Thermal Expansion

PS253 – Physics Laboratory for Engineers
Embry-Riddle Department of Physical Sciences
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All materials expand and contract as their temperatures vary, some more so than others. In this lab you will investigate the material property of thermal expansion and analyze it quantitatively using a simple linear model. You will be given a selection of metal rods made of different materials. Based on your experimental data and a literature search you must successfully identify three different metals from their thermal expansion coefficients to within a 5.0% difference of the literature values.

Introduction

⚠ **!WARNING!** Do not turn on the hot plate until you are actually told it is time to use it. Having it sit on while unused is a significant burn hazard.

We will measure the expansion of metal rods, as temperature increases from room temperature to approximately the boiling point of water. The change in length is measured using a very accurate machinist's dial indicator, and the temperature will be measured using a thermistor or possibly a thermocouple electronic sensor. The physics of the thermistor is quite different from the thermocouple. Thermistors are made of semiconductors that have a relatively large change in resistance over a small temperature variation. Thermocouples directly produce a voltage that varies by fractions of a millivolt over small temperature ranges. As a lesson on the functions and processes of electronic instrumentation used in research and industry, students will also perform tests to determine the accuracy of the temperature sensor and the electronics that process the sensor output, including effects of analog to digital conversion.

The process of thermal expansion, as you may well imagine, is one that we need to minimize for designs that require very accurate position control. For example, the curve on a quality lens or mirror surface has to be accurate within one ten thousandth of a millimeter for visible light. Therefore, a small deviation due to thermal expansion can ruin an optical instrument. Thermal properties must also be well determined when various materials are attached together in panels, trusses, and other structures. This becomes incredibly complicated for say a satellite or space telescope, which might change from a fixed attitude with respect to the Sun to a varying, rotating one and likely has some components casting shadows on others.

One important point that is overlooked in a general physics text is that the thermal expansion property *is not* a fixed constant over all temperature ranges. It varies by small amounts for some materials over certain temperature ranges, and in professional design analyses one must carefully research the materials that may be used and compute the effects of the change in the thermal expansion "constant".

Metals that show very small expansion coefficients include "Invar" and "Super-Invar." They are used to make chassis for devices that must maintain positions within a millionth of a millimeter or so. However, even though the expansion coefficient may be tiny for a very limited temperature range, it can grow very fast outside the design temperature range.

On the other hand, there are some interesting materials that contract upon heating. A Titanium-Nickel alloy has been discovered that shows very large contraction when heated. It is available under the product name "Muscle-Wire" and, as the name suggests, hair thin strands of the alloy can be made to contract by simply sending an electrical current through the wire, and the resistive heating provides a relatively easy means for controlling the contraction by changing the applied current.

Linear Thermal Expansion Model

We assume that over a sufficiently small range of temperatures, that the thermal expansion, ΔL, follows a simple linear model with a fixed proportionality constant. It is directly proportional to the temperature change and to the initial length, L_o. The constant of proportionality is defined as α. Its value depends on the composition of the object under study. The formula for thermal expansion is then:

$$\Delta L = \alpha L_o \left(T_f - T_i\right) \tag{1}$$

In our experiment:

- ΔL is measured with a delicate machinist's dial indicator with length precision ± 0.005mm. Check the dial so you know how to read it properly.
- L_o is measured with a meter stick which has ± 0.5mm *position* precision.
- T_f and T_i are measured using electronic instrumentation and the precision will be determined by statistical analysis of "steady state" temperature measurements.
- α will be calculated from the measured quantities using Eq. 1. Notice the units: length/[length degree]. Although the lengths cancel, you need to include them as a scale factor, i.e. mm/[mm K]. α will be determined experimentally for three of four different metals, and compared against values that you will determine from literature research.

Analysis of Electronic Instrument Uncertainties

The following description pertains to the *Pasco Capstone* software, the sensors, and data acquisition devices that are supported by this software; however, it can be generalized for nearly any digital sensor or device. For more technical information on the Pasco thermistor temperature probe you will be using, follow the link- CI-6605A.

