

Department of Mechanical and Aerospace Engineering
MAE 334 - Introduction to Instrumentation and Computers

Laboratory 1

Static and Dynamic Calibration of Thermocouples

Objectives

This introductory experiment will give you a first experience in our Instrumentation and Systems Lab. You can expect to become familiar with the most basic concepts of using transducers for measurement and the acquisition of data with a computer based data acquisition system. You will use the National Instrument's software product called Virtual Bench which is a part of the LabView data acquisition package. Data is gathered through an analog to digital converter (ADC) which is also a National Instrument's product. The data acquisition system will be reading the output voltages of a temperature sensor called a thermocouple which you will calibrate and use to estimate several water and air temperatures. Specifically, the objectives of the experiment are:

- (1) to become familiar with thermocouples as very common transducers for measuring temperature;
- (2) to carry out a formal static calibration of a thermocouple as a typical transducer, in order to explore the linearity of a typical calibration curve and to evaluate the accuracy of measurements that can be made using the calibration;
- (3) to perform a dynamic calibration of a thermocouple considering a first order dynamic model of its transient behavior and to explore the factors which influence the dynamic response of thermocouples.

Background

Thermocouples are probably the most widely used industrial and laboratory temperature sensor because they are simple, relatively inexpensive, and reasonably linear. The thermocouple outputs a small electromotive force (emf or voltage) which is proportional to the temperature difference between the two junctions of the sensor. This small voltage can be readily conditioned and sampled by a data acquisition system. The

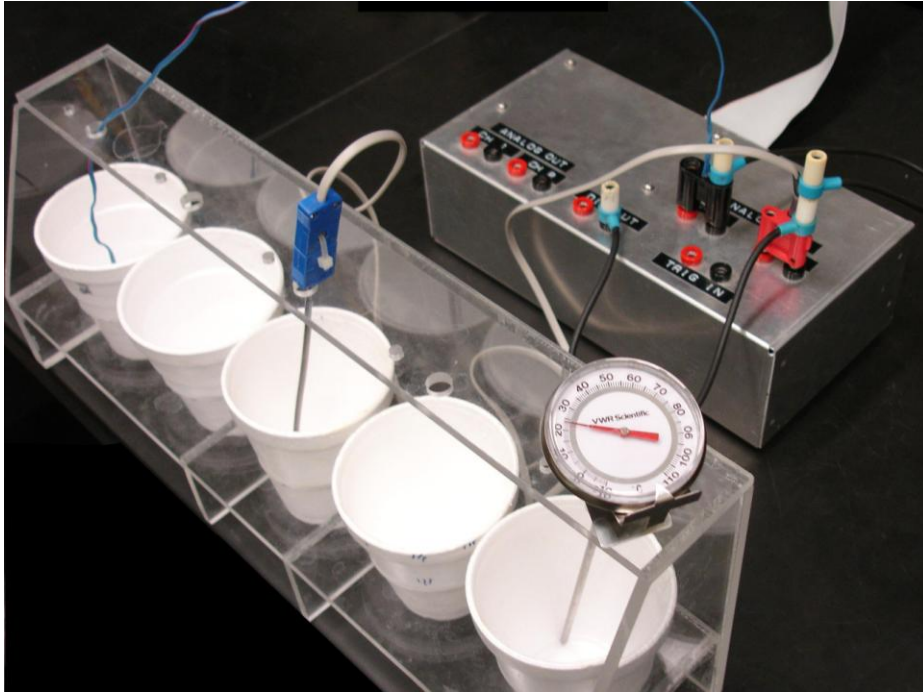


Figure 1. The lab setup showing the thermocouples, thermometer and data acquisition inputs on the right

physical phenomenon which creates the voltage produced by the thermocouple is referred to as the Seebeck effect – where a voltage is produced when two dissimilar materials are connected together at junctions which are at different temperatures. See your text¹ for details (Section 7.5 or 8.5 depending on the edition). You will also want to read over the material in our “Further Background” section at the end of this write-up.

The equipment used in this experiment includes an accurate dial thermometer, a commercial thermocouple probe and a simple “homemade” thermocouple of copper and constantan. You will use the digital multimeter (DMM) and the data logger of National Instrument’s Virtual Bench. There is also a collection of Styrofoam cups for you to use in providing multiple temperature sources for your calibrations and transient experiments. Figure 1 shows a typical lab station.

Getting Started

Start the PC operations by logging in with your user name and password. Of course, if the PC is powered off, turn it on first. After you have logged in, you should find that your Engineering home directory maps as drive N on the laboratory PC. You will want to save your data here at the end of your lab sessions. You can also use the “My

¹ Figliola, R. S., Beasley, D. E., Theory and Design for Mechanical Measurements, John Wiley, New York.

Documents” folder on the PC during your lab which will normally store directly into your Engineering home directory. You can use the “Temp” directory on the laboratory computers for temporary storage but don’t rely on it as being a permanent storage space for you from lab to lab. USB flash disks are ideal to carry your data home or to other computers. Always make sure you have backed up your data files. Some of our saddest experiences are with students losing data. Also, don’t forget to Logoff when you have finished your lab session to close your login (and access to your account).

