EXPERIMENT 3

DETERMINATION OF THE COEFFICIENT OF THERMAL CONDUCTIVITY OF COPPER BY SEARLE'S APPARATUS

Structure

3.1 INTRODUCTION

You now know that **conduction** is a mode of transfer of heat in which actual movement of atoms does not occur. And, this is the most common mode of heat transfer in solids. If you take a metallic rod and heat it at one end, you will experience that the other end of the rod gets hot after some time. This happens because heat has travelled from the hotter end to the colder end via the vibrations of the atoms about their respective mean equilibrium positions. In fact, these atoms transfer energy to atoms in their immediate neighbourhood. This process continues till such time that a steady state is reached.

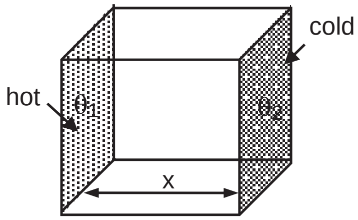

Fig. 3.1: **Heat flow through a rectangular block.**

Experiments show that different materials transfer heat at different rates. Let us consider a rectangular block, as shown in Fig. 3.1 The heat *Q* flowing through the block in time *t*, when its opposite faces, having cross-sectional area *A* are maintained at temperatures θ_1 and $\theta_2 (< \theta_1)$, is given by

$$\frac{Q}{t} = K \frac{A(\theta_1 - \theta_2)}{x} \tag{3.1}$$

Here x is the distance between the two faces of the block and K is the coefficient of thermal conductivity of the material.

From Eq. (3.1) we can write K as:

$$K = \frac{Qx}{A(\theta_1 - \theta_2)t} \tag{3.2}$$

Note that the value of K is large for good conductors like metals and low for poor conductors like air, asbestos and ebonite.

In Eq. (3.2) if we take

$$A = 1\,\text{m}^2, \theta_1 - \theta_2 = 1°\text{C}, t = 1\,\text{s} \text{ and } x = 1\,\text{m},$$

then

$$K = Q$$

In other words, the coefficient of thermal conductivity of a material is the quantity of heat that flows in one second through the opposite faces of a block of the material having a cross-sectional area of $1\,\text{m}^2$ when the distance between the opposite faces is $1\,\text{m}$ and they are maintained at a temperature difference of 1°C.

Note that the value of K will be different for different materials. The SI unit of K is W m^{-1} K^{-1}.

Expected Skills

After performing this experiment, you should be able to:

- identify the factors affecting the value of K;
- discuss the importance of steady state in the context of this experiment; and
- determine the coefficient of thermal conductivity of a good conductor using Searle's apparatus.

Before proceeding further, we list the apparatus you will use to perform this experiment.

Apparatus Required

Searle's apparatus, four sensitive (1/10)°C thermometers, graduated measuring cylinder, metre scale, vernier callipers, Bunsen burner and an accurate stop watch.

3.2 ONE DIMENSIONAL HEAT FLOW

Consider a long rod/bar AB whose one end is placed in a heat chamber at high temperature (Fig. 3.2). You will agree that heat will travel from the hot end to the cold end of the rod along its length. Suppose the temperature of hotter end is θ_1. Four thermometers are placed in the grooves engraved along the length of the rod. These are used to observe steady state.

When the temperature of each portion of the rod rises continuously, we say that the rod is in the variable state. As you continue to heat, you will observe that after some time the temperature at every point along the rod attains a constant value. In this stage, no net heat is absorbed by any section (say *XY*) of the rod, even if you continue to heat the rod. This is known as **steady state** and is depicted in Fig. 3.2. You will note that each thermometer shows a different constant temperature.

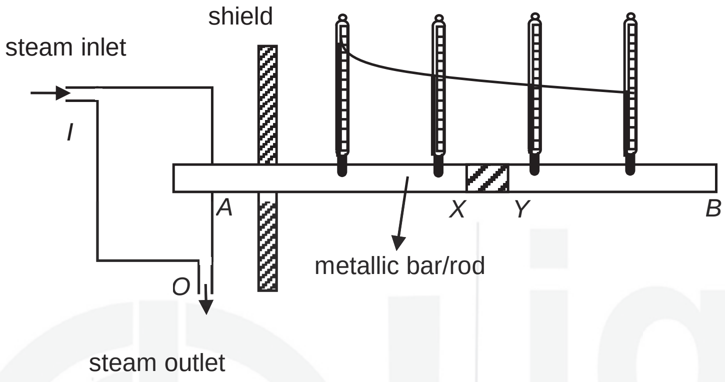

Fig. 3.2: **Steady state in 1-D heat flow.**

You may now ask: Why is it important to attain steady state to determine *K*? This is because before the steady state is reached, the heat flow in and hence the temperature of the rod depends on the thermal conductivity as well as the thermal capacity. However, in the steady state, thermal capacity plays no role.

