EXPERIMENT T1

MEASURING THE THERMAL CONDUCTIVITY OF COPPER

Objectives:
• To get acquainted with the idea of dynamic equilibrium
• To investigate the characteristics of heat flow
• To determine the thermal conductivity of copper

Background:
You know from experience that heat flows from hot to cold. If you stick a poker into a fire, the end that you’re holding gradually gets warmer – the heat from the fire only slowly travels up the poker.

How fast or slow heat travels through an object depends on many things. You know that certain materials conduct heat better than others. Touching a cold piece of wood or a cold piece of metal tells you this straight away – wood conducts heat poorly, and therefore the cold sensation is only passing, but metals transport heat much better – the heat from your fingers is used to heat up the entire piece of metal, and if you’re not careful the metal might freeze to your fingers! The extent to which materials conduct heat can be quantified by a parameter known as the *thermal conductivity*, symbol $k$.

Heat conduction is not only determined by the material, but also by its shape, and by the temperature difference between the two ends. You will probably guess straight away that the higher the temperature difference between the ends, the more heat will flow. If you were to grab a longer poker and stick it into the fire, it would take longer for the end you hold in your hands to get warm. However, if you made the poker wider it would be easier for the heat to get across. Finally the heat input is important as well: the more heat you put into one end of the bar, the more heat will flow to the other end.

From these considerations it follows that in order to measure the thermal conductivity of a certain material, we need to measure the heat input, its length, its diameter and the temperature difference. In its simplest form, an experiment might look like this: one end of the bar will be heated by means of a power supply, and you measure the amount of energy (heat) going in per second. You measure the length and diameter of the rod, and the temperature difference between the two ends of the rod. There is however one difficulty with this approach: eventually, the heat will spread out throughout the bar, and the entire bar will attain the same temperature. To circumvent this problem we keep the other end of the bar cooled.

Experimental set-up:
You are going to use Searle’s apparatus (shown below) to measure the thermal conductivity of copper. We input heat at one end of the bar by means of an electrical power supply. The other end of the bar we cool by wrapping tubing around it through which water flows at a
constant rate. The flowing water will carry off the heat reaching the cold end of the copper bar. In this way we eventually get a balance between the heat input on one end, and the heat carried away at the other end. As a result the temperature at each position of the bar becomes constant in time; we have reached what is called a **dynamic equilibrium**. The adjective “dynamic” is used since heating and cooling goes on continuously, and there is equilibrium because their net effect is to produce no change).

**Figure 1.** Searle’s apparatus for measuring the thermal conductivity of a copper bar.

We will now use a technique that applies, at least in principle, to every dynamic equilibrium: we can verify our measurements by measuring the heat flowing out as well as by the heat flowing in, since they have the same magnitude. We can thus measure the thermal conductivity twice, and a comparison of the two results will give us a good indication of the accuracy of our measurements. When the water carries off heat from the cold end of the bar, its temperature increases; by measuring this temperature increase, we can measure the heat output. We must be careful to keep the water flow constant; this can be done using a device called a constant pressure head.

**Now answer questions A1 through A3 on the answer sheet**

**Procedure:**

1. **Preparation:**
   - Ensure the thermometers are sitting correctly on the bar
   - Adjust the constant pressure head device to provide a steady flow around the cold end of the bar
   - Connect up the power supply
   - Get a demonstrator or technician to check your set-up.

2. **Starting up:**
• **Only when the water is flowing**, switch on the power supply, and record the input current and voltage.
• After a while you will see that the water starts to get hotter until a constant temperature difference is reached. For good experimental results, adjust the water flow so that the temperature difference is about 5 °C.

3. **Making the final measurements:**
• Wait until all thermometers reach a constant value, and record the temperatures of each thermometer
• Measure the rate of water flow by collecting the total water flow for a certain time interval that you measure (typically around 1 minute)

**Analysis:**
As you will learn in the physics lectures, the heat flowing into the copper bar is given by

$$ H_{in}^{\text{hot end}} = V \cdot I $$  \hspace{1cm} (1)

while the heat flowing out of the hot end (to the cold end) is given by

$$ H_{out}^{\text{hot end}} = kA \frac{T_h - T_c}{L} $$  \hspace{1cm} (2)

In equilibrium the heat in equals the heat out. Equating the two right-hand sides of (1) and (2) we get:

$$ k = \frac{VIL}{A(T_h - T_c)} $$  \hspace{1cm} (3)

The cross-sectional area $A$ is equal to $\frac{1}{4} \pi d^2$; we substitute this into Equation 3 to write the unknown thermal conductivity $k$ in terms of measured quantities:

$$ k = \frac{VIL}{\frac{1}{4} \pi d^2 (T_h - T_c)} $$  \hspace{1cm} (4)

Assuming that all of the heat flows to the cooler end of the bar, we get from Equation 2:

$$ H_{in}^{\text{cold end}} = H_{out}^{\text{hot end}} = kA \frac{T_h - T_c}{L} $$  \hspace{1cm} (5)

while the heat absorbed by the water is given by

$$ H_{out}^{\text{cold end}} = H_{in}^{\text{water}} = \frac{mc(T_2 - T_1)}{t} $$  \hspace{1cm} (6)

Combining these two equations gives
\[ k = \frac{mc(T_2 - T_1)}{\frac{1}{4}\pi d^2(T_h - T_c)t} \] (7)

The units of \( k \) are Wm\(^{-1}\)K\(^{-1}\). The constant \( c \), called the specific heat of water, is equal to 4190 Jkg\(^{-1}\)K\(^{-1}\).