EXPERIMENT NO. 5

Thermal Conductivity Measurement

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1 Introduction

In this experiment it is required to evaluate the thermal conductivity of copper experimentally and the get the temperature distribution for constant and variable area copper bars.

The transfer of heat is normally from a high temperature object to a lower temperature object. Heat transfer changes the internal energy of both systems involved according to the First Law of Thermodynamics.

Conduction is heat transfer by means of molecular agitation within a material without any motion of the material as a whole. If one end of a metal rod is at a higher temperature, then energy will be transferred down the rod toward the colder end because the higher speed particles will collide with the slower ones with a net transfer of energy to the slower ones.[1]

An empirical relationship between the conduction rate in a material and the temperature gradient in the direction of energy flow, first formulated by Fourier in 1822 who concluded that "the heat flux resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign". For a one directional conduction process this observation may be expressed as:

$$q'' = -k\frac{\partial T}{\partial x} \qquad (5.1)$$

Where the vector q is the heat flux (W/m^2) in the positive x-direction, dT/dx is the (negative) temperature gradient (K/m) in the direction of heat flow (i.e., conduction occurs in the direction of decreasing temperature and the minus sign confirms this thermodynamic axiom) and the proportionality constant k is the Thermal Conductivity of the material (W/m.K). Fourier's Law thus provides the definition of thermal conductivity and forms the basis of many methods of determining its value. Fourier's Law, as the basic rate equation of the conduction process, when combined with the principle of conservation of energy, also forms the basis for the analysis of most Conduction problems.[2]

From Fourier's Law the heat transfer rate q (W) through a material with cross-sectional area A (m^2) is given by:

$$q = q''A = -kA\frac{\partial T}{\partial x} \qquad (5.2)$$

solving heat rate to get the temperature distribution for a bar with constant cross sectional area we get:

$$T(x) = \frac{(T_2 - T_1)}{L}x + T_1 \qquad (5.3)$$

Where L is the length of the rod, T_1, T_2 are the temperatures at the beginning and end of the bar respectively, assuming that the surfaces of the bar are at constant temperatures.

For the variable area bar following the same previous procedure we get the temperature distribution as:

$$T(x) = \frac{d\,L\,T_1 - d\,T_1\,x + D\,T_2\,x}{d\,L - d\,x + D\,x} \qquad (5.4)$$

Where d and D are the diameters at the beginning and ending of the bar respectively.

To evaluate the thermal conductivity a surface energy balance done at the end of the bar. Therefore, the heat transferred to the cooling water can be expressed as

$$\dot{q}_x = -kA\frac{dT}{dx} = \dot{m}C_p \Delta T_{H_2O} \qquad (5.5)$$

Where, Where, $\Delta T_{H_2O} = \left(T_{H_2O}\right)_{out} - \left(T_{H_2O}\right)_{in}$

Solving for k we get

$$k = \frac{-\dot{m}C_p \Delta T_{H_2O}}{A\frac{dT}{dx}} \qquad (5.6)$$

2 Apparatus and Techniques

2.1 Apparatus

As shown in figure 5.1 a thermal conduction system is used to measure the thermal conductivity and the get the temperature distribution for constant and variable area copper bars. The system consists of two hot plate type heat sources copper bars and 10 thermocouple junctions on each bar. Unit 3 (shown in figure 5.2) has a tapered bar with 1 inch diameter at the lower part of the bar and 2 inch diameter at the upper part and Unit 4 (shown in figure 5.3) has a cylindrical bar with 2 inch diameter. As shown in figure 5.4 a thermocouple and a controlling switch (to select the junction) was used to get the temperature difference at each junction between the junction and the room temperature. Both bars are of the same diameter at the upper end and in contact with water as a coolant heat sink. As shown in figure 5.5 the coolant water flow is measured for each bar and the difference in temperature between the water inlet and outlet is measured to get the amount of heat transferred to the water.