Part 1 – Static Calibration

Setting Up the Virtual Bench DMM for Thermocouple Measurements

- Place the dial thermometer on top of the aluminum input box for the analog to digital converter (ADC). This is to estimate the reference junction temperature which is approximately the lab air temperature.
- Note the thermocouple probe and ADC cable connections. The thermocouple probe should be connected to ADC input channel 0 and a ground connection should be in place between the digital output ground and the ADC input ground of channel 0. Please note that the “first” input channel is usually referred to as channel zero (this makes sense in a computer world). But sometimes the first channel is also referred to as channel 1. This may seem confusing but it is a continuing issue so you should just “get used to it”.
- Click on the desktop icon for the VirtualBench. Then look for the VirtualBench DMM (Digital Multi-Meter) in the options window that opens. Click on this and when the DMM opens click on *Edit, Settings, General* Tab. Set the Channel to 0 and the Sample Rate to Slow. See Figure 2.

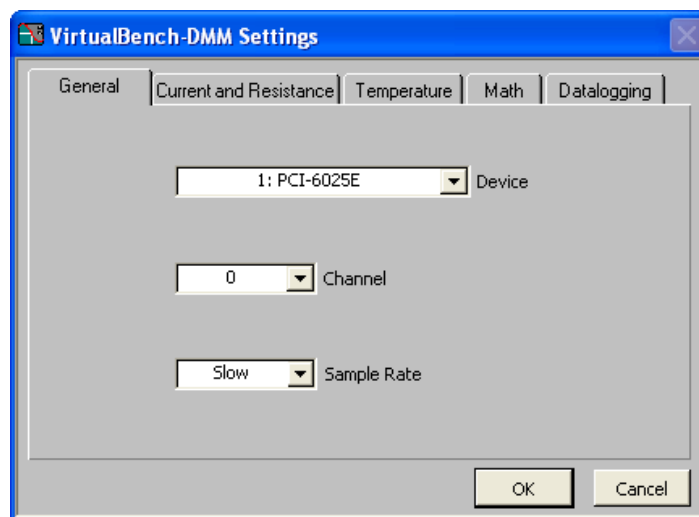


Figure 2. The DMM General Settings Window

- Under the *Edit, Settings, Temperature* Tab (Figure 3), set the Temperature Sensor to "T Thermocouple" (for copper-constantan), the Temperature Units to "Celsius", the TC Cold Junction Source to "Constant" and the Cold Junction Temperature (Degrees) to your dial thermometer measurement. If your thermocouple measurements show obvious offset as you begin your calibration runs, this Junction Temperature may be adjusted. Keep in mind that the ice bath is the very best known temperature in this experiment and it's always 0 C.
- In the main DMM window (Figure 4) set the Range to Auto, the Mode to Volts DC and, when ready, click the Run Continuously button. The DMM is switched over to a direct temperature reading mode by clicking on the thermometer icon as shown in Figure 5.

Making the Temperature Measurements

1. Obtain a supply of crushed ice and tap water including a cup of hot water. With the ice and hot and cold tap water, produce five cups with more or less equally spaced water temperatures from 0 C to the temperature of the hottest water (about 40 C). Be sure to stir the containers to ensure uniform temperatures before recording any data. There should be plenty of ice in the ice water bath as you take measurements and no ice in any other cup.
2. Open an Excel spreadsheet to record your dial thermometer temperatures and thermocouple data. The data can then be immediately plotted to find bad or incorrectly entered data points and analyzed using a linear regression to obtain the calibration slope and intercept. This calibration data must also appear in your lab notebook (calibration curves and linear regressions will be required for the lab report).
3. Place the dial thermometer and the thermocouple probe in each cup of water until the thermometer reading remains constant (approximately 30 seconds). Gently tapping the dial thermometer may be helpful here. For each point, record the thermometer temperature as well as the thermocouple voltage and the thermocouple temperature from the Virtual Bench Digital Multi-Meter (DMM). Detailed suggestions for gathering data are described directly below.

Collecting the Static Calibration Data

- Record the temperature of each of the five cups of water using the dial thermometer, the corresponding thermocouple probe voltage from the DMM, as in Figure 4, and the temperature output from the DMM, as in Figure 5. Sample the temperatures in random order.
- Enter this data in an Excel spreadsheet, as in Figure 6, and in your lab notebook for temperature measurement.

