ENGN3220: Thermistor Temperature Measurements

I. Introduction

The first part of this lab investigates the linearization and calibration of a thermistor using a series parallel circuit with and without an operational amplifier to amplify the output voltage.

Thermistors are a resistive device with a negative temperature coefficient (NTC). NTC simply means the resistance decreases with increase in temperature. Thermistors have a large change in resistance for a small change in temperature. This would be fantastic to use as a temperature measuring device if the change was linear. However, this is not the case, the change is exponential in nature. An approximation of the thermistor can be found using the Steinhart-Hart Equation [1]

$$\frac{1}{T} = A + BlnR + C(lnR)^3 \qquad \text{(Equation 1)}$$

or the simplified version [2]

$$R = R_0 e^{\beta(\frac{1}{T} - \frac{1}{T_0})} \qquad \text{(Equation 2)}$$

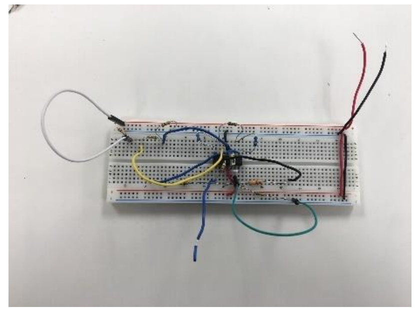
Where T is the measured temperature, T_0 is the temperature the thermistor was tested at in degree Kelvin; A, B, and C are constants; R is the resitance measured at the recorded temperature, R_0 is the resistance at T_0, and β is a constant.

As meantioned before the large change in resistance for change in temperature would be ideal for temperature measurements if it was linear. This would simplify the measurement system because an amplifier wouldn't need to be used and the system could simply be calibrated to read the voltage drop across the thermistor. In the case of it being linear the slope would have an equal change in voltage for an equal change in resistance. Where this is not the case, a measurement system using this device would need to rely on a lookup table to provide it with comparative data to determine the temperature at any given resistance/voltage value. This creates increased complication and increased hardware and computational requirements. Due to this it is more convenient and likely cost effective to linearize the reading using a simple linearization circuit shown in Figure 1.

The second part of this lab focused on the creation and use of an instrumentation amplifier to amplify the voltage generated by a thermocouple. The intent was to calibrate the thermocouple using the calibrated thermistor. Due to the difficulty with creating the instrumentation amplifier no measurements were successfully taken using the thermocouple.

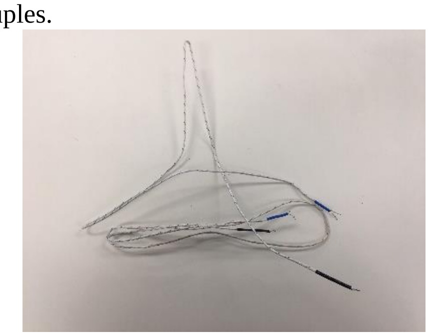
II. Equipment

For this lab we used breadboards to create our thermistor linearization circuit and amplification circuits using various resistors ranging from 10Ω – 330kΩ. The thermistor we used was a 10 kΩ 25 ℃ negative temperature coefficient thermistor.



We used a LM358AN op-amp to amplify the output from the thermistor linearization circuit and were to use the LM324AN op-amp to create the instrumentation amplifier to amplify the thermocouple's output. We used the labs power supply and Amprobe multimeter to power the circuit and take readings.

Once we thought we had the instrumentation amplifier working we attempted to test it using the provided thermocouples.



During the construction of the circuits we were at times unsure whether we were getting good connections, so we used the Weller soldering irons in the lab to create solid connections between components. We also used this in the fourth lab to solder our working instrumentation amplifier to the prototyping board.

On the first day of the lab we used ice water in an insulated container and boiled water in a kettle on a hot plate to calibrate the thermistor.

III. Procedure

The first part of this lab was focused on linearizing a thermistor. To accomplish this we used a thermistor with a specified resistance of 10 kΩ at 25 ℃ and tested its resistance value at several known temperatures by submerging it into the solution until we thought the resistance measurement normalized (it was noted that the resistance value never settled but would oscillate around some value). These temperatures included 0℃ ice water in a thermos, 22.1℃ which was the temperature reading in the lab, 30℃ approximate temperature of your fingertips at room temperature [3], and 100℃ boiling water using a kettle and a hot plate.

