EXPERIMENT 4

DETERMINATION OF THE COEFFICIENT OF THERMAL CONDUCTIVITY OF A BAD CONDUCTOR BY LEE AND CHARLTON'S DISC METHOD

Structure

4.1 INTRODUCTION

You know that the coefficient of thermal conductivity *K* for a solid characterizes heat flow in it. You learnt to determine the value of *K* in the previous experiment for a good conductor. It may be mentioned here that heat conduction equation (Eq. (3.1) is valid even for bad conductors of heat such as wool, glass, asbestos, cork, ebonite and card board etc. You should visit your kitchen at home and prepare a list of bad conductors of heat and how are they being used.

A material is said to be bad conductor of heat if the value of *K* is in the range 10^{-3} – 10^{-4} cal s^{-1} cm^{-1} $°C^{-1}$. Such materials are used as heat insulators.

The main problem in measuring the coefficient of thermal conductivity of such materials lies in accurate measurement of small rate of flow of heat even with reasonable temperature differences between the ends. This rules out the use of long bars, as in the case of metals. A method suggested by Lee and Charlton is used for determining the thermal conductivity of such samples.

Heat conducted per unit time in a solid is given by

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

From Eq. (3.1) you may recall that the rate of heat flow in a solid is directly proportional to its area of cross section *A* and inversely proportional to its thickness *x*. It means that rate of heat flow will be more in a specimen having (i) small thickness and (ii) large area of cross section. That

is why the specimen of bad conductor was taken in the form of a thin circular disc / plate with a large area of cross-section by Lee and Charlton.

Expected Skills

After performing this experiment, you should be able to:

❖ explain why a long rod/bar of a good conductor was used in Searle's method while a thin circular disc of bad conductor is required in Lee and Charlton's method;

❖ determine the value of K for a bad conductor.

You will use the following apparatus in this experiment.

Apparatus Required

Lee and Charlton's apparatus, two (1/10)°C thermometers, a circular disc of the specimen, a stop watch, screw gauge, vernier callipers and spirit level.

Now we will familiarize you with the apparatus.

4.2 DESCRIPTION OF LEE AND CHARLTON'S APPARATUS

Refer to Fig. 4.1. It shows Lee and Charlton's apparatus. A circular metallic brass disc (D) is suspended using three strong threads/ wires from a large ring on a retort stand. The non-conducting (cardboard, glass, ebonite)

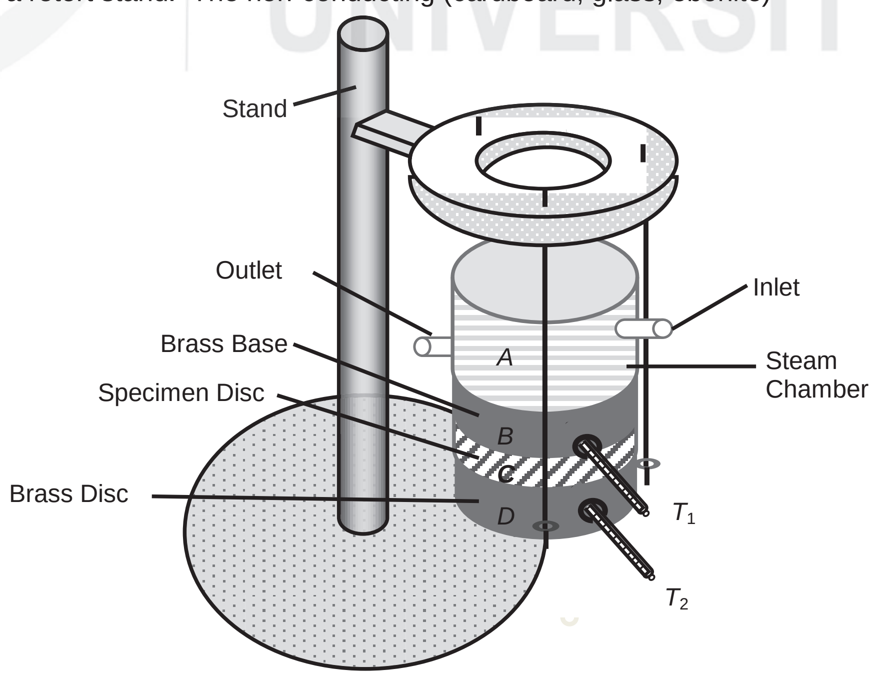

Fig. 4.1: **Schematic Diagram of Lee and Charlton's apparatus.**

specimen for which we wish to measure the thermal conductivity is in the form of a thin circular disc (*C*). The area of cross-section of *C* is same as that of the metallic disc *D*. *C* is placed on *D*. A steam chamber *A* having a thick metallic base *B* is placed over *C*. The upper part of the steam chamber is a hollow cylinder with two projecting side tubes. These serve as the inlet and outlet for steam. The base of the steam chamber has the same diameter as *C*.

