Thermodynamics: Calorimetric Measurements and Linear Expansion
2016

Part I: Calorimetric Measurements
Procedure

Precautions:
(1) Do what you do here very carefully and don't burn yourself.
(2) Don't sit in a location where you can be burned from the system in the event of an accident.
(3) Don't let my pot boil dry.

My note: there are more accurate ways to do this experiment but equipment and safety concerns are more significant with these other methods.

You are provided with a calorimeter which consists of a small Styrofoam cup which will need to have about 100 g of water placed into it. You will want to weigh the (small!) cup **before** you put water in it so that you can obtain the mass of the water easily. You also have 2 pieces of metal (Cu and Al). You will want to weigh each of these materials.

You can tie a piece of thread around the metal samples, to insert and remove the metal from the water. When measuring aluminum, use thread to tie 4 pieces together. When using copper, use thread to tie 3 pieces together. While your metal is heating, record the initial temperature of the water in your calorimeter. The metal will be heated to a temperature of about 100 ^{0}C with relatively small uncertainty here (do not let it sit on the bottom of the pot). Carefully but quickly transfer the metal from the boiling water to your calorimeter. Stir the water several times with your temperature probe and then place the tip of the probe on the metal to record the maximum temperature. In an ideal world, no heat would be lost from the calorimeter but this experiment is taking place in the real world where black body radiation and Newton's law of cooling become important.

Theoretical Considerations

Since energy is conserved, we have the net heat transfer (Q) is given by Q=0. Thus:

$$Q=0$$
$$\Rightarrow m_{calorimeter} c_{calorimeter} [T_f - T_{i,\ calorimter}] + m_{water} c_{water} [T_f - T_{i,water}] + m_{metal} c_{metal} [T_f - T_{i,metal}] = 0$$

We can find from this the specific heat of the metal:

$$-m_{metal} c_{metal} [T_f - T_{i,metal}] = m_{calorimeter} c_{calorimeter} [T_f - T_{i,\ calorimter}] + m_{water} c_{water} [T_f - T_{i,water}]$$
$$\Rightarrow c_{metal} = -\frac{m_{calorimeter} c_{calorimeter} [T_f - T_{i,\ calorimter}] + m_{water} c_{water} [T_f - T_{i,water}]}{m_{metal} [T_f - T_{i,metal}]}$$

In today's experiment, the calorimeter and the water in it are initially at the same temperature (I'll call this $T_{i,w}$) so this reduces to:

$$c_{metal} = -\frac{(m_{calorimeter} c_{calorimeter} + m_{water} c_{water})[T_f - T_{i,w}]}{m_{metal}[T_f - T_{i,metal}]}$$

This calculation, of course, assumes perfect measurements, no loss due to radiation, etc. In our measurements today, you'll notice immediately that the resolution of our digital thermometers is not particularly high. In fact, as part of your work you will be able to estimate the error which comes from a degree error of 0.25 degrees which is reasonable given our equipment. In fact, accurate measurement of temperature will be your largest source of error in this lab: the second largest source of error will be due to energy loss in transferring the metal to the calorimeter. You will probably see from the spreadsheet that even a relatively small error in the temperature measurement can produce a rather large uncertainty in the measured specific heat value.

In today's lab, however, you are going to be using a Styrofoam cup which has very little specific heat and mass compared to all the other materials involved in today's lab. This will result in a much simpler calculation. In the calculation above, by setting the specific heat of the calorimeter to zero, we obtain a simplified result:

$$c_{metal} = -\frac{m_{water} c_{water}[T_f - T_{i,w}]}{m_{metal}[T_f - T_{i,metal}]}$$

Uncertainties in specific heat calculations

By far, the largest source of error for the lab today is from temperature measurement. You can anticipate at least a 1 degree total error from any given measurement. In estimating the error here, we are assuming a standard temperature measurement error of ±0.25 C.

The error calculation is given by the following method which is generally applicable[1]:

Suppose you have a derived value which depends upon x measurements as:

$$f = f(x_1, x_2, \ldots, x_n)$$

Further suppose each of the x measurements has an associated uncertainty σ_i .

To calculate the uncertainty in a given measurement:

(a) calculate $f_0 = f(x_1, x_2, \ldots, x_n)$ which is just the derived value without errors included.

(b) calculate $f_i = f(x_1, x_2, \ldots, x_i + \sigma_i, \ldots, x_n)$ for each of the uncertainties.

(c) calculate $\sigma_f = \sqrt{\sum_{i=1}^{n} (f_i - f_0)^2}$ which is the uncertainty in the measurement.

I have reproduced this on the spreadsheet for today's lab for you.

These uncertainties are calculated automatically for you today.

Part II: Coefficient of Linear Thermal Expansion

Precautions:

(1) Wear safety goggles when working on this experiment.
(2) The metal jacket which the steam goes through becomes quite hot. Don't touch it.
(3) Hot plates are hot when they are hot. Don't touch the hot plates.
(4) If you hear something that sounds like steam pressure building up, move away and ask for my assistance.

Don't place your hand in the steam: steam can cause nasty burns!
Don't let my tea kettles boil dry.