Once this data was collected, we built a thermistor linearization circuit, seen in Figure 1, using 56KΩ and 4.4KΩ for R1 and R2, connected it to a 5V power supply and measured the voltage at Vout using the same 4 temperatures as the initial resistance test. The leads of the thermistor were too small to stick into the breadboard, so we used small pieces of wire to help hold them in the sockets and ensure we had a connection.

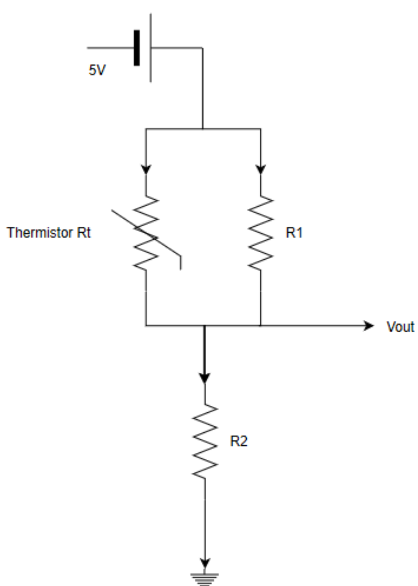


Figure 1: Thermistor linearization circuit set up on a bread board to measure the voltage for different temperatures and values of R1 and R2.

On the first day of the second part of this lab we were supposed to connect the output of the linearized thermistor circuit to the non-inverting input of the LM358 op-amp and utilize gain to increase the spread of our readings to increase the resolution of the measurement. Equation 3 was used in conjunction with the setup shown in Figure 2.

$$Gain = 1 + \frac{R_f}{R_g} \qquad \text{(Equation 3)}$$

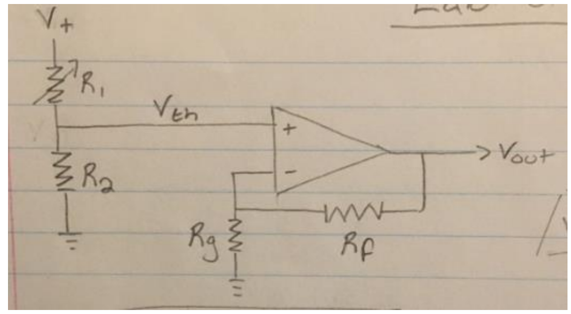


Figure 2:Operational Amplifier, non-inverting gain circuit

For our first attempt we decided to try a gain of ~3 for our circuit. We selected a 330kΩ and 170kΩ resistor as Rf and Rg. This did not give the voltage value we had expected so we spent the rest of the class troubleshooting the circuit. We tried several solutions which included:

- comparing the circuit to our drawings and the pin out for the device,
- changing the values of Rf and Rg to lower and higher valued resistors,
- soldering components together to ensure we had good connections,
- testing voltages where we felt we knew what the voltage should have read,
- changing to different op amps,
- installing RC filters on the supply to the non-inverting input and on the supply to the op-amp.

We even started over from scratch and rewired the circuit using solid core wire that was cut to specific lengths to keep the board tidy and make it easier to troubleshoot. We were unable to get the op amp circuit working with the thermistor circuit and did not have the appropriate technical knowledge to troubleshoot the circuit further, so we were unable to move on to the thermocouple circuit.

I was able to get into the lab early on the second day of the second part of the lab. I had some basic information on how to troubleshoot the op amps and was able to get the thermistor circuit working correctly by lowering the value of R2 to reduce Vout and changing the gain to ~1.5, by switching Rf and Rg. Refer to the schematic shown in Figure 3. This new setup gave us the output voltage we were expecting. We changed the thermistor out for a potentiometer and adjusted the op amps input voltage to 1 V. We then tested the output of the op-amp to give us a precise reading for the gain. We then moved on to the thermocouple circuit.