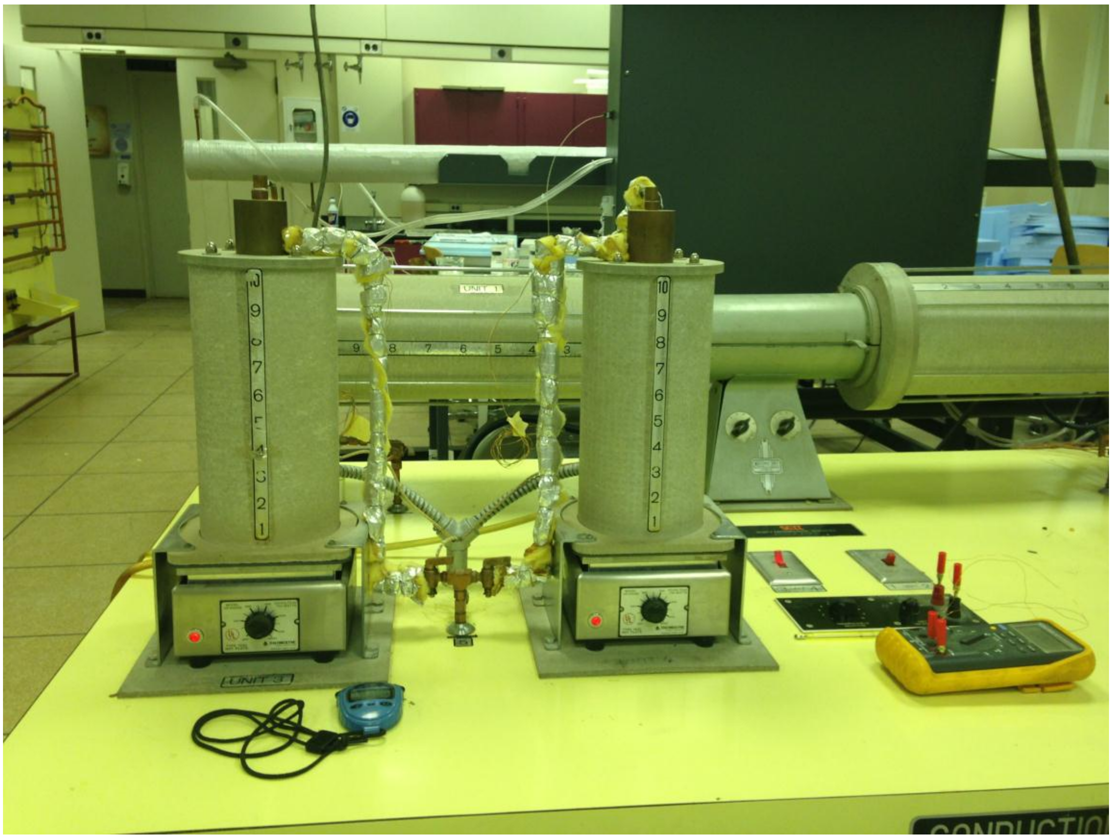

Fig 5.1 thermal conduction system

Fig 5.2 unit 3 tapered copper bar

Fig 5.3 unit 4 cylindrical copper bar

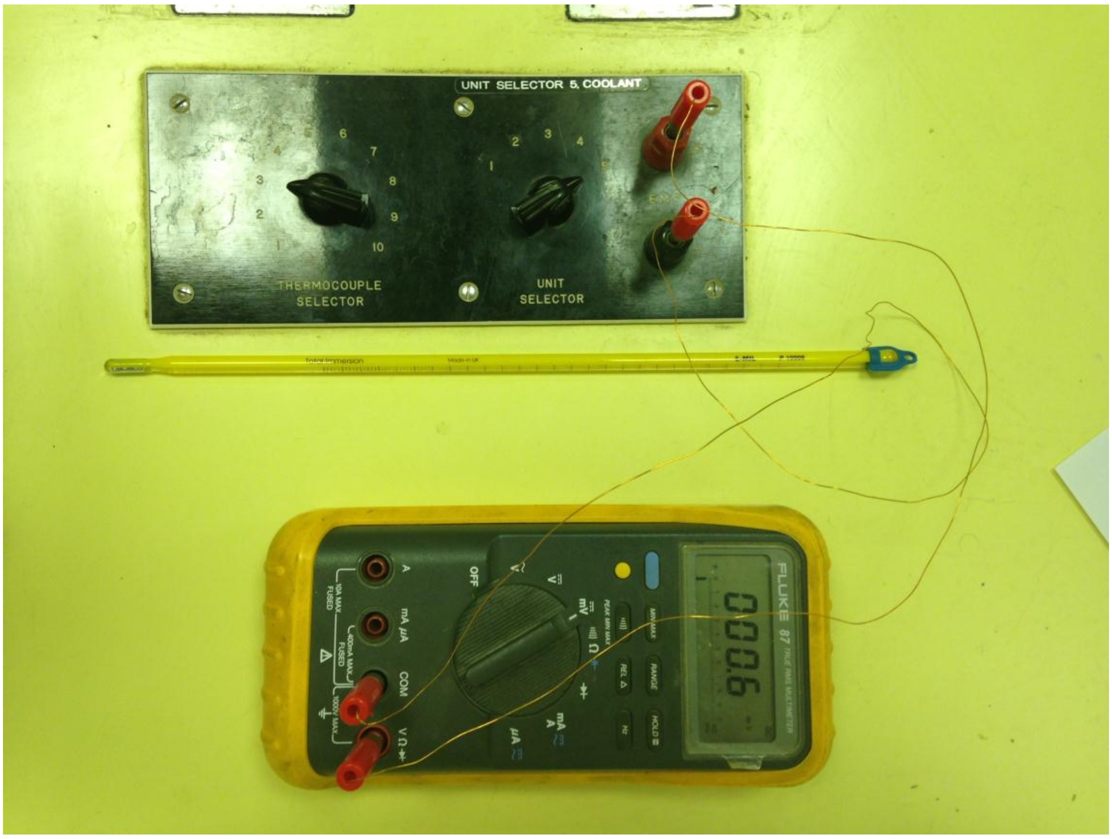

Fig 5.4 *thermocouple and controlling switch*

Fig 5.5 *water flow measurement system*

2.2 Procedures and Techniques

In this experiment the temperature distribution was measured at 10 junctions for both the variable and constant area bars. By using the controlling switch and the thermocouple the temperatures were measured three times for the constant area bar and two times for the variable area bar. Also the flow rate and temperature difference of the water was measured three times for the constant area bar and two times for the variable area bar to perform the uncertainty analysis.

3 Results and Discussions

The atmospheric temperature during the experiment was measured to be $19 \pm 1/2\ C$. The density and specific heat of water were taken as 998.2 $kg/m3$ and 4.183 kJ/kg.K respectively [3].