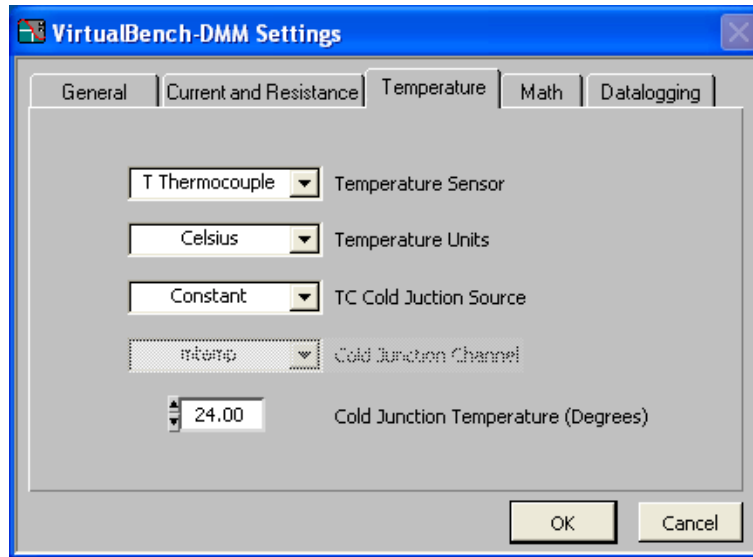


Figure 3. The DMM Temperature Settings Window

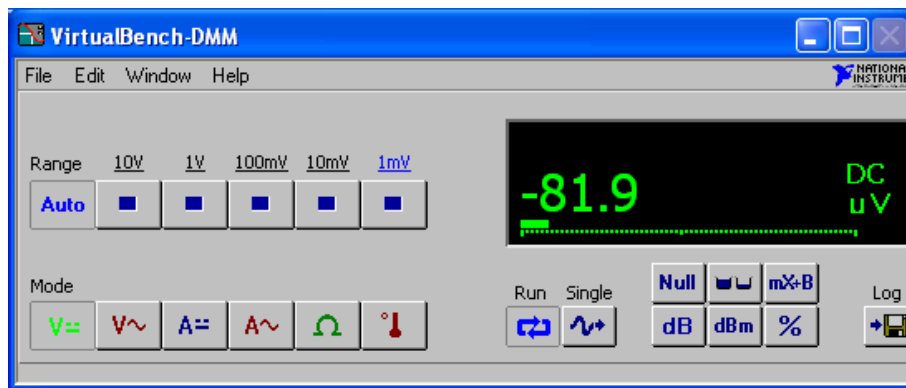


Figure 4. The VirtualBench-DMM main window in Volts DC mode. Note the mode setting (DC) and units displayed to the right of the digital output

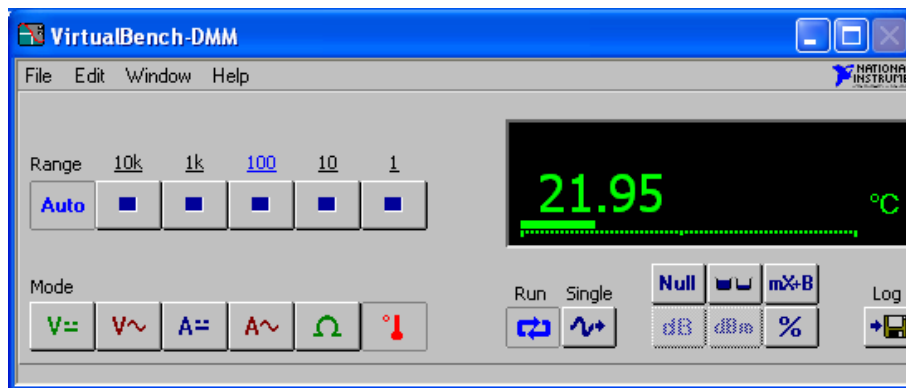


Figure 5. The VirtualBench-DMM in Temperature Mode

Point Number	Thermometer Reading [C]	DMM Value (uV)	Virtual Bench Temp Reading [C]
1	0.5	-616	7.63
2	21	213	28.25
3	41.5	1050	48.44
4	30.5	580	37
5	33	695	40
6	21.5	217	28.25
7	3.2	-590	8.05
8	40.3	984	46.65
9	22	229	28.55
10	14	-79	21.1
11	31.8	637	38.45
12	22.5	250	29.1
13	2	-583	8.6
14	22	240	28.9
15	15	-38	22.05
16	36	814	42.65

Figure 6. Example Excel spreadsheet used to record the static calibration data

- Repeat the procedure above with your original water cups so that you have at least 10 sets of data points obtained in this manner (you should take the temperature of each cup of water two separate times and record the DMM voltage and temperature reading). Careful with microVolts and milliVolts.
- Refill your water cups to obtain a different set of temperatures for calibration. Repeat the process above with one pass through the refilled cups so that you have an additional five data points and a total of **15 data points** for the calibration.

Processing the Static Calibration

We now assume that the dial thermometer provides an accurate measure of temperature. The thermocouple probe is to be calibrated based on the dial thermometer readings.

We would like to generate two working calibration curves – the first one using the thermocouple voltage as measured by the DMM – this plots dial thermometer temperature (on the y axis) vs. thermocouple probe voltage (on the x axis). The second working calibration curve should use the thermocouple probe temperature as indicated by the DMM. This curve should plot dial thermometer temperature (on the y axis) vs. thermocouple probe temperature (on the x axis). The two curves allow a choice for measuring temperature with the thermocouple probe: (1) Read the voltage from the

DMM and use the curve to find the temperature. This is the traditional approach to temperature measurement. (2) Read the temperature value directly from the DMM (using its built-in thermocouple calibration) and get a corrected result using the second curve.

