Expt-7
Thermal Conductivity by Lee's Disc

Objective

To measure coefficient of thermal conductivity of a poor/bad thermal conductor using electrically heated Lee's disc apparatus

Introduction

Lee and Charlton's original method of thermal conductivity determination is not fully clear, the earliest mention of their work was found to be in the Philosophical Magazine's 41st volume, 1896. This method is a simple and effective way to estimate the thermal conductivity of materials with poor thermal conductivities, widely known as Lee's Disc method. With the use of easy-to-find parts, it is fairly easy to assemble and operate a Lee's disc apparatus with the goal of thermal conductivity calculation. Eventually Lee's Disc method provides a better insight of how to calculate thermal conductivity. In this experiment, you will use a simplified version of this method.

Principle

The electrically heated Lee's disc apparatus for the measurement of thermal conductivity of an insulating sheet is shown schematically in *Fig. 1*, in which, a disc shaped heater is placed between two identical copper discs (*1* and *2*) and a thin disc of the insulating sample of thickness (t_s) is placed between the identical copper discs (*2* and *3*). All the discs, heater and the sample have nearly equal radii. At steady state, the quantity of heat flow through the bad thermal conductor is equal to the heat radiated from the Lee's disc (*Disc 3*). The exposed surface areas of the discs are A_1, A_2, A_3, and those of the heater and sample are A_h and A_s, respectively. T_1, T_2, and T_3 represent the measured temperature (using thermocouples) of *Disc 1*, *Disc 2*, and *Disc 3*, respectively.

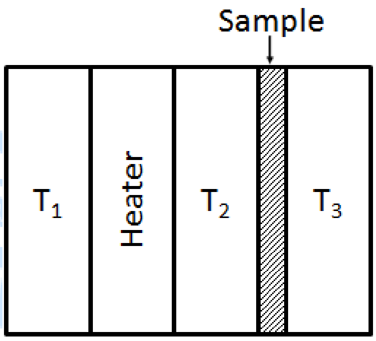

Fig.1: Schematic design of a Lee's disc

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The rate of heat flow (H) through the sample of thermal conductivity (λ) is given in *equation 1*.

$$H = \lambda A_s \left[\frac{T_2 - T_3}{t_s}\right] \tag{1}$$

where, t_s is the thickness of the sample and $A_s = \pi r_s^2$ (r_s : radius of sample).

The heat radiated from Lee's disc (*Disc 3*) is given in *equation 2*.

$$H = M_3 C_3 \frac{dT}{dt} \tag{2}$$

where, M_3, and C_3 are the mass and specific heat capacity, and $\frac{dT}{dt}$ is the rate of fall of temperature of *Disc 3*.

Equating *equation 1* and *equation 2*, the co-efficient of thermal conductivity of bad conductor (λ) is given in *equation 3*.

$$\lambda = \frac{M_3 C_3 \frac{dT}{dt}}{A_s \left[\frac{T_2 - T_3}{t_s}\right]} \tag{3}$$

Fig. 2 shows the variation of temperature with time, which gives the rate of fall of the temperature (slope of the cooling curve).

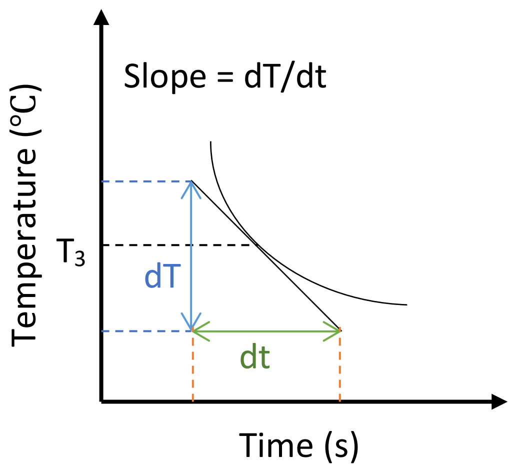

Fig. 2: Variation of temperature with time

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Experimental Set-up and Apparatus Details