The thermocouple resolution was set to be 0.1 which led to an error in all the thermocouple measured temperatures as $\pm$ 1.3 C.

After calculating the data the temperature distribution for each bar was drawn. Figures 5.6 shows the temperature distribution for both the tapered and cylindrical bar.

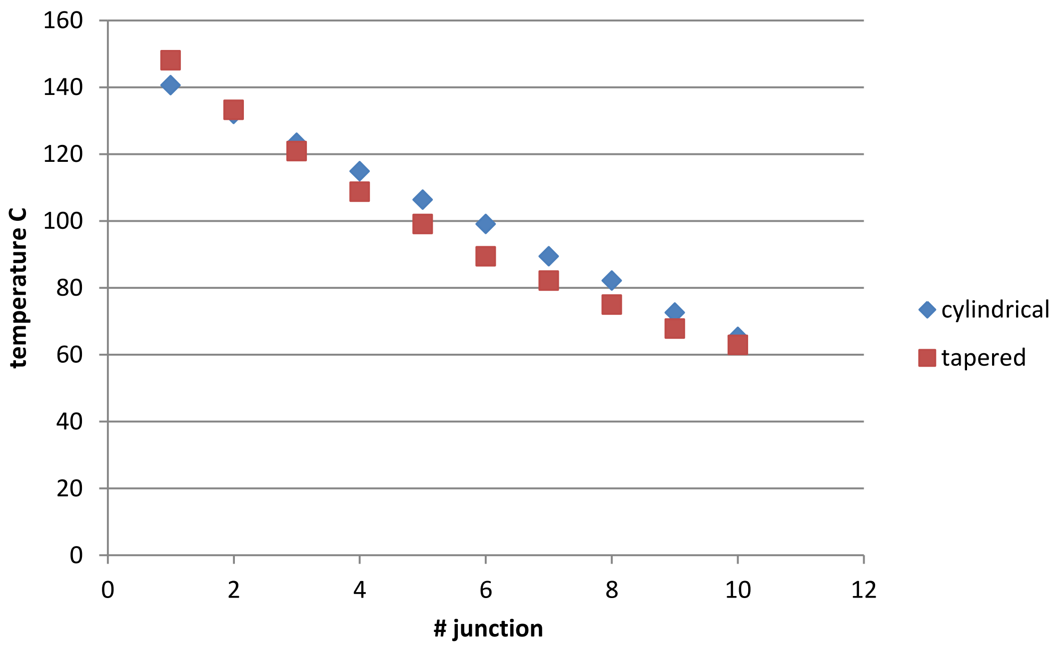

Fig 5.6 the temperature distribution for both the tapered and cylindrical bar

It can be clearly seen from the figure that the temperature distribution for the cylindrical bar is linear following equation 5.3. The function of the temperature distribution from line fitting the measured distribution is

$$T(x) = -8.38x + 148.64 \qquad (5.7)$$

Where the calculated function is

$$T(x) = -7x + 140.5 \tag{5.8}$$

Figure 5.7 shows the measured and calculated temperature distribution for the tapered bar. Equation 5.4 was used to get the calculated temperature distribution.