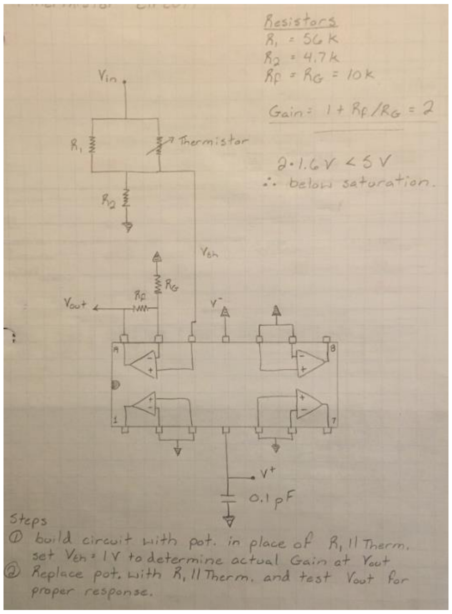


Figure 3: Thermistor linearization circuit with amplifier

For the thermocouple circuit we were to build an instrumentation amplifier with a gain of about 900. To accomplish this, we built and tested the first stage of the amplifier using the LM324 op-amp. The set up can be seen in Figure 4. We used a voltage divider with R7=R9=100 kΩ and R8 = 550 Ω. This provided us with a voltage difference of 3.6 mV to supply to the first stage non-inverting inputs. We created a gain of 40 by using R5=R6=10 kΩ and Rg = 500 Ω. This setup gave us an appropriate output of 122 mV measured between the outputs of the two op amps.

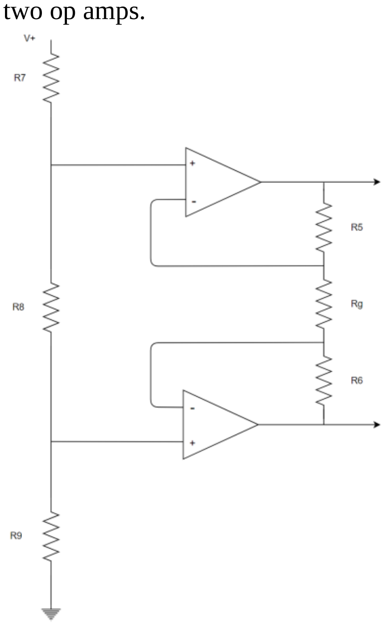


Figure 4: First stage of instrumentation amplifier

We then hooked the second stage of the op amp to the first stage.

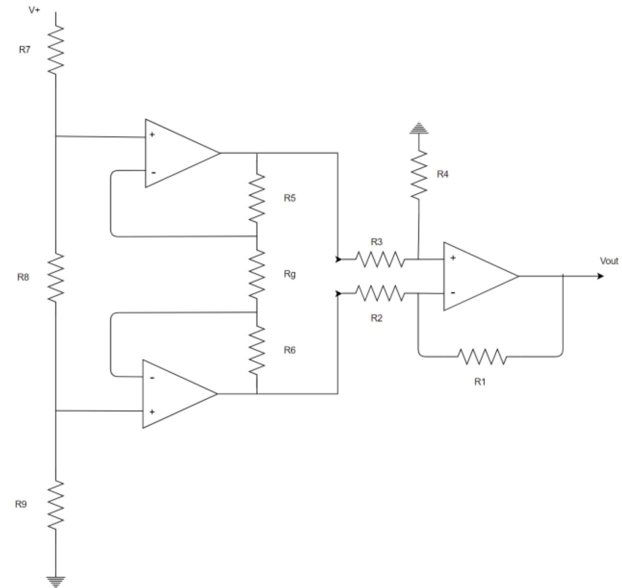


Figure 5: Instrumentation amplifier, stage one and two

This did not give us the output voltage we had calculated. We spent some time troubleshooting the circuit to make sure it was connected and correct and then tried hooking the second stage up directly to the voltage divider used to test the first stage. This was a recommended step to ensure the second stage was working correctly. Our expected gain from the second stage was ~25. We determined this by setting R5 = R6 and R4/R3 = R2/R1 by setting these values in this manner we should have been able to approximate Vout with the following formula [5].