The temperatures of the base of the cylinder *B* and the metallic disc *D* are measured by thermometers T_1 and T_2, which are placed in the holes near the bottom of the cylindrical vessel and the lower disc, as shown in Fig. 4.1. For good thermal contact of thermometer bulbs with the disc, you should put a little mercury, if available, in the holes. The disc and the cylinder are nickel plated so that their emissivity is same.

Now that you are familiar with the apparatus, let us discuss in brief the theory underlying this experiment.

4.3 THEORY: DETERMINATION OF *K* FOR A BAD CONDUCTOR

You may recall that in Searle's apparatus, which is used to determine K for a good conductor, the entire apparatus was insulated to prevent heat loss by radiation. But in Lee and Charlton's method, the loss of heat due to radiation is inevitable at the curved surfaces of metallic disc *D* and base of the hollow cylinder *B*. It is actually this loss of heat energy which plays a significant role in achieving steady state condition. In this condition, the amount of heat conducted through the specimen (say cardboard) *C* in unit time is totally lost due to radiation from metallic surface of disc *D*. This ensures that there is no net absorption of heat by disc *D* and thermometer T_2 records constant value of temperature. Note that steady state is reached on passing steam through the cylindrical vessel.

The radiation lost by disc *D* in steady state in the first part of the experiment is only from its lower surface and the curved surface, which is why the cooling rate is measured with the insulating layer on top. If the disc D is cooled without the insulting layer on top of it, heat loss due to radiation would be from the entire surface of the disc. In that case it becomes essential to add a correction term to the calculated cooling rate to account for the heat loss due to radiation from the top surface. This correction is termed Bedford Correction.

The amount of heat conducted per second across the specimen *C* is given by

$$\frac{Q}{t} = \frac{KA(\theta_1 - \theta_2)}{d}, \quad (4.1)$$

where θ_1 is steady state temperature of *B* and θ_2 is steady state temperature of metallic disc *D*. Here *d* denotes the thickness of specimen *C* of thermal conductivity *K*.

In the steady state, the amount of heat conducted per second through the *C* into the disc *D* is given by Eq. (4.1) and is equal to the amount of heat radiated by it per second. To determine the amount of heat radiated by *D* per unit time, i.e., the rate of cooling of the disc *D*, the specimen *C* is removed and disc *D* is heated directly by the steam chamber to a temperature higher than its steady state temperature θ_2 by 10°C or so. Then the steam chamber is removed, the insulating layer is placed on *D* (read margin remark) and it is allowed to cool. The temperature is noted at intervals of 30s till its temperature falls to at least 10°C below the steady state. A graph is then plotted between θ and *t*. This is known as cooling curve. On the cooling curve, a tangent is drawn at point *P* corresponding to $\theta = \theta_2$. The slope of the tangent gives $\left(\frac{d\theta}{dt}\right)_{\theta=\theta_2}$.

If mass of the metal disc *D* is *M* and its specific heat is *s*, the energy lost due to radiation per unit time from the surface of disc *D* is given by

$$\frac{Q}{t} = Ms\left(\frac{d\theta}{dt}\right)_{\theta=\theta_2} \qquad (4.2)$$

where $\left(\frac{d\theta}{dt}\right)_{\theta=\theta_2}$ defines the rate of fall of temperature at θ_2.

On equating Eqs. (4.1) and (4.2), we can write

$$\frac{KA(\theta_1 - \theta_2)}{d} = MS\left(\frac{d\theta}{dt}\right)_{\theta=\theta_2}$$

so that the coefficient of thermal conductivity can be calculated using the relation

$$K = \frac{MSd}{A(\theta_1 - \theta_2)}\left(\frac{d\theta}{dt}\right)_{\theta=\theta_2} \qquad (4.3)$$

4.4 EXPERIMENTAL PROCEDURE

1. At the start, weigh the metallic disc *D* to determine its mass *M* accurately. The specific heat *s* of the material of the disc should also be noted down (or consult your Counsellor to obtain it).

2. Next measure the thickness (*d* in Eq. 4.3) of the specimen disc *C* for which the thermal conductivity is to be determined. Since the specimen is thin, use a screw gauge and measure thickness at a number of places. Record your readings in Observation Table 4.1. In case there is any zero error, make the correction by subtracting the zero error with proper sign.

Observation Table 4.1: Measurement of Thickness of Specimen

Least count of screw gauge = …………… cm

Zero-error of screw gauge = ……………. cm (with sign)

Sl. No.	Main Scale Reading	Circular Scale Reading	Thickness *d* (cm)
1.			
2.			
3.			
4.			
5.			

Mean *d* = ... cm

3. Next measure the diameter of the disc to determine the area of cross-section (A) of the specimen disc C. To measure diameter, you should use Vernier callipers and take readings in mutually perpendicular directions at a number of positions and record your readings in Observation Table 4.2. Make sure that you account for zero error, if any, in your vernier callipers.