Theory

For a system undergoing temperature changes, a change in the physical dimensions is observed. To a good approximation, over small changes in temperature, the changes can be approximated as:

$$\Delta L = L_0 \alpha [\Delta T]$$

where L_0 is the initial length, α is the coefficient of thermal expansion, ΔT is the change in temperature and ΔL is the change in length. It turns out that this equation can not be correct (strictly said) since the following exists: if you start at a low temperature, and a system expands due to a change in temperature then at the higher temperature, L_0 would be different for cooling than heating ... Whew!

If we plot a graph of the length of an object as a function of the temperature of the object, the slope of this graph will then be given by:

$$\frac{\Delta L}{\Delta T} = \alpha L_0 \quad .$$

A bit more detail about the analysis and the graph is in order. On the y axis we plot the scale reading. At a particular temperature, the total rod length is

$$L = L_0 + \text{constant} + \text{scale reading} \quad .$$

Now if we plot then scale reading on the y axis, when we calculate slope we have:

$$\Delta L = \Delta(\text{scale reading})$$

But then the theoretical slope from the linear expansion is given by:

$$\frac{\Delta L}{\Delta T} = L_0 \alpha$$

Which means that plotting only the scale reading on the y-axis and plotting temperature on the x-axis will be good enough so long as the changes in length are very small compared to L_0. This is the case in today's lab. If another type of experiment was done in which is were not true, it would be necessary to plot L on the y-axis as a function of temperature and then the fit would not be linear; rather it would quite possibly be exponential. The linear approach works just fine for today's lab.

If L_0 is much bigger than the changes in length, then to a good approximation, we can treat it as a constant. In today's lab, we will assume L_0 is 60 cm. Then, you can divide the slope of your graph by L_0 to give you the coefficient of linear expansion.

You will find equipment for this portion of the lab for 2 metals: aluminum and copper. You will need to do both of these metals in order to satisfy the lab today. However you will need to switch locations: half of the lab setups have copper and half have aluminum rods.

There are several methods for measurement here. I am going to give you one variation. Connect your system and allow the tea kettle to heat up to the boiling point of water. It is quite possible that the thermometer measuring the temperature of your system will record a temperature over 100 C. When your system is at the maximum temperature, adjust your micrometer scale so that it reads somewhere between 90 and 0. Adjust your second screw so that the light bulb just starts to glow. You probably will want to give this a tiny bit of an additional turn in order to extend the initial temperature interval. I should have set the voltages on your power supplies low enough so that the bulbs will not be burned out. You should not increase this voltage since this could lead to increased experimental error from an arcing of the electrons across the gap. When you are sure that you are ready, you will want to record the initial temperature. Look at the spreadsheet. I have blocked out the place to record the initial length beside the highest temperature. This is because I want you to record your initial length below this cell. The temperature at which the light goes out (while the system is cooling) will be the temperature associated with this measurement.

Cooling Method

Be careful here: do not burn your hand!

Remove (carefully) your stopper from the steam kettle.

At the instant the light completely goes out, record the temperature. Then, give the micrometer a small turn towards smaller numbers (for example, 97->94->...) until the light comes back on. Read out this number to your lab partner (quickly). At the instant the bulb goes out, record the temperature beside the measurement you just gave your lab partner. Repeat this procedure until you reach temperatures of about 50 C, although you can go lower if desired. Newton's law of cooling says though that it will decrease in temperature more slowly as you approach room temperature. I have found that a temperature range from about 100C down to about 40C provides some of the best results.

Now place your values in the spreadsheet provided and, from the slope of your graph, calculate the linear coefficient of thermal expansion for your material. You will probably notice significant deviations in the results. There are several reasons for this. Firstly, your temperature resolution is only about 0.5 C^{0}. The temperature is not the same throughout your metal jacket. Also, the coefficient is only a linear approximation to actuality. As with other experimental work, however, a comparison of the results for copper and aluminum will show you that the larger the quantity is that is being measured, the lower will be your relative error. This indicates the presence of a systematic error which is approximately the same for each of the experiments. You may also have varying results due to the fact that different treatments for metals may result in different expansion coefficients.

Writeup

Your writeup should include an introduction, the graphs in part two and calculations in part 2 with a sentence about the results, the work related to the specific heat measurements with a sentence about the results, the sample calculation below and references.

sample calculations :

You must show clearly the units in your sample calculations.

SC1: Suppose you have a cube of copper which weighs 0.2 kg. The density of copper is 8940 kg/m^3. Use your α that you measured for copper (this is cell c5 on the linear expansion spreadsheet) to determine the change in volume when the copper is expanded against the pressure of 1×10^5 Pa through a temperature difference of 100C. You should assume $\gamma = 3\alpha$ here.

SC2: Suppose you have a cube of copper which weighs 0.2 kg. Use your measured specific heat for copper (this is cell B8 on your spreadsheet) to determine Q when this block of copper goes through a temperature difference of 100C.

SC3: Use the results from SC1 and SC2 to determine the change in internal energy when a cube of copper is expanded against the atmospheric pressure through a temperature change of 100C.

Footnotes

[1] A Practical guide to data analysis for physical science students, by Louis Lyons (c) 1991, ISBN 0-521-42462-1, page 26.