$$V_{out} = \left(V_{R_{7-8}} - V_{R_{8-9}}\right)\left(1 + \frac{2R_5}{R_g}\right)\left(\frac{R_2}{R_1}\right) \qquad \text{(Equation 4)}$$

Where $\left(1 + \frac{2R_5}{R_g}\right)$ is the first stage gain and $\left(\frac{R_2}{R_1}\right)$ is the second stage gain. We were using R1 = R3 = 100 kΩ and R2 = R4 = 4 kΩ. We noticed that the voltage supplied from the voltage divider, shown in Figure 6, was pulled up from 3.7 mV to 6.6 mV when it was hooked up directly to the second stage amplifier. With this new value we were only seeing an output of 56 mV a gain of approximately 9 which was well below what we were expecting. Even though the result of the test was questionable we reconnected the first stage to the second stage and got what we deemed to be an acceptable output. This was after also discovering that we had the positive and negative connected in each other's position. Once we swapped them, we saw a gain of ~860, reading approximately 3.1 V output from the 3.6 mV input. We then connected the thermocouple. With the thermocouple connected we were getting a steady reading of approximately 500 mV which was well below what we were expecting. We then attempted to connect two thermocouples in series to form a thermopile to give us a larger output voltage. However, this also failed to work. We ran out of time and had to leave the lab.

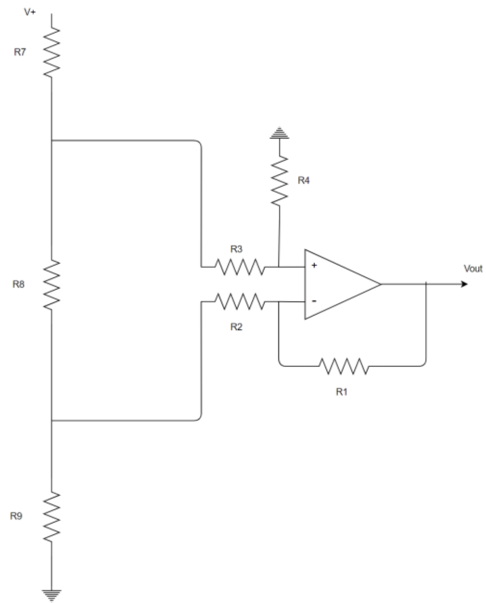


Figure 6: Second stage of instrumentation amplifier connected to voltage divider

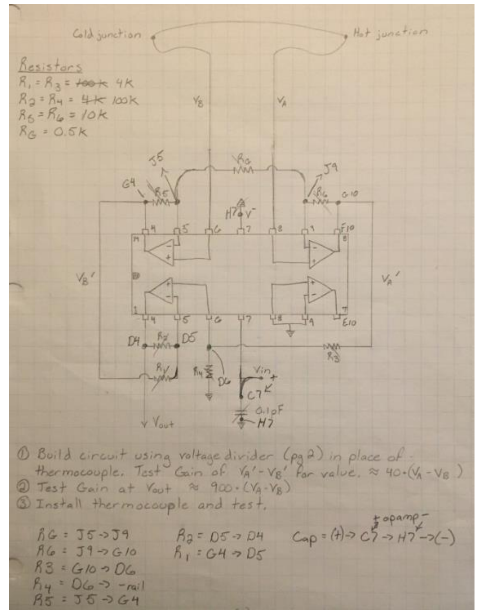


Figure 7: Thermocouple circuit with nodes labeled for prototyping board

Our third day went much better. We discovered that R1 was causing our grief due to an intermittent connection. When wiggling it back and forth and touching the thermocouple to the soldering iron we were showing an output voltage well above 3 V and potentially saturating around 3.6V. Due to the poor connection it was difficult to get a good reading. We also measured the ohmic value of each resistor in our circuit and attempted to match them as best we could with what was available to us. Once we had proven that our amplifier worked with the thermocouple, we soldered our circuit to a prototyping board.

Prior to soldering our circuit, we created a layout drawing, shown in Figure 7, labeling each common point that needed to be connected. We then placed the components based on our layout drawing and had each member double check it to ensure the connections were correct. We then soldered the components into place.

