly.

In the present work, we have measured the variation in thermal conductivity with respect to displacement, area, and time. In our analysis, we observed a notable discrepancy in the thermal conductivity of pure metal, particularly copper, compared to iron and stainless steel, as shown in figures 4–7. From the obtained results of data tables 1, 2, 3, and 4, we observed that transferring heat through a metal like copper takes less time than that of iron and stainless steel i.e., copper takes less time to maintain its uniformity for its thermal conductivity in the whole rod. In Table 1, the initial temperature is equal to the value of room temperature. As there is an increase in the displacement heat passed through the rod, the temperature goes on increasing in the rod. Hence, temperature takes more time to become constant. In tables 2 and 3, for the metals, it shows that with an increase in time, the rise in temperature becomes constant very shortly (approx. t = 480–420 sec). So, we further observed in data table 5 at a time interval (t = 420 sec) for all samples that showed the same temperature.

COMMUNIQUE

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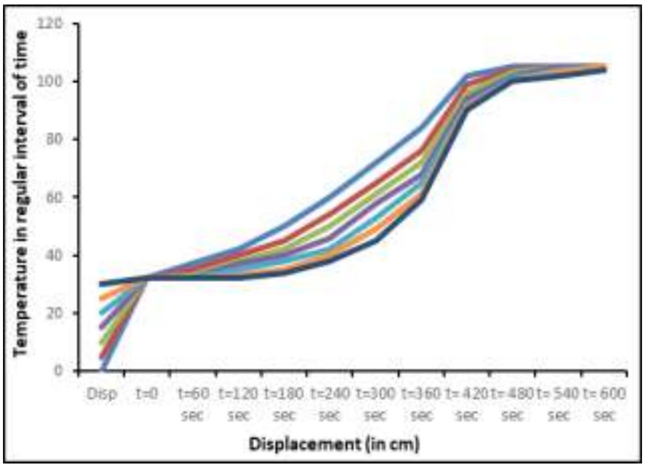

Fig. 4

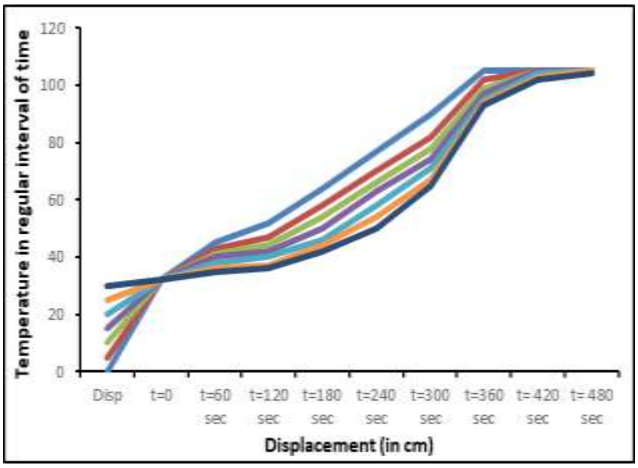

Fig. 5

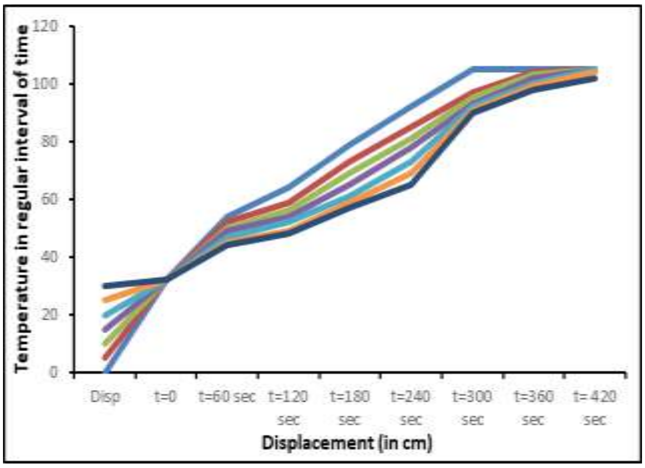

Fig. 6

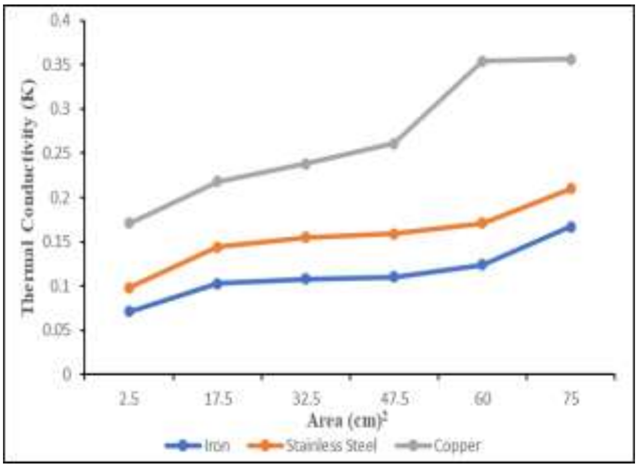

Fig. 7

Table 1 Temperature measured for steel rod.

