Experiment 16: Heat conduction

Introduction

In this laboratory you will study heat flow across a temperature gradient. By comparing the temperature difference across one material to the temperature difference across a second material of known thermal conductivity, when both are conducting heat at a steady rate, you will be able to calculate the thermal conductivity of the first material. You will then compare the experimental value of the calculated thermal conductivity to the known value for that material.

Thermal conductivity is an important concept in the earth sciences, with applications including estimating of cooling rates of magma chambers, geothermal explorations, and estimates of the age of the Earth. It is also important in regard to heat transport in air, to understanding the properties of insulating material (including the walls and windows of your house), and in many other areas.

The objective of this laboratory experiment is to apply the concepts of heat flow to measure the thermal conductivity of various materials.

Theory

Temperature is a measure of the kinetic energy of the *random* motion of molecules with a material. As the temperature of a material increases, the random motion of its molecules increases, and the material absorbs and stores a quantity which we call *heat*. The material is said to be hotter. Heat, once thought to be a fundamental quantity specifically related to temperature, is now known to be simply another form of energy. The equivalence of heat and energy is one of the foundations of thermodynamics.

As the molecules in one region of a material move, they collide with molecules in neighboring portions of the material, thus transferring some of their energy to other regions. The net result is that heat flows from regions with higher temperatures to regions with lower temperatures.

An exact calculation of this heat flow can be very difficult for materials with complicated shapes and complicated temperature distributions, but in some simple cases the heat flow can be calculated. In this experiment, we will consider the heat flow across a plate of material of cross sectional area $\boldsymbol{A}$ and thickness Δx when its faces are held at constant (and different) temperatures, as indicated in Fig. 1.

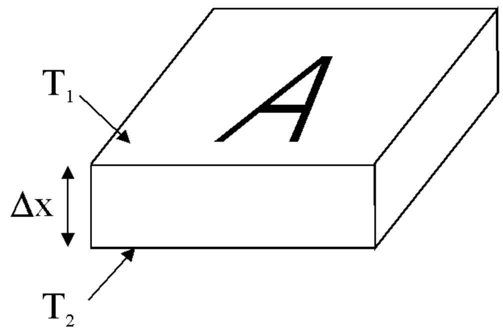

Figure 1 Heat flow across a plate.

In this case the rate of heat flow H across the material is given by

$$H = KA\left(\Delta T/\Delta x\right) \tag{1}$$

where $\Delta T = \left|T_2 - T_1\right|$ is the temperature difference across the plate and K is a quantity called the *thermal conductivity*. Note that this equation only applies because we keep the top and bottom at fixed temperature. In a more general situation, the flow of heat would alter the temperature of the top and bottom, and a more complicated approach would be required to deal with the situation.

Heat is transferred more efficiently through shapes with a large area that are subject to a large temperature difference, but more slowly through thicker materials. If the units of H are J/s, that of A are m^2, Δx is in m, and the units of temperature are ºC or K, then the units of K must be W/m-^{o}C. **Prove this** for yourself, and show it in your laboratory book. Since the Celsius degree is the same size as a degree on the Kelvin scale, the units of thermal conductivity are usually expressed as W/m-K.

We will use Eq. (1) to measure the heat flow through a material of known thermal conductivity and then use this result to determine the thermal conductivity of unknown samples forced to conduct heat at the same rate.

Thermocouples

In order to apply Eq. (1) we will need to measure the temperature difference ΔT across our samples. It would be difficult to insert a thermometer into the gap between plates without disrupting the heat flow, so we will instead use a temperature probe that uses a device known as a *thermocouple*.

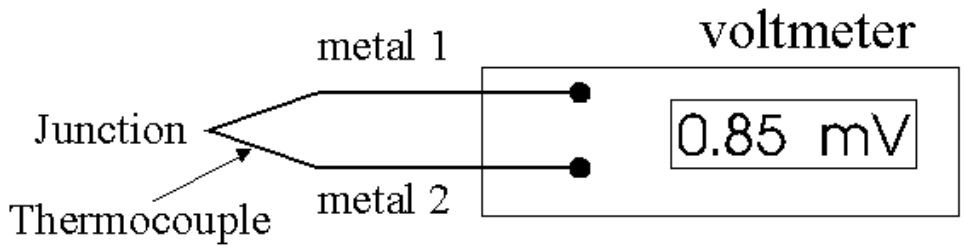

Figure 2. A Thermocouple

A thermocouple is simply two connected wires made of dissimilar metals. Whenever two different metals contact each other, a small voltage difference is generated. This voltage difference is dependent on the temperature of the junction. If we measure this voltage difference with an accurate voltmeter, we can look up the temperature of the junction *relative to the temperature of the connection to the voltmeter* in a thermocouple table. The instrument used in this lab does the conversion for you, so can read the temperature directly.

The thermocouple probe is now a very common device for measuring temperature, particularly in small places. For, example many medical thermometers are now based on thermocouples rather than the more traditional liquid in a glass tube.

Experiment:

Apparatus:

The apparatus for this experiment are shown in the following figure, which also demonstrates how you will use the equipment.