We will consider only the uncertainties in the electronic measuring system that can be determined by computing the standard deviation of many samples recorded under controlled "constant" conditions. We will also review the data to find the minimum change in temperature that can be measured with the electronic system- its resolution. Keep in mind for this analysis we are ignoring any potential systematic errors, such as a poorly calibrated or manufactured temperature probe. This could of course be checked for by running many probes in parallel at the same location to see how well they agree on the temperature. However, the statistical analysis of steady state conditions alone will only determine random uncertainties whether they be inherent to the sensor and its capabilities or to the steady temperature of the room itself.

The minimum measurable temperature change, or resolution, is determined by the device that converts the continuously varying sensor/amplifier signal to a discrete form for computer processing. This is done by an Analog to Digital Converter (ADC). The resolution of an ADC is determined by its internal circuit design, specifically:

- Upper and lower limit of voltage values that it is designed to accept
- Number of binary digits that it is designed to output.

To illustrate the basics of ADC operation, consider an ADC that is designed to measure voltages from 0 to 2V [Volts], with an output of 4 binary digits, corresponding to a temperature range of 10-20°C. The assignment of voltages could be:

Input Voltage [V]	Binary Value	Temperature Output [°C]
$x \leq 0$	0000	10.00000
$0 < x \leq 0.133$	0001	10.66666
$0.133 < x \leq 0.267$	0010	11.33333
$0.267 < x \leq 0.400$	0011	12.00000
…	…	…
$1.867 < x \leq 2.000$	1111	20.00000

Consider the column on the right. Note that the computer output shows seven digits but that the minimum measurable temperature change is 2/3 of a °C. The device cannot distinguish between temperatures within these 2/3 °C intervals. Typical ADC's have 8 to 24 binary digit outputs so the resolution is better than in this simple example, but the same limitations occur. There is a tradeoff in any electronic sensor between maximizing the range of physical values to be covered and maximizing the resolution within that range.

Determining Sensor Resolution and Temperature Precision

Set up Capstone to recognize your temperature probe:

1. Make sure that the temperature sensor is plugged into one of the Analogue Channel ports on the Pasco Interface box.
2. Using the PC that is attached to the Pasco interface by USB, open the program *Capstone*.

3. When *Capstone* opens, in the left-side menu, click on the *Hardware Setup* button to open a window where you can add your sensors.
4. Click on the virtual input where you plugged in the temperature sensor and select *Stainless Steel Temperature Sensor* from the menu to add the sensor. Then exit the *Hardware Setup* window.
5. In the central display area select the option *Two Small, One Large Display*. Click on each display area that appears and set the small display panels to a *Digits* display and a *Table* display; set the large display to a *Graph* (Display options are in the right-side menu).

   In the displays, wherever it indicates <*Select Measurement*> set the fields so that the *Digits* shows temperature, the *Table* lists temperature and time, and the *Graph* plots temperature over time.
6. Click *Record* to collect 1-2 seconds of data. If no one was holding the steel part of the sensor and the temperature is vastly different from room temperature, 19-23°C, speak to your instructor.
7. Select the *Digits* display and adjust the decimal precision to show temperature to two decimal places. Select the *Table* display and adjust the decimal precision on the temperature column to show four or five decimals for temperature.
8. You can adjust the size of each display by moving the cursor to the inner edges and click/drag the display edges around. The smaller displays only need to be a column on the left or right, most of the screen should be used by the graph.
9. In the bottom menu, adjust the sampling rate to 25 samples per second.
10. With the probe in equilibrium, in the ambient air, *Record* 5-9 seconds of temperature values. Inspect the data set to determine whether it was nearly in equilibrium or whether it was actually cooling or heating due to prior handling of the probe. Repeat for another run until you obtain data at equilibrium.
11. Select the *Table* display and in its menu options find the *Statistics* button (**Σ**). Select it and use the dropdown settings to only show the *Standard Deviation*.
12. Inspect the dataset to find the minimum temperature resolution of the ADC (remember this will be a small step size change between two values that likely repeat often). The *Graph* might be helpful in visually finding this smallest step size, but the *Table* will give you the values to actually calculate it. This will give you two options for choosing an estimated temperature uncertainty.

    Record both values for your report, but use the larger of the two as the uncertainty estimate for all temperature measurements taken in this experiment.

Determining Thermal Expansion Coefficients of Unknown Metal Rods

13. Obtain your choice of three out of the four different types of metal rods available (not multiple rods of the same material). Using a meter stick, measure the initial length of your first trial rod to the nearest 0.5mm.