S. No	Disp.	Temperature measured in different time intervals for steel rod										
		t=0 sec	t=60 sec	t=120 sec	t=180 sec	t=240 sec	t=300 sec	t=360 sec	t= 420 sec	t= 480 sec	t= 540 sec	t= 600 sec
1	1	32	37	42	50	60	72	84	102	105	105	105
2	7	32	35	40	45	54	65	76	99	104	105	105
3	13	32	33	38	42	50	61	72	96	103	105	105
4	19	32	32	37	40	46	58	68	94	102	105	105
5	24	32	32	35	38	42	53	65	92	101	104	105
6	30	32	32	33	35	40	49	61	91	100	103	105

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Table 2 Temperature measured for iron rod.

S. No	Disp.	Temperature measured in different time intervals for iron rod								
		t=0 sec	t=60 sec	t=120 sec	t=180 sec	t=240 sec	t=300 sec	t=360 sec	t= 420 sec	t= 480 sec
1	1	32	45	52	64	77	90	105	105	105
2	7	32	43	47	58	70	82	102	105	105
3	13	32	41	44	54	66	78	99	105	105
4	19	32	40	42	50	63	74	97	105	105
5	24	32	38	40	46	58	71	95	104	105
6	30	32	36	37	44	54	67	94	103	105

Table 3 Temperature measured for copper rod.

S. No	Disp.	Temperature measured in different time intervals for copper rod							
		t=0 Sec	t=60 sec	t=120 sec	t=180 sec	t=240 sec	t=300 sec	t=360 sec	t= 420 sec
1	1	32	54	64	79	92	100	105	105
2	7	32	52	59	73	85	97	104	105
3	13	32	50	56	69	81	95	103	105
4	19	32	49	54	65	78	93	102	105
5	24	32	47	52	61	73	92	100	105
6	30	32	45	49	59	69	91	99	104

Table 4 Conductivity variations of rods.

S. No	Distance (cm)	Area $(cm)^2$	Conductivity (K)		
			Iron	Stainless Steel	Copper
1	1	2.5	0.071	0.027	0.073
2	7	17.5	0.074	0.041	0.103
3	13	32.5	0.083	0.047	0.108
4	19	47.5	0.102	0.049	0.110
5	24	60	0.124	0.047	0.183
6	30	75	0.146	0.043	0.167

COMMUNIQUE

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Table 5 Increase in Temp. w.r.t Displacement

Disp.	Steel	Iron	Copper
1	102	105	105
7	99	105	105
13	96	105	105
19	94	105	105
24	92	104	105
30	91	103	104

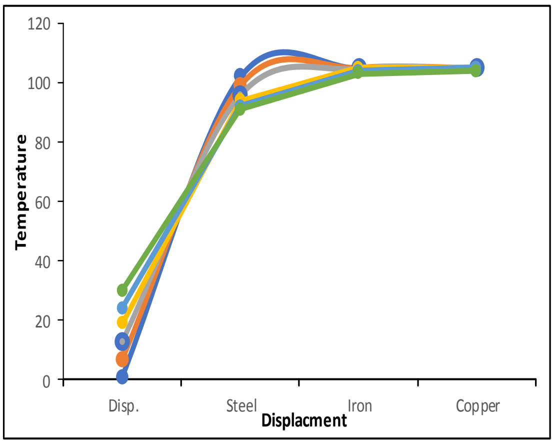

Fig. 8

Fig. 8 shows that there is more variation in temperature at the initial stage. With the passage of time, the difference in temperature gets reduced and becomes constant for all samples under study at a distance 30 cm at a time 420 sec, i.e., the rate of flow of heat becomes constant with respect to the increase in displacement. Specifically, a greater degree of variation was observed in the thermal conductivity of copper as compared to iron and stainless steel, as shown in Fig. 7.

4. Conclusion

From measured observations, we conclude that the different sensations felt by us can be explained by the fact that different materials conduct heat at different rate. Thus, we can say that, in the case of the tiles, they conduct heat faster than the carpet, so the tile transfers heat out of our feet faster than the carpet. This study also explains why it is better to stir the soup with a wooden spoon and roast marshmallows with a wooden stick. Our conclusion underscores the potential benefits of incorporating metals and alloys in applications where controlled thermal conductivity is desired. Hence, from the obtained results, we conclude that copper transfers the most heat and is followed by iron and stainless steel, which are the least conductors of heat. This finding suggests that employing pure metals with different alloys may prove more effective than utilising pure metals. Finally, this study gives physical ideas about the flow of heat through thermal conductors and insulators at the microscopic level.

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