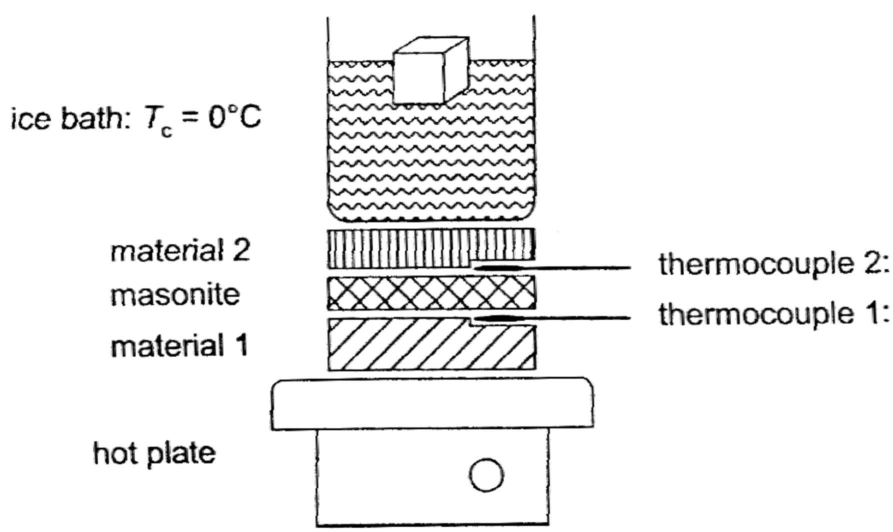

Figure 3. The apparatus for measuring thermal conductivity.

The apparatus for this experiment consists of a hot plate to supply heat, an ice bath to absorb heat, and plates of various materials through which heat will follow. Temperatures of the plates will be measured with a glass thermometer. In addition, the diameter and thickness of each plate will be measured with vernier calipers.

Method

Measure the diameter and thickness of each plate provided. Calculate the areas of the plates. Create the following table in your report and fill it in.

Table 1. Dimensions of various plates

Material	**Diameter** (cm)	**Diameter** (m)	**Area** (m^2)	**Thickness** (cm)	**Thickness** (m)
Masonite					
Aluminum					
Plexiglass					
Plywood					
Teflon					

Using the glass thermometer, measure the temperature of the room and ice bath. Record your values.

I. Thermal Conductivity of Plexiglass

Construct a "sandwich" consisting of aluminum, masonite and plexiglass with the slots arranged so that thermocouples can be inserted on either side of the masonite plate. Place the sandwich on the hot plate **with the aluminum side down**. Place the ice bath on top of the sandwich.

Switch the hotplate controller on and set the Variac to approximately 40% power. The exact value is not important, but if the power is set much higher some of the materials may get too hot.

WARNING: Use extreme caution around the hot plate and when handling any of the materials that come into contact with it for the remainder of the experiment. The

It will take up to 30 minutes for the heat flow to achieve a steady state. Monitor the progress by plotting the temperature readings T_1 of the thermocouple 1 and T_2 of thermocouple 2 as a function of time. Expect a maximum time of 45 minutes. Take readings every 1 to 2 minutes. If you miss a reading, skip it and record the next reading at the appropriate time on your plot.

You should find that the temperature readings eventually approach constant values. Even if they are still drifting after 30 minutes, the small changes to the heat flow will have only a small effect on your results. Record final values of the temperatures for the aluminum/masonite/plexiglass sandwich.

You now have all the data needed to calculate the thermal conductivity of plexiglass. See the "analysis" section later in these notes for details about how to do this. Calculate its value.

II. Thermal conductivity of Plywood

Carefully remove the Plexiglas plate and replace it with the plywood sheet (with slot down). Reinsert thermocouple 2 and place the ice bath back on top of the sandwich.

Since a steady state heat flow has already been established in the aluminum and masonite, this new configuration should take only about 20 minutes to achieve a steady state. While you are waiting for the temperature readings to stabilize, you may wish to use the time to calculate the thermal conductivity of Plexiglas. If you do this, keep an eye on the temperature readings so that you know when a steady state has been achieved. Record the steady state values of the temperature for the sandwich of aluminum/masonite/plywood.

III. Thermal Conductivity of Teflon

Carefully remove the plywood plate and replace it with the Teflon plate (with slot down). Reinsert thermocouple 2 and place the ice bath back on top of the sandwich. Again, a steady state will probably be achieved in about 20 minutes. Record the steady state values of the temperatures for the sandwich of aluminum/masonite/Teflon.

<u>Analysis</u>

If we neglect the heat that escapes from the edges of the plates (due to convection and radiation), all of the heat provided by the hot plate must flow through each of the plates and into the ice bath, once a steady state has been achieved. Thus the heat flow through each plate must be the same throughout the sandwich. In particular, this means that the heat flow through the masonite is equal to the heat flow through the top material. Therefore we can write $H_m = H_{top}$. Using Eq. (1) we find that

$$K_m A_m \left(\Delta T_m / \Delta x_m\right) = K_{top} A_{top} \left(\Delta T_{top} / \Delta x_{top}\right) \qquad (2)$$

The thermal conductivity of masonite is known to be 0.0476 W/mK. You can derive an expression from Eq. (1) for the thermal conductivity of the top plate.

Use your measured values and the known value for the K_m to calculate the thermal conductivities of each of the top plates used. Prepare a table like that shown below and fill in the values in your report.

Table 2. Thermal conductivities of materials used in this laboratory.

Material	**Calculated thermal conductivity (W/mK)**	**Published value of K (W/mK)**
Aluminum		
Masonite		
Plexiglass		
Plywood		
Teflon		

The least accurate measurements in this experiment are the thermocouple voltages, which are only measured to 0.1 mV accuracy. Based on this accuracy, estimate the uncertainty in the temperature difference across the masonite plate. Considering the uncertainty in this temperature difference *only*, what is the approximate percentage error in your calculated thermal conductivity values?

Questions:

1. Use Eq. (1) to calculate the total rate of heat flow H through each of the plates in Part 1. (Note: The same value of H must hold for each plate, so you only need to use Eq. (1) once).

2. Do your results agree with the expected values? If not, what measurements, processes, and/or assumptions do you suspect to have been significant sources of error?