    Note that when measuring length on a ruled scale you are actually measuring the displacement between two *position* measurements. This is important for correct propagation of uncertainties (required for this lab and your report).

14. Make other observations about your rods such as color, weight/mass, luster, magnetic properties, etc. to assist in any difficult identification later; however, the primary means of successfully identifying the metal must be the thermal expansion coefficient.

15. Fill the metal boiler tank no more than 1/3 full with hot water from the sink. Connect as shown in Figure 1. Also, fill the overflow beaker about half full with cool water to condense steam that passes through the system.

!WARNING! There are many hot objects that can cause contact or steam burns in this experiment. Only the boiler should be on/near the hotplate, clear the area of other objects. Steam is likely to escape from the temperature probe inlet so do not place your face or ungloved hands near it. The plastic tubing might dislodge at some point, if it does immediately remove the boiler from the hotplate and with gloved hands reattach the tubing as quickly as possible. All metals in contact with the steam will be hot long after the steam is gone.

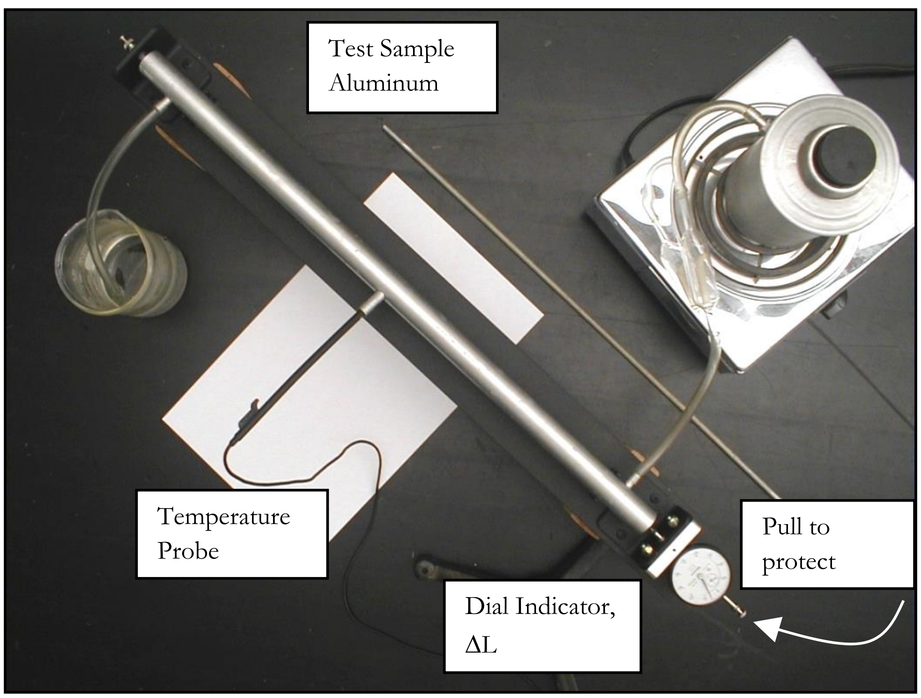

Figure 1: Thermal Expansion Apparatus. The metal steam boiler on the upper right supplies steam to the pipe running from the lower right to the upper left where the steam then vents and condenses in a cool bath of water.

To insert a metal sample rod:

16. Obtain a hollow insulated pipe; insert a metal sample rod into the pipe center.
17. Pull back the dial indicator shaft and hold it pulled back. Gently place the pipe in the apparatus so that one end of the metal sample rod rests against the end stop screw.
18. Place the pipe flat, and slowly release the dial indicator shaft so it rests against the metal rod.
19. Connect the inlet and outlet plastic tubing to the pipe. Insert the temperature probe

Recording data during a trial:

20. Set the sampling rate to 2 Hz and begin recording temperature data continuously. When you are sure the temperature is steady at equilibrium, record the initial temperature T_i. Continue recording temperature continuously for the rest of the trial run.
21. By twisting, adjust the outer machinist dial scale so zero is aligned with the pointer. The large outer dial scale is in increments of 0.01mm while the smaller inner dial counts revolutions of the outer dial [1mm].
22. Record the initial position and uncertainty of the dial indicator, both scales summed together, for the room temperature rod.