IV. Measurements

Table 1: Thermistor resistance for an assumed temperature

Calibration	Temperature (℃)	Resistance (Ω)
Ice Water	0	18750
Lab ambient temp.	22.1	11500
Specification	25	10000
Finger tips	30	7120
Armpit	37	6580
Boiling water	100	1080

Table 2: Voltage divider, Vout reading for assumed temperatures

Temperature (℃)	Voltage reading					
	Resistor (kΩ)		Resistor (kΩ)		Resistor (kΩ)	
	R1	R2	R1	R2	R1	R2
	15	1	39	3.3	56	4.7
0	0.586		0.838		0.378	
22.1	1.210		1.410		1.600	
32	1.400		1.540		1.900	
100	3.230		3.840		4.050	

V. Results

The physical measurements taken during this lab were limited to the thermistor measurements taken during the first day in the lab and a few notes that we took to record the resistor values, Vin, Vout, and gain when testing the instrumentation amplifier. Figure 8 shows the plot of the Thermistor resistance values measured at the different temperatures listed in Table 1.

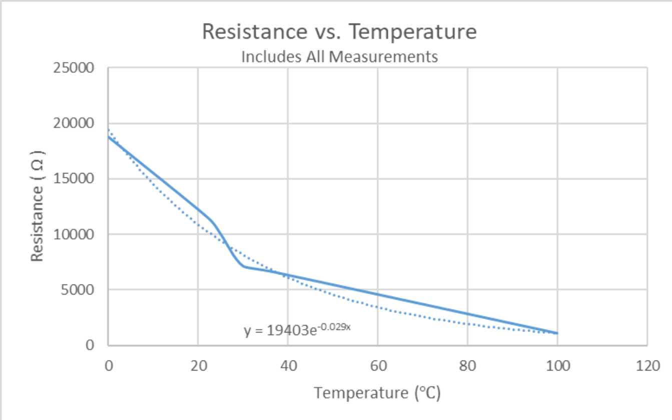


Figure 8: Resistance vs. temperature curve plotted from Table 1

We were not confident in the measurement taken at 0℃, so we removed it from the plot to see how it would affect the best fit line. Figure 9 shows the plot with the resistance value for 0℃ removed.

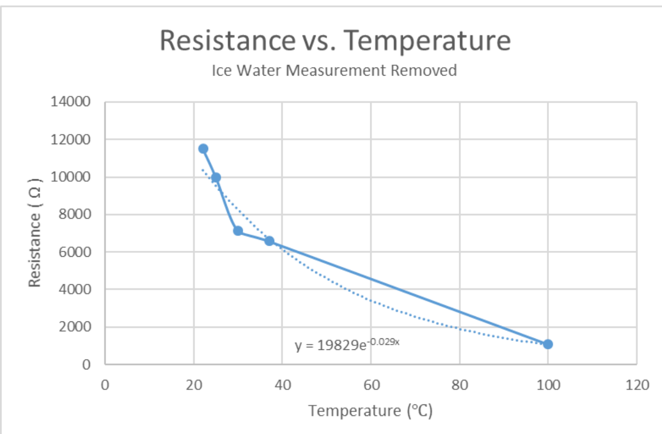


Figure 9:Resistance vs. temperature curve plotted from Table 1 with 0℃ measurement removed

The resistance value expected at 0℃ for this type of thermistor is approximately 31 KΩ [4]. Due to this discrepancy I decided to find a best fit curve based on the measurements I had the most confidence in. These were the specification, armpit, and boiling water values from Table 1. Using these numbers with Equation's 5-7 I was able to use the system of linear equation method to solve for A, B, and C in Equation 8.

$$Ax = B \text{ then } x = A^{-1}B \quad \text{(Equation 5)}$$

$$x = \begin{bmatrix} A \\ B \\ C \end{bmatrix} \quad \text{(Equation 6)}$$

$$B = \begin{bmatrix} \frac{1}{T_1} \\ \frac{1}{T_2} \\ \frac{1}{T_3} \end{bmatrix} \quad \text{(Equation 7)}$$

$$\frac{1}{T} = A + B(lnR) + C(lnR)^3 \quad \text{(Equation 8)}$$

Once these values were found I was able to plot the best fit curve, shown in Figure 10, for the thermistor based on the measured data. This method produced a resistor value of approximately 29 KΩ at 0°C. This result would seem to be far more accurate than the original measurements and corresponding best fit curve.