Based on the values of their thermal conductivity, solids can be classified as good or bad conductors of heat. All the solids which have values of *K* in the range of $10^{-2} - 10^{-1}\text{cal sec}^{-1}\,\text{cm}^{-1}\,{}^\circ\text{C}^{-1}$ are classified as good conductors of heat. All metals come under the class of good conductors of heat.

3.3 SEARLE'S APPARATUS

The coefficient of thermal conductivity of a good conductor like copper, brass, etc. is determined by using Searle's apparatus. We would first like to familiarize you with the apparatus that you will use.

3.3.1 Description of Apparatus

Refer to Fig. 3.3. It shows Searle's apparatus used to determine thermal conductivity of a good conductor only. The essential parts of the apparatus are:

i) a rod/bar whose coefficient of thermal conductivity is to be determined;

ii) a steam chamber with an inlet and an outlet for steam. One end of the rod is inserted in this chamber;

iii) a coil *C* of a copper tube, wound around the cold end to maintain a steady flow of water;

iv) a few, normally four holes/sockets along the length of the tube to insert thermometers and record temperatures. The temperature of incoming and outgoing water is recorded with the help of thermometers T_3 and T_4, respectively;

v) a beaker used to collect water.

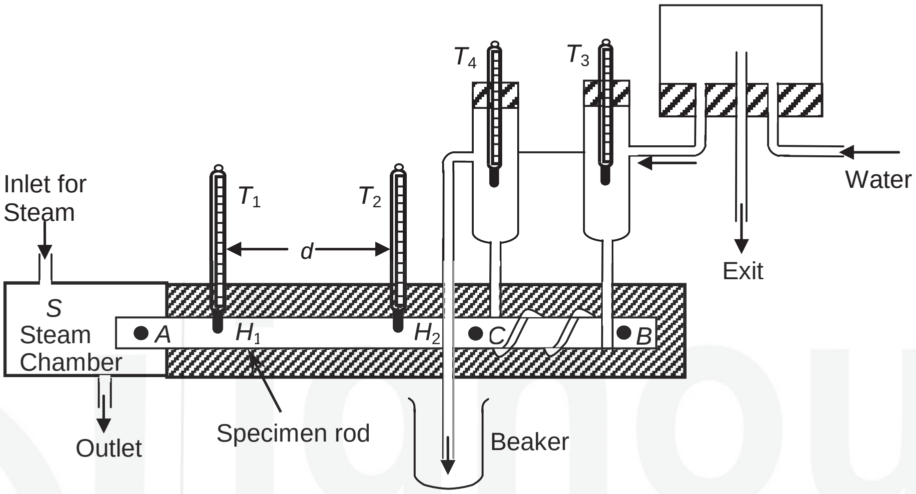

Fig 3.3: **Searle's apparatus**

The specimen rod and Searle's apparatus are wrapped around in a non-conducting material like wool to minimise loss of heat by radiation.

Now follow the steps listed below to determine *K*.

3.3.2 Determination of *K* from Searle's Apparatus

When steam is passed through the steam chamber *S*, one end (*A*) of the specimen is heated. The heat absorbed at the hot end *A* is conducted to the cold end *B* of the specimen bar. Due to the insulation, no loss of heat energy is assumed to take place from the specimen bar. Some of heat energy which reaches *B* is absorbed by the water flowing in the copper tube *C*. The flow of water in the copper tube *C* is regulated till a steady state is reached. This will be reflected by the constant temperatures shown by thermometers T_1, T_2, T_3 and T_4. In steady state, the total heat energy absorbed at end *A* of the specimen bar will be exactly equal to the heat loss at *B* due to absorption of heat by water circulating in tube *C*.

Let θ_1 and θ_2 be the temperature recorded by thermometers T_1 and T_2 placed at a distance *d* from each other. The heat conducted from H_1 to H_2 in time *t* is therefore given by

$$Q_1 = \frac{KA(\theta_1 - \theta_2)\,t}{d} \tag{3.3}$$

where A is the area of cross-section of specimen bar.

If θ_3 and θ_4 are the temperatures recorded by T_3 and T_4 of water flowing into the inlet and coming out from the outlet, then the amount of heat absorbed by m gram of water is given by

$$Q_2 = ms(\theta_3 - \theta_4) \tag{3.4}$$

where s is the specific heat capacity of water.