On your working calibration curves, make use of all of your fifteen data points. For each curve, show the linear trend line and its equation for the calibration data on the plot. For both calibrations, calculate the standard error (for the y axis) in your calibration data. You may use the Excel function LinEst to do this – free help from your TA.

Part 2 – Dynamic Calibration

The dynamic calibration will utilize the Virtual Bench Logger program of Figure 7. The Virtual Bench Logger will sample the thermocouple voltage repeatedly after you specify the desired sampling rate and total sampling time. The VBLogger is intended to operate over longer time periods compared to “scope” type displays such as VBScope (which will be used in Experiment 2).

Setting up the Virtual Bench Logger

- Exit the Virtual Bench-DMM. **DO NOT INVOKE THE DIGITAL MULTIMETER AND THE DATA LOGGER SIMULTANEOUSLY. THIS MAY LOCK-UP YOUR COMPUTER**
- Select the Logger from the Virtual Bench tool bar. Then select the *Edit, Settings* menu item to see the Logger Settings window of Figure 8. Set the Start Channel and End Channel to the lowest available channel. Typically this

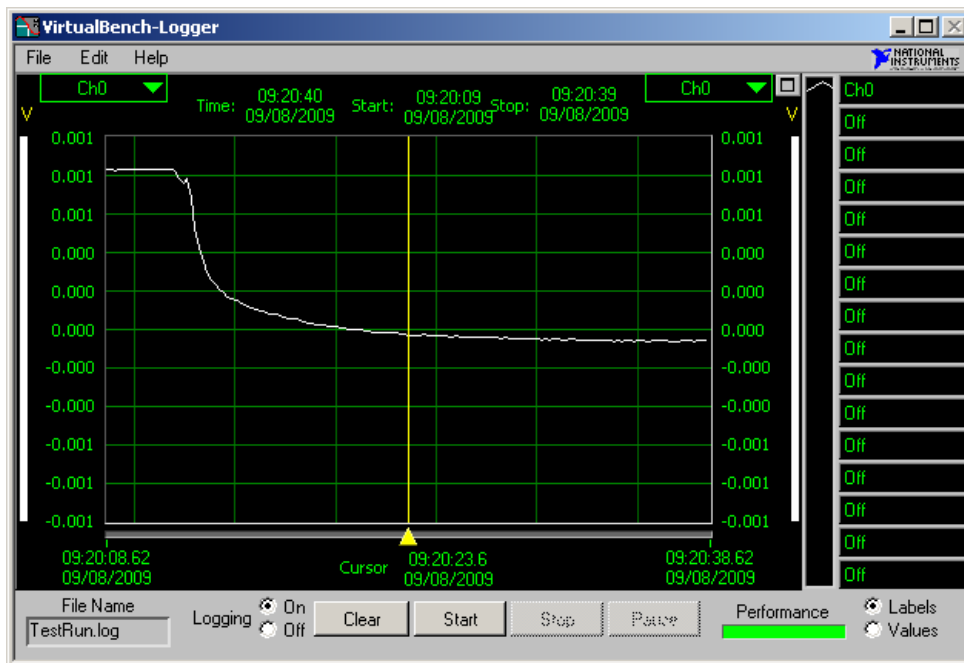


Figure 7. The Virtual Bench-Logger program

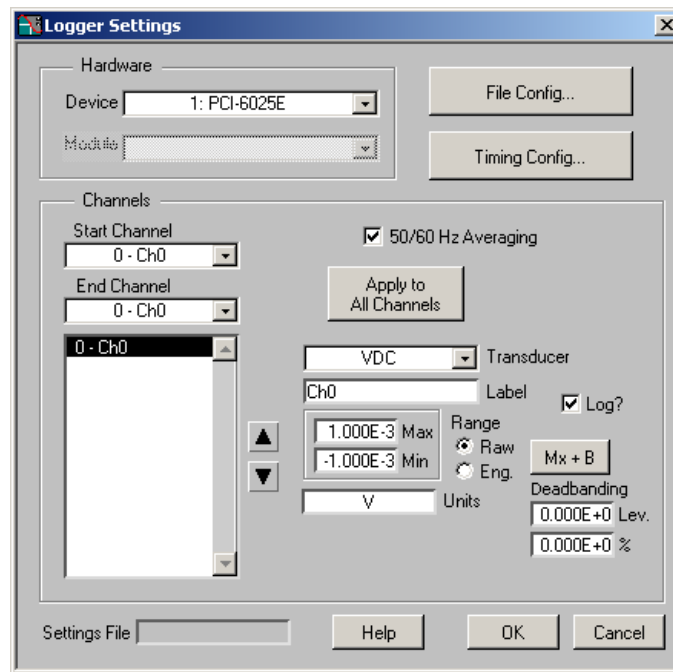


Figure 8. Logger Setting Window

- will be 0-Ch0. But in some cases it may be 1-Ch1. This is a common programming issue – is the first item in a list numbered “0” or numbered “1”?
- Set the *Transducer* to VDC and be sure that 50/60 Hz averaging is checked.
 - Set the *Range* Max to 1.0E-3 and the Min to -1.0E-3 (i.e. plus or minus 1 mV). Also select 50/60 Hz averaging to minimize the effect of stray electrical noise.
 - Next click the *Timing Config...* button. This will allow you to adjust the Logger sampling rate and sampling time.
 - In the **Timing Configuration** window of Figure 9, set the *Time Interval* = (1/sampling rate), to 0.20 sec (this is compatible with the filtering selection).