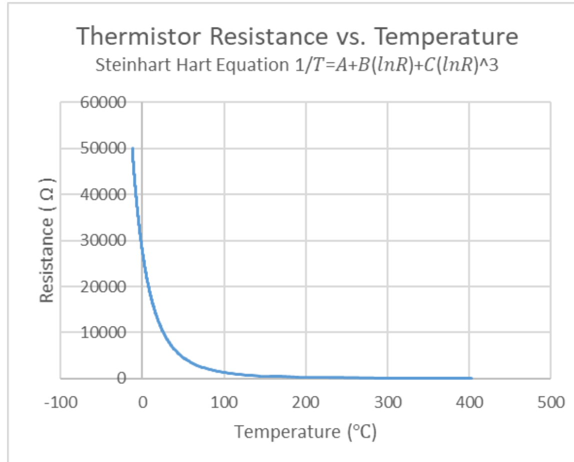


Figure 10: Best fit line for the thermistor used in this lab, based on the Steinhart Hart equation

Figure 11 shows the graph of the measured voltage values shown in Table 2. It can be seen from the graph that the voltage readings appear linear which was the expected result from the linearization circuit.

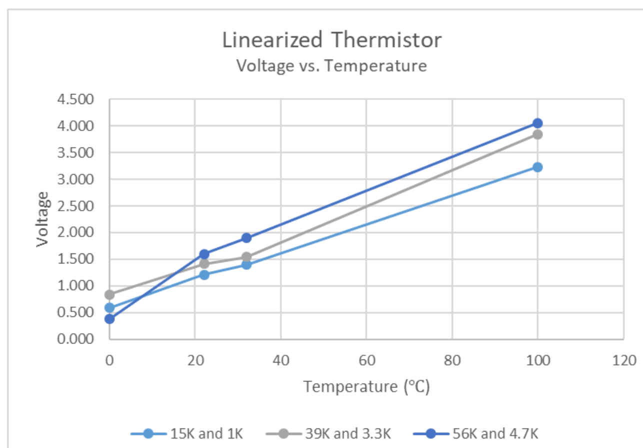


Figure 11: Output voltage from the linearized thermistor circuit for different temperatures

Using Equation 11 which was the best fit curve from Figure 9 and Equation 9 for V_{out}, I plotted the graph for each of the resistance configurations that we used. This can be seen in Figure 12.

$$V_{out} = V_{in}\left(\frac{R_2}{\left(\frac{1}{R_t}+\frac{1}{R_1}\right)^{-1}+R_2}\right) \quad \text{(Equation 9)}$$

$$R_t = R_0 e^{\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)} \quad \text{(Equation 10)}$$

$R_t = 19829e^{-0.029x}$ (Equation 11)

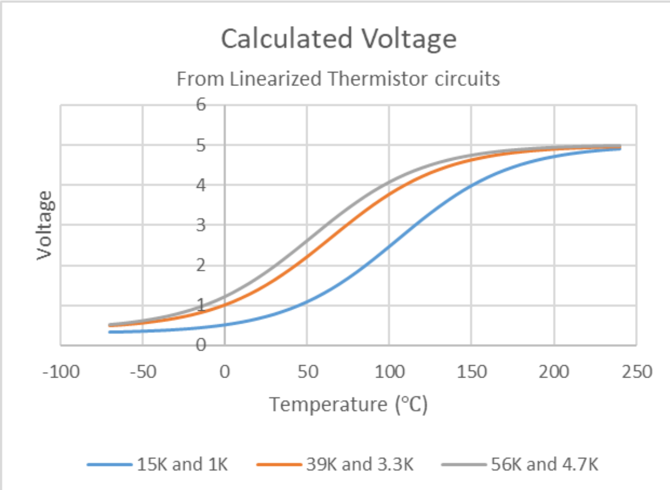


Figure 12: Voltage curves calculated using Equation 9

Table 3