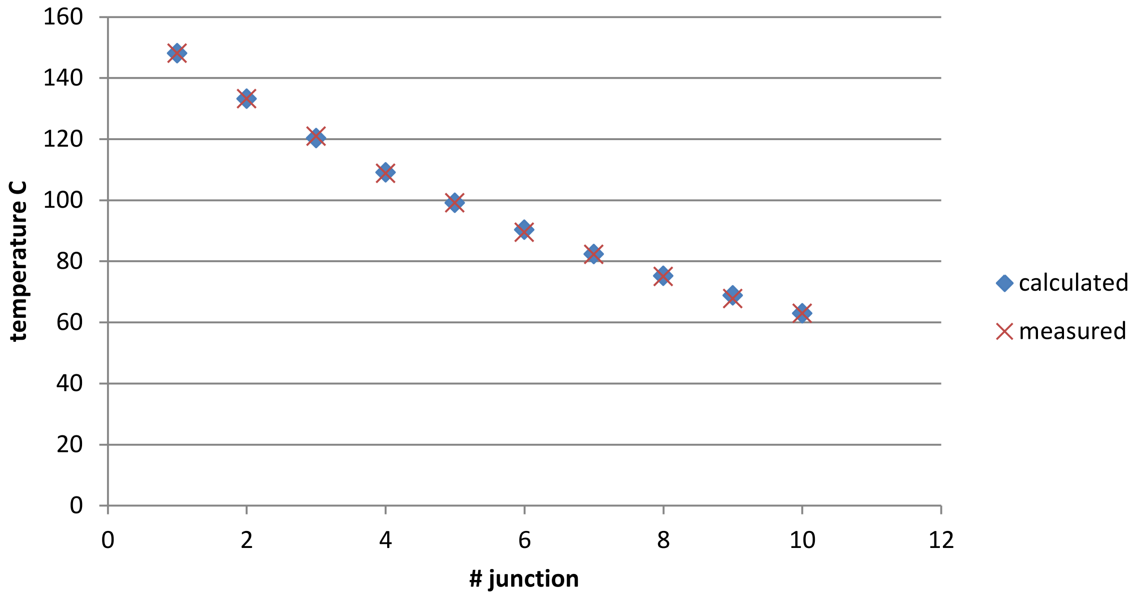

Fig 5.7 the measured and calculated temperature distribution for the tapered bar

It can be clearly seen from the figure that the measured and calculated temperature distributions are nearly identical. Substituting in equation 5.4 with numerical values we get

$$T(x) = \frac{1525 - 174.90\,x + 125.85\,x}{10.3 - 1.18\,x + 2\,x} \tag{5.9}$$

The thermal conductivity was calculated for the cylindrical bar to be 452.53$\pm$12.94 W/m.K. While the conductivity of pure copper is given in the literature as 401 W/m.K at a 25C.[3] The given thermal conductivity is near to the calculated one but still not in the uncertainty region mainly because the copper in the measured bar may not be pure. Also the assumption that the temperature is constant at the upper part of the bar is not accurate.

3.1 Uncertainty Analysis

Uncertainty analysis is performed based on Calculating the thermal conductivity for the cylindrical bar using equation 5.6 using 9 temperature gradients and 3 water flow rates we get a total of 27 thermal conductivity readings. The readings are shown in table 5.1.

The thermocouple resolution was set to be 0.1 which led to an error in all the thermocouple measured temperatures as $\pm$ 1.3 C.

Table 5.1 thermal conductivity results

377.19	431.49	454.14	433.82	447.30	435.55	445.18	436.78	444.15
384.43	439.77	420.99	442.14	455.89	443.91	453.72	445.16	452.68
545.83	468.14	492.72	470.67	485.30	472.55	483.00	473.88	481.88

The thermal conductivity was taken as the average value from all the results and the error was estimated using the following equation.

$$U_k = t_{\alpha/2,\nu}\frac{std}{\sqrt{n}} \tag{5.10}$$

Where t the t-distribution and $\alpha = 0.05$ is the level of significance, and $\nu = n - 1$, where $n = 27$ is the number of observations and *std* is the standard deviation.

4 Conclusions

In this experiment the thermal conductivity was measured for a copper bar and the temperature distributions were drawn for both a cylindrical and tapered bar and we get the following conclusions:

- The thermal conductivity for copper in a cylindrical bar was calculated to be 452.53 ± 12.94 W/m.K .

- Main source of difference between the measured and given thermal conductivity is because that the bar may not be made of pure copper also the constant surface temperature assumption is not accurate.

- The temperature distribution for the cylindrical bar made a linear relation between the temperature and the distance. Also the measured and calculated distributions for the tapered bar were nearly identical.

References

[1] http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/heatra.html

[2] http://www.thermopedia.com/content/781/

[3] http://www.engineeringtoolbox.com/