 - Set the *Stop Timing* entry to *Stop After Elapsed Time* of 30 seconds. Finally set the *Display Length* to 30 seconds.
 - Press OK. A *Time Interval* of 0.20 seconds results in a sampling frequency of 5 samples per second. A 30 second data record will produce a 150 point data file (30 x 5 = 150).
 - The final item to setup is the file configuration. This includes enabling the program to log the data to a file and specifies the file name. To accomplish this click the *File Config...* button in the **Logger Settings** Window (Figure 8).
 - In Figure 10, **use the Browse button** to locate an appropriate location (perhaps MyDocuments or c:\temp) and change the file name to something meaningful to you (make sure to keep the .log extension).

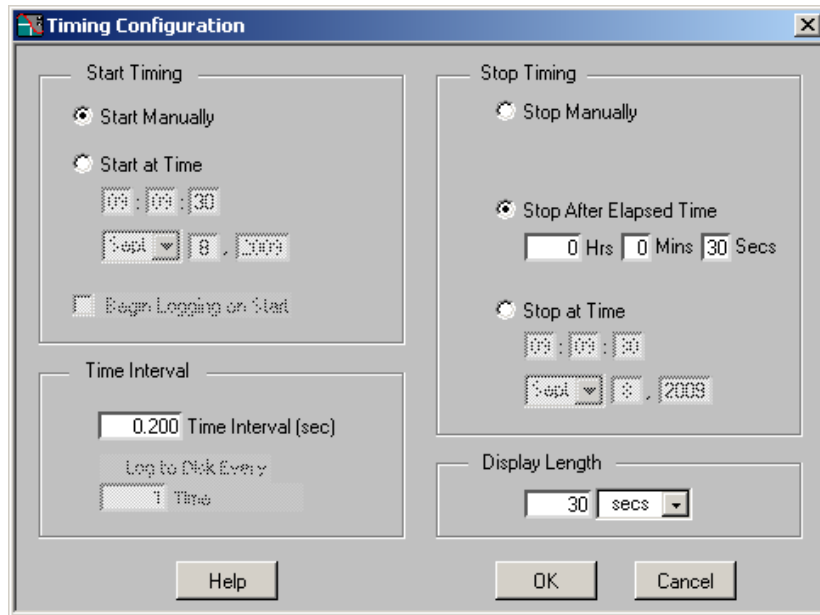


Figure 9. Data Logger Timing Configuration Window

- Check the *Enable Logging* check box. **Do not check** the *Begin Logging on Start* box.

Note: After each data set is saved, the **file name will need to be changed before logging starts again** to avoid writing over previously saved data. Also, be aware of the Append/Overwrite option. Overwrite is preferred.

- Change the *Field Length* to 12 and the *Precision* to 9.
- Click OK to exit the File Configuration window.
- Click OK to exit the Logger Settings Window.
- To run the logger without saving data, just click the START button with the Logging Off check box setting. To log data (save to file) enable logging by checking the Logging ON check box as shown in Figure 7. Then click the START button. The next 30 seconds of data (150 points at 0.20 second intervals) will be logged to the data file you specified.

Collecting the Dynamic Calibration Data

1. Immerse the thermocouple probe in the hot water for approximately 30 sec (required to reach an equilibrium state).
2. Update the comments and file name in the *Edit, Settings..., File Config...* window to reflect the contents of this step input data log (be sure logging is enabled).

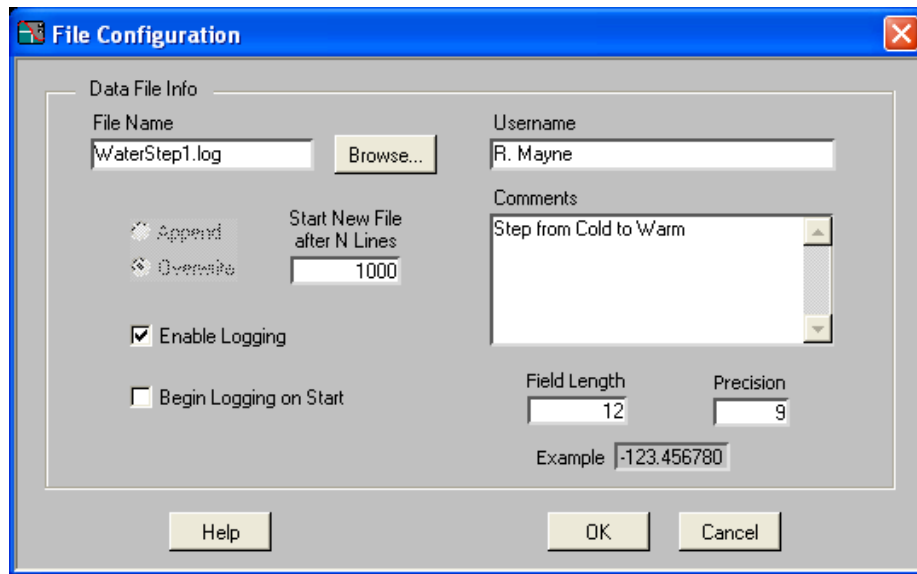


Figure 10. Data Logger File Configuration Window

3. Click the Logging On button (just to the left of the Clear and Start buttons)
4. Click Start to begin data logging and then quickly move the thermocouple probe from the hot water cup to the ice water cup. Expect a transient like Figure 7.
5. Repeat steps 2 - 4, but now move the probe from a cool water cup (not ice) to the ice water cup.
6. Repeat steps 2 - 4 as appropriate to now create a step input from hot water to room air. When you first expose the thermocouple probe to air, pull it through a paper towel as it leaves the hot bath to quickly dry it in order to minimize the effect of evaporation. Log the data using the following new settings in the *Timing Configuration* window: *Time Interval* = 1 sec, *Stop After Elapsed Time* = 10 minutes, *Display Length* = 10 minutes.

That's two "water to water" step input data sets and one "water to air" step input data set.

Processing the Dynamic Calibration Data

The dynamic calibration focuses on evaluating the time constant of the first order model of the thermocouple probe's dynamic behavior described by Equation (1) in the **Further Background** section. Before proceeding into the dynamics, however, use your static calibration linear equation to convert your three dynamic data sets from voltage to temperature. Plan to use Excel to create plots of temperature vs. time.

For the first dynamic case in items 2 – 4 above (hot water to ice water), apply the "two thirds rule" illustrated in Figure 13 to estimate the time constant for the transient

temperature change. Use Equation (1) and Excel to simulate your first dynamic transient with your estimated time constant value. Plot your simulated response on the same axes as the original data so that you can compare the modeled transient behavior against the actual transient. You may time shift the data as needed to adjust time “zero”.

Normalized forms are often used to compare behaviors for conditions that are not exactly the same. Equation (2) uses the error function as a type of normalization. Use the left hand side of Equation (2) to “normalize” your two water-to-water data sets (hot to ice and cool to ice). Using the left hand side of Equation (2), both of the transients should now go from “one” to “zero”. Plot these two data sets on the same Excel graph so they can be readily compared. This works easiest if you time shift the two data sets so that both temperature changes begin at time “zero”.

Finally, use Excel to plot and study your water-to-air transient. Again apply the “two thirds rule” to estimate the time constant. Use your estimated time constant to simulate the air transient. In a carefully labeled Excel plot, compare the simulation against your original data of temperature vs. time for water-to-air.

Part 3 – Simple Thermocouple vs. the Thermocouple Probe

The second channel on your ADC connection box includes a simple copper-constantan thermocouple. Set up the data logger to allow you to plot both channels simultaneously (Start Channel = 0-Ch0 and Stop Channel = 1-Ch1). Apply the default thermocouple calibration by selecting the “Transducer” on both channels in the Logger Settings to be a type T thermocouple with an appropriate constant reference temperature. Adjust the range in the Logger Settings to cover the range of cold and hot cup temperatures in Celsius. Using the time range of thirty seconds with a 0.10 second sampling interval will be adequate.

Start with both the thermocouple probe and the simple thermocouple in the hot water cup. Move them quickly from hot to ice, record the transients for both on the data logger. Obtain a “print screen” of the combined transient for your report. Based on the “two thirds rule”, estimate the time constants for each thermocouple.

Before You Leave the Lab...

have your teaching assistant check off your Excel spreadsheets showing your first draft of the plot for the calibration of thermocouple voltage (this will become ReportFigure 1). Also present your Excel plot for the air transient simulation (this will be ReportFigure 7).

Report

In your Summary, briefly describe your lab experiment and results. Be sure that your Results section contains:

1. The two working calibration Excel plots of part 1 showing the fifteen data points along with trend lines and equations for the trend lines (ReportFigures 1 and 2). Discuss your LinEst results which show the standard error measures for the two

cases. How do the LinEst results compare to the trend line calculations? What additional information do you gain? Include one example clipping from Excel of your LinEst calculations (ReportFigure 3).

2. An Excel plot of the temperature vs. time data for your hot to ice water transient (ReportFigure 4) and your estimate of the simple time constant (2/3 rule) as a dynamic calibration. Also show an Excel plot for the simulation with your estimated time constant from the 2/3 rule. On this plot, include the original data points along with the simulation (ReportFigure 5). The Excel plot comparing the two normalized water-to-water transient curves (ReportFigure 6). Calculation of the time constant estimate for the air transient. An Excel plot comparing the experimental data points to the simulation for the air transient using the estimated time constant (ReportFigure 7).
3. Your data logger results for the two channel transient comparing the dynamics of the thermocouple probe to the simple thermocouple (ReportFigure 8). Also your simple time constant estimates for the two thermocouples.