The electrically heated Lee's apparatus is shown in *Fig. 3*. It consists of three nearly identical flat circular copper discs (*1*, *2*, and *3*) in which holes are drilled along their radii to insert metal shielded chromel-alumel thermocouples. The electrical heater, which is also sealed within a copper disc of similar dimensions, is sandwiched between the *Disc 1* and *Disc 2*, while a thin disc of insulating material of the same radius is sandwiched between *Disc 2* and *Disc 3*. This assembly of three copper discs, heater and the sample are clamped together within a metallic stand by using teflon spacers. The assembly is secured by placing on the small disc aligning tray and tightening the knob on the right side of the metallic stand. An extra thermocouple is placed on the side of the stand to measure the ambient temperature. A DC power supply is used to supply power to the heater. Coarse and fine voltage control knobs are provided to set the output voltage. Coarse and fine current control knobs are used to set the upper limit of the current in the heater circuit. Digital voltmeter and ammeter are provided for displaying output voltage and current. The temperatures of the three discs and the ambient are displayed on a calibrated temperature monitor, which has provisions for connecting four chromel-alumel thermocouples (marked 1, 2, 3, 4) at the rear panel. A selector knob is provided on the front panel for displaying the temperature corresponding to each of the four thermocouples.

Fig.3: *Experimental setup*

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Procedure

1. Measure the diameter (d) of the insulating sample with Vernier calipers and thickness (t_s) with a screw gauge by taking three readings at different locations.
2. Measure the mass (M_3) of disc 3.
3. Place the disc aligning tray in between and parallel to the two rods at the base of the metallic stand. Sequentially arrange *Disc 1*, heater, *Disc 2*, sample, and *Disc 3*, as shown in *Fig. 1,* so as to form a cylindrical assembly and place this assembly on the disc aligning tray. Rotate the discs and the heater to bring the radial holes and the heater wire on the upper side and nearly aligned along a horizontal line.
4. Slightly adjust the position of the metallic stand to ensure that the teflon spacers touch the two extreme discs (*1* and *3*) at nearly their centers. Secure the disc and heater assembly between the teflon spacers by gently tightening the knob on the right side of the stand. Lift the stand with the disc assembly and remove the empty tray.
5. Insert the thermocouples (1, 2, 3) into the corresponding discs and leave the thermocouple 4 to rest on the side of the stand for measuring the ambient temperature.
6. Connect the heater wires to the output of the power supply. Check that the voltage control knob of the power supply is minimized and then maximize the coarse and fine current control knobs.

At this stage, Request the instructor to check the circuit, before switching on the power supply.

7. Switch ON the DC power supply and turn the voltage knob to slowly increase the voltage and keep at 25 *V*. Note down the values of the applied voltage and the output current.

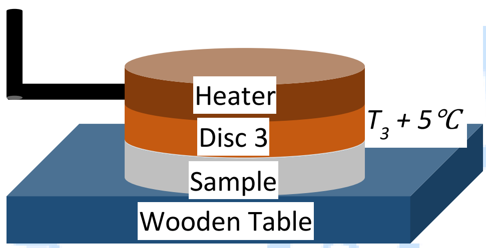
   8. At intervals of 5 *min*, note down the temperatures (T_1, T_2, T_3, and T_4) corresponding to discs *1*, *2*, *3* and the ambient temperature, respectively, till the temperature T_3 becomes 20°C above the ambient temperature T_4. Note down the time and temperatures when this happens.

   This part of the experiment will take about 30 minutes. Use this time for calculations, planning the rest of your experiment, making graphs etc.

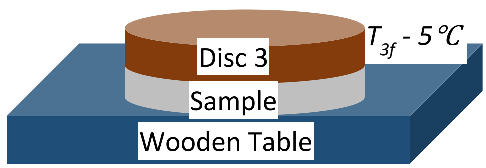
9. At this point, reduce the heater voltage to 20 V. Continue as before: at intervals of 5 *min*, note down the temperatures (T_1, T_2, T_3, and T_4) corresponding to discs *1*, *2*, *3* and the ambient temperature, respectively, till the temperatures stabilize to nearly constant values. This part of the experiment will take about 30 minutes. Take two readings of the temperatures (at intervals of 5 *min*) after steady state is reached. Let us denote the final temperature as T_{3f}.

10. **Closing heating up experiment**: Minimize the voltage knob of the power supply and switch it OFF. Minimize the current control knobs. Disconnect the heater cable from the output connectors of the power supply. Remove the thermocouples from the discs. Dismantle the discs and heater assembly with care as these are hot, use gloves or cloth.

11. **Cooling Rate Experimental Exercise**: In this exercise, we place sample disc on wooden table followed by heater and then *Disc 3* with a care of not burning the hand. *Disc 3* thermocouple gets plugged in and we monitor the temperature, which might have fallen down from T_{3f}. Start the heater again, but with a voltage of 25 V monitor the temperature rise of *Disc 3* up to (T_{3f} + 5 ℃).