⚠ **!CAUTION!** Make sure the cord for the temperature probe is not in contact with the hot plate and does not touch any surface that will get hot from the steam. The cord will melt and damage the wires, making the probe unusable.

23. Turn on the hotplate, place the boiler centered on the hotplate, and wait for the water to start boiling. It will take 5-10 minutes for the steam to reach all the way to the end of the pipe and fully heat the rod, watch the temperature readings.
24. Watch the temperature and dial indicator: after the temperature has spiked and held steady and the dial reaches its maximum value and holds steady for 15 seconds or so, record the final temperature and the final dial indicators, both dial scales summed together.
25. Turn off the heater. Let it cool down a little before removing the sample rod.

To remove a metal sample rod:

26. With the hotplate off, put on gloves since the pipe will be hot, and remove the temperature probe.
27. At the pipe, disconnect the plastic tube from the boiler to the pipe, and raise it above the boiler to empty any trapped water back into the boiler.
28. Pull back the dial indicator shaft and hold it pulled back. Slowly tip the pipe upward at the indicator end to drain any trapped hot water into the cool bath beaker.

⚠ **!WARNING!** The hot metal rod and some hot water will remain in the pipe.

29. At the pipe, remove the plastic tube connecting the pipe to the cool bath and carefully walk the pipe over to the sink.
30. At the sink remove the metal rod from the pipe and leave the rod in the sink. Run the pipe under cold water at the sink flushing out the pipe through the tubing connectors until the pipe is near room temperature again.
31. Repeat Steps 16-28 to test the other metal rod(s) until you have successfully tested <u>three different material rods</u>.
32. When finished make sure the hotplate is turned off, place the metal boiler on the table, and leave your hollow pipe in the sink to cool off.

Data Analysis

33. Compute the expansion coefficient α for each tested metal rod before leaving.
34. Compute the percent relative uncertainties in the following quantities: initial length, the change in length, the initial and final temperatures, and the change in temperature.
35. Since you have uncertainty values on each of your measured quantities, use propagation of uncertainties to determine the propagated uncertainty in your three expansion coefficients. You MUST show all your steps for determining one of these in your report's *Calculations* section.
36. Do a literature search to find reference values for the expansion coefficients of common industrial metals. State the temperature ranges to which they apply or note that none was given, also include any other notes the reference gives for these values. Identify the references in a proper manner in your report's reference section.
37. Compute the percent difference between your experimentally determined expansion coefficients and the reference values.
38. Discuss the experimental range of $\pm\sigma$ [sigma], $\pm$uncertainty, values needed to cover the difference between your α value and the reference value for each metal: $\pm 1\sigma$, $\pm 1.5\sigma$, $\pm 2\sigma$, or more. In other words: How many propagated uncertainty values away from the reference value was your experimental value?
39. Did you successfully identify the metal each of your three rods was made out of based solely on its coefficient of thermal expansion?

Appendix I: Thermal Expansion Guidelines

- Include signed raw data sheet
- One column abstract, two column for everything else (except very large graphs, figures, tables)
- Correct units and sigfigs on all numbers
- Cite anything taken from the lab module
- Cite any text, values, equations, figures taken from anywhere else
- **Abstract:** Very briefly describe the experiment, state goals, summarize results including experimental values, expected values, and percent errors/differences or standard errors, state degree of success
- **Background:** Why doing experiment, state goals, give background and historical info, explain any deviations from procedure
- **Theory & Methods:** Thermal expansion formula, stated *and* explained; constants used including their values and sources, anything important to point out or clarify about the procedure and equipment's setup/operation *including* sensors and relevant physics as well as approximations or assumptions
- **Discussion of Results:** Expansion coefficient value(s) with propagated uncertainty, reference values with cited source(s), percent differences, table for relative errors, sigma range of experimental value from the reference, did you achieve the 5% difference criteria for successful metal identification, describe at least two sources of uncertainty.
- **References:** Proper format as seen in Good Lab Report and Example Reports
- **Calculations:** *One complete example of calculating all the following.* expansion coefficient, relative error, percent difference, propagated error including partial derivatives for all five measured variables.

These are just guidelines. You may need to add more items, as these are just some of the things expected.