In the Discussion of Results indicate how successful you were in meeting the objectives. How linear is the static calibration data? Based on your experience, is the first order dynamic model of Equation 1 adequate to describe the dynamic calibration data? From your two water-to-water step responses, does the time constant depend significantly on the size of the temperature step? Explain.

Specific Questions

1. Using your LinEst standard error results for the working calibration, what is your estimate of the expected accuracy of thermocouple measurements made with the laboratory thermocouple probe? Explain. Modify your Excel calibration plot of ReportFigure 2 by adding upper and lower error bound lines (adjusted by your accuracy) to show your expected range of error (ReportFigure 9). Explain.
2. For the calibration plot of the dial thermometer vs. the thermocouple probe using the DMM temperature display, what is the slope of the trend line? What is the y intercept? Which of these things is most influenced by the input of the constant reference temperature and why? Is the slope result as expected? Explain.
3. Discuss the results of the thermocouple transient comparison for the thermocouple probe and the simple thermocouple. Why is there such a substantial difference? Cite any references that you use.
4. Make a visit to the library or use the web to find an application of temperature measurement using an electrical transducer. This should describe the use of temperature sensing in an actual consumer or commercial product, not in a research study. Briefly discuss the application. Was a thermocouple chosen for the application? Why or why not? Was dynamic response a consideration in the application? What company provided the transducer components?

Further Background

In Figure 11, the simplest arrangement for a thermocouple temperature measurement is shown and described. The thermocouple shown is measuring temperature T_1 while the connection to the voltage measurement device is at temperature T_2 . Figure 12 shows another common configuration for thermocouple measurements using a known constant temperature reference (usually an ice bath) to control the temperature T_2 . This arrangement eliminates a junction of dissimilar metals at the voltage measurement device so that the generated voltage depends only on T_1 and the well controlled reference temperature T_2 .

Use of a reference junction at a known temperature is cumbersome, particularly when temperatures at remote sites are to be monitored. An alternative is to use a secondary sensor, usually a semiconductor, and a compensation circuitry to correct for variations in the reference junction temperature. See Figure 8.16 in the text (Figure 7.16 in the 1st Edition). In our experiments, the thermocouple junction is “local” (in the lab on the bench next to you) and the only temperature change experienced is that of the thermocouple itself. And so, for this simple situation, we are working without compensation circuitry or a controlled reference junction. We do this for simplicity. However, a reference junction or compensation circuitry is normally recommended.

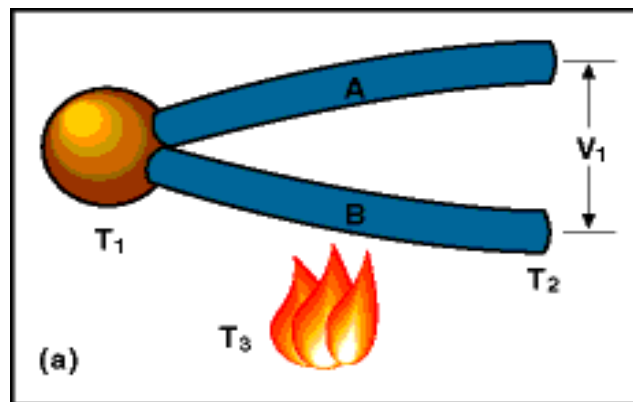


Figure 11. Typical thermocouple as it would be attached to a measurement system. The first thermocouple junction is at T_1 , the second junction, made at the measuring device, is at T_2 . The voltage V_1 produced depends on the temperature difference between T_1 and T_2 . It is not affected by the temperature of the wires between the two junctions (T_3).

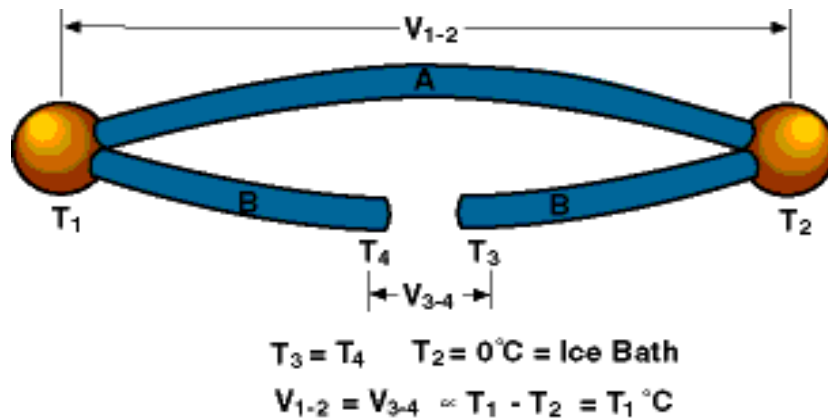


Figure 12. A thermocouple circuit employing a constant temperature cold junction. The second junction, at temperature T_2 , is held at a constant known temperature (typically an ice bath). The voltage produced depends on the temperature difference between the ice bath and T_1 . Note that the junction at the measurement device no longer contains dissimilar metals (wire type B is connected to both terminals) and therefore does not effect the voltage as in Figure 11. With one junction held at a known temperature, the voltage generated depends only on the temperature of the other junction.