Observation Table 4.2: Measurement of Diameter of Specimen

Least count of vernier callipers = …………… cm

Zero error of vernier callipers = …………… cm (with sign)

Sl. No.	Main Scale Reading	Vernier Scale Reading	Diameter (cm)
1.			
2.			
3.			
4.			
5.			
6.			
⋮			

Mean diameter = ………………. cm

Mean radius = r =………………. cm

Area of Cross-section $A = \pi r^2$ = …………………… cm^2

4. Set the apparatus as shown in Fig. 4.1. Suspend the metallic disc *D* with the help of three threads/wires attached to a large ring on a retort stand.

5. Place disc *C* of specimen (say cardboard), whose thermal conductivity is to be determined, on top of metallic disc *D*. The flat surface of the disc should be horizontal. Ensure this using a spirit level. You must make sure that diameter of the specimen disc *C* is equal to that of metallic disc *D* and that the thickness of *C* is uniform throughout . You may like to ask: Why is it necessary to have discs of identical size? This is to minimise losses due to radiation by *D*.

6. Next place the steam chamber on top of *C*. It has an inlet and an outlet for steam. Attach the inlet to a steam generator and the outlet to a pipe to allow steam to escape from *D*.

7. Insert thermometers T_1 and T_2 in position at the bases of *B* and *D* respectively, as shown in Fig. 4.1. Note that both thermometers should show the same temperature, which is the room temperature.

8. Pass steam through the steam chamber. Heat will be conducted through *C* and *D* will get heated up. The temperatures in both the thermometers will rise for a while and finally become steady. Note down the temperatures θ_1 and θ_2 in thermometers T_1 and T_2 respectively, at intervals of 1 minute till steady state is reached. Record your readings in Observation Table 4.3. Let us denote these as θ_1 and θ_2. Once the steady state is reached, stop the flow of steam in the chamber.

Observation Table 4.3: March towards Steady State

Least count of thermometer T_1 = …………… °C

Least count of thermometer T_2 =……………. °C

Sl. No.	Time (s)	Temperature	
		θ_1 (°C)	θ_2 (°C)
1.	60		
2.	120		
3.	180		
4.	240		
5.	300		
6.	360		
⋮	⋮		
	Steady State		

Steady state temperatures in T_1 and T_2 are θ_1=……..°C and θ_2=.……..°C respectively.

9. Remove the cardboard disc *C* and place the steam chamber directly on *D*. Pass steam through the chamber so that temperature of *D* rises and is about 10-15°C above the steady state temperature for the disc *D*, θ_2. Alternatively, you can heat *D* directly with a burner.

10. Next remove the steam chamber and cover the disc *D* with the insulating specimen. As a result, the metallic disc will begin to cool. Start taking readings of thermometer T_2 to determine the rate of cooling of the disc *D*.

11. Note down the temperatures at regular intervals of 30s and record your readings in Observation Table 4.4. Continue this exercise till the temperature of *D* falls nearly 10°C below θ_2.

Observation Table 4.4: Variation of temperature of metallic disc with time

Sl. No.	Time, *t* (s)	Temperature θ (°C)
1.	30	
2.	60	
3.	90	
4.	120	
5.	150	
6.	180	
⋮	⋮	

12. Draw a graph by taking time *t* along the *x*-axis and temperature θ along the *y*-axis. This gives cooling curve. You will note that at the temperature θ_2 corresponding to the steady state, the cooling curve shows a distinct change.

13. Draw a tangent at the point corresponding to the steady state temperature θ_2, as shown in Fig. 4.2.

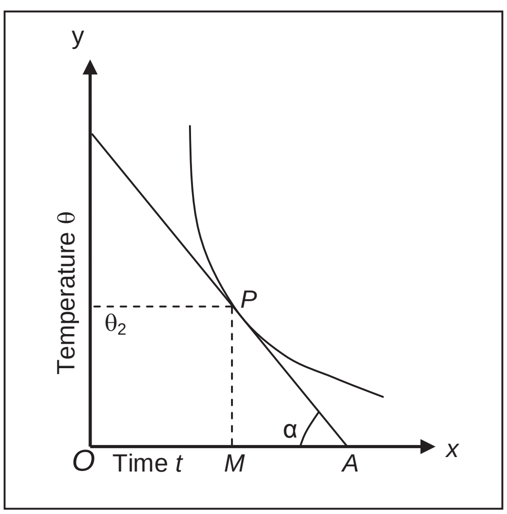

Fig. 4.2: **Expected nature of cooling curve**

Extend the tangent to meet the x-axis at A. Draw PM perpendicular to OA. The slope of the tangent is given by

$$\left(\frac{d\theta}{dt}\right)_{\theta=\theta_2} = \tan\alpha = \frac{PM}{MA}$$

14. From Eq. (4.3) we note that once $\left(\frac{d\theta}{dt}\right)_{\theta=\theta_2}$ is determined, we can calculate K. We have already determined M and s, and calculated the thickness d, the area of cross-section A and the steady state temperatures θ_1 and θ_2 in the earlier steps.

15. Calculate K using Eq. (4.3) by substituting the values of various quantities. Discuss your result with your Counsellor.

Result: The value of K for a bad conductor determined using Lee and Charlton's method is = ……………… $J\,s^{-1}\,m^{-1}\,{}^{\circ}K^{-1}$.