Since it is assumed that there is no loss of heat energy from the apparatus, we can write

$$Q_1 = Q_2$$

$$\Rightarrow \frac{KA(\theta_1 - \theta_2)\,t}{d} = m(\theta_3 - \theta_4) \quad (\because s = 1)$$

or,
$$K = \frac{md}{At}\,\frac{(\theta_3 - \theta_4)}{(\theta_1 - \theta_2)} \tag{3.5}$$

The coefficient of thermal conductivity can be calculated using Eq. (3.5) if the mass m of the water collected in unit time is known.

Now follow the steps listed below to determine K.

3.4 EXPERIMENTAL PROCEDURE

1. Place Searle's apparatus shown in Fig. 3.3 on a horizontal table.

2. To ensure good contact between the rod and thermometer bulb, place small amount of mercury in each hole made along the length of the rod and insert thermometers T_1 and T_2. Make sure that the rod is thermally insulated

3. Half fill the steam generator (not shown in the diagram) with water and start heating. When steam is formed freely in steam generator, connect it by a rubber tube to the inlet of the steam chamber.

4. Start a steady flow of cold water through the copper tube C. Place thermometers T_3 and T_4 at the inlet and outlet, respectively as shown in Fig. 3.3. You should start with very low flow. Connect one end of coil C to constant level tank so that water is available at all times.

5. Note readings of thermometers T_1, T_2, T_3 and T_4 at regular intervals of, say 60s, till the thermometers show constant temperatures $\theta_1, \theta_2, \theta_3$ and θ_4, respectively. This defines steady state and may take about half an hour to reach. Record the readings in the Observation Table 3.1.

Observation Table 3.1: March towards Steady State

time (min)	θ_1 (°C)	θ_2 (°C)	θ_3 (°C)	θ_4 (°C)
1.				
2.				
3.				
4.				
5.				
⋮				
Steady state				

The steady state temperatures are …….°C, …….°C, …….°C, and …….°C .

6. Once steady state has been attained, start collecting the water coming out of the outlet for say 5 minutes. Note the volume of water collected using a graduated measuring cylinder. Record your readings in the Observation Table 3.2. Calculate mass *m* by multiplying volume and density of water.

Observation Table 3.2: Measurement of volume of water

Least count of stop watch = ………….. s
Least count of graduated cylinder = …………….. cc

S. No.	Volume V of water collected (cc)	Mass m of water collected (g)	Time taken (s)	Steady State Temperature			
				θ_1 (°C)	θ_2 (°C)	θ_3 (°C)	θ_4 (°C)
1.							
2.							
3.							
⋮							

7. Repeat step 5 by changing the rate of flow at least three times and note the corresponding steady state temperatures. You can take more observations, if time permits.

8. Next you have to measure distance *d* between the pair of holes where thermometers T_1 and T_2 have been inserted. You can use a pair of dividers or simple metre scale.

9. You should also determine area of cross section *A* of the specimen rod/bar. For this you have to measure diameter of the rod. You can work with vernier callipers. Measurements should be taken along mutually perpendicular directions as shown in Fig. 3.4 and at different points along the length of the rod. In this way, you can minimise lack of uniformity, if any, in the rod. Record your readings in Observation Table 3.3.

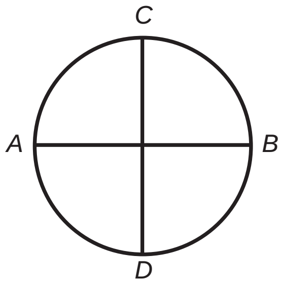

Fig. 3.4: **Measurement of specimen radius**

Observation Table 3.3: Area of Cross-section of the Specimen

Distance between the centres of holes where thermometers T_1 and T_2 are placed = …… cm

Least Count of vernier callipers = …… cm

S. No.	Reading along *AB*			Reading along *CD*			Mean
	Main Scale	Vernier Scale	Reading	Main Scale	Vernier Scale	Reading	
1.							
2.							
3.							
4.							
5.							

Area of cross section of the specimen = *A* =…………… cm^2.

10. By substituting the measured values of *m*, *A*, *d*, $\theta_1, \theta_2, \theta_3$ and θ_4, calculate the value of thermal conductivity using Eq. (3.5).

11. Discuss your result with your Counsellor. You must make sure that the rod is thermally insulated so that there is no loss of heat to the environment. Moreover, the flow of water should be regulated so that the steady state temperature is not affected.

Result :

The value of thermal conductivity of the given copper rod is

=……………… $J s^{-1} m^{-1} {}^{\circ}K^{-1}$.