In this experiment, we use a simple linear calibration of the thermocouple to yield a slope and an offset, i.e. $mx + b$. The offset is proportional to the temperature of the room and thus if the room temperature changes, the thermocouple system should be recalibrated to remain accurate (the slope, indicated by m , would not change but the intercept, b , would). The advantage of a reference junction is that changes in the room temperature would not change the reference junction temperature and recalibration would not be necessary.

The thermocouple, like most temperature sensors, does not respond instantaneously to changes in temperature. Since the thermocouple has a finite mass, heat must be transferred to the thermocouple in order to raise its temperature. The time required to heat the sensor is determined by the heat transfer process, which is governed by the mass of the sensor, its specific heat and thermal conductivity, and the properties of the surrounding fluid. For typical thermocouple applications, a first order dynamic model adequately describes the transient behavior. A relatively easy method to characterize the response of a first order system is to observe its response to a step change in input. The step response of first order systems is described in the section on “first order systems” in the text. The first order transient response of a temperature T is described by:

$$T(t) = T_\infty - (T_\infty - T_0)e^{-t/\tau} \quad (1)$$

where $T(t)$ is the temperature as a function of time (the data you will record), T_0 is the initial temperature, T_∞ is the final temperature, t is time and τ is the time constant of the system.

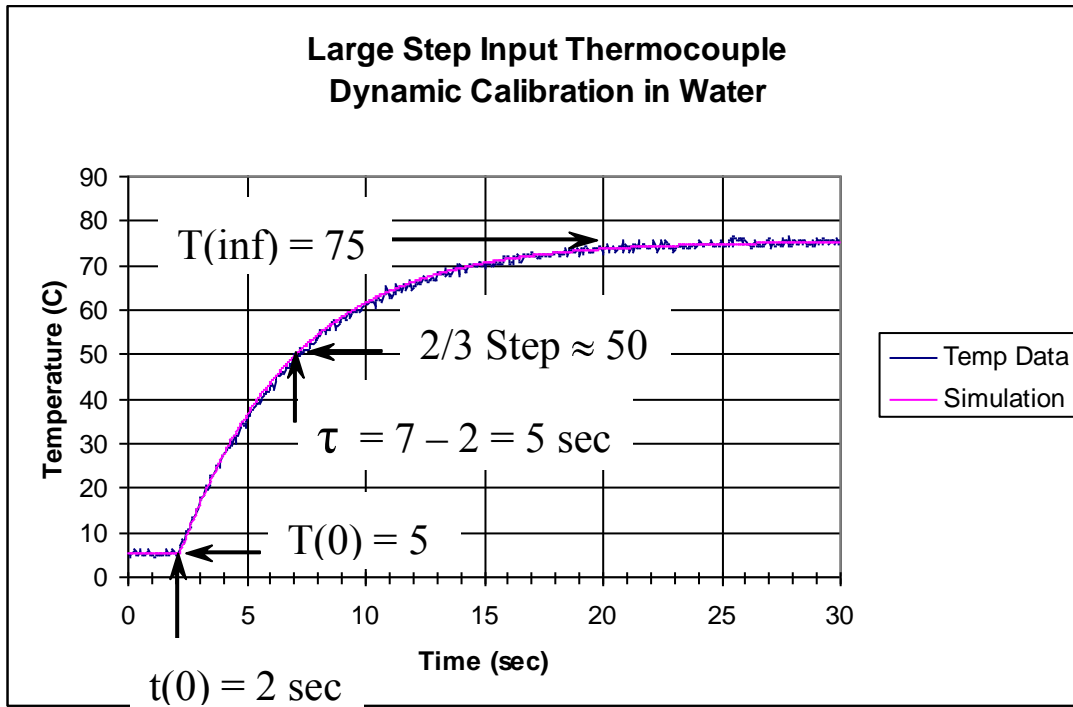


Figure 13. A typical dynamic response of a thermocouple subjected to a step input temperature change. In this graph, the initial temperature, T_0 , is approximately 5 C and the final temperature, T_∞ , is approximately 75 C. The simulation was calculated using these parameters and Equation (1). Time, t , in Equation (1) was offset to start the transient at 2 seconds (where the temperature change began).

Or, rearranging into error function form,

$$(T_\infty - T(t))/(T_\infty - T_0) = e^{-t/\tau} \quad (2)$$

The term on the left hand side is referred to as the error function and varies between one and zero.

In your transient temperature studies with a step input in temperature, the data you record will have a shape similar to Figure 13 (perhaps showing falling temperature instead of rising). The curve in Figure 13 is the result of using Equation (1) to generate the time response in Excel. In this case, the start of the simulated transient has been shifted to occur at $t = 2$ to agree with the start of the transient data. An alternative (probably more common) would be to adjust the transient data so that $t = 0$ corresponds to both the start of the simulation and the start of the data.