12. At this stage, with proper care, we remove heater and leave *Disc 3* on the sample disc and start recording the thermocouple reading every 30 seconds time interval until it reaches (T_{3f} – 5 ℃). This exercise should typically take 12-14 minutes. Plot a graph as shown in *Fig 2*. Draw a tangent at T_{3f} point to determine the cooling rate (dT/dt) at stabilized temperature T_{3f}. You will have to draw two more approximate tangents for your uncertainty analysis later.



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Results and Calculations

1. Tabulate the measured values of the diameter (d_s) and thickness (t_s) of sample and calculate the average value in each case.
2. Calculate the exposed area of the sample (A_s).
3. Tabulate T_1, T_2, and T_3 as a function of time.
4. Plots the graphs of T_1, T_2, and T_3 on the same graph sheet (using different symbols), during the increase and stabilization of temperatures.
5. Take the specific heat capacity of copper disc C_3 = 0.385 J.g^{-1}°C^{-1}
6. Measure the mass of *Disc 3* using weighing machine (M_3).
7. Using *equation 3*, calculate the value of λ.
8. Estimate the error $d\lambda$ as given in *equation 4*. (Note – you can calculate some of the terms while the heating experiment is under way).

$$\frac{d\lambda}{\lambda} = \sqrt{\left(\frac{dM_3}{M_3}\right)^2 + \left(\frac{dC_3}{C_3}\right)^2 + \left(\frac{d\frac{dT}{dt}}{\frac{dT}{dt}}\right)^2 + \left(\frac{dA_s}{A_s}\right)^2 + \left(\frac{dT_2}{T_2}\right)^2 + \left(\frac{dT_3}{T_3}\right)^2 + \left(\frac{dt_s}{t_s}\right)^2} \quad (4)$$

Precautions

1. There should be no exposed surfaces other than those considered above. To ensure that, secure the discs, heater and sample in the stand in such a way that the assembly is nearly cylindrically aligned. Remember to remove the support beam before starting heating/cooling.
2. Insert and remove the thermocouples in and out of the discs with utmost care. Handle all equipment with care.
3. Before connecting the heater, make sure that the voltage knobs are at zero. Increase the current limit first, then gently set the voltages to desired values.
4. Do not apply excessive force on the disc support screws, or the screw gauge.
5. Mishandling of any equipment will be penalized.

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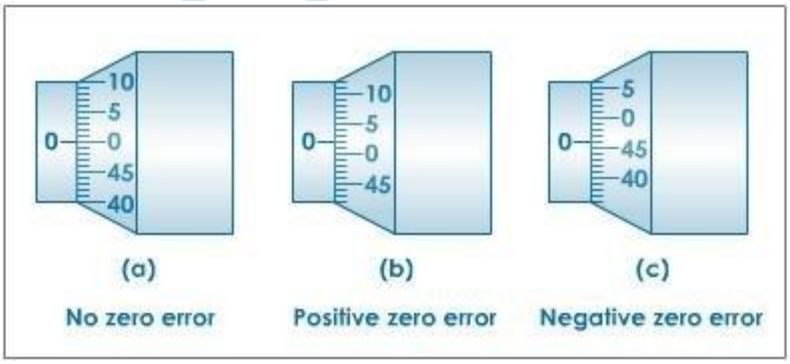
Suggested Reading:

1. https://thermtest.com/history-6-lees-disc-method
2. Charles H. Lees, J. D. Chorlton; LIV. On a Simple apparatus for determining the thermal conductivity of cements and other substances used in the Arts; Philosophical Magazine; Vol 41; Issue 253, 1896.

Calculating zero error in screw gauge:



Actual reading = X | X - error | X + error

List of thermal conductivities:

Material	Thermal conductivity [W·m⁻¹·K⁻¹]
Silica aerogel	0.02
Polyurethane foam	0.03
Expanded polystyrene	0.033–0.046
Fiberglass or foam-glass	0.045
Snow (dry)	0.050–0.250
Alcohols, oils	0.100
Acrylic glass	0.170–0.200
Epoxy	0.17
PVC	0.19
Epoxy glass fibre	0.23
Nylon 6	0.25
Polyethylene, low density (PEL)	0.33
Polyethylene, high density (PEH)	0.50

Ref: https://en.wikipedia.org/wiki/List_of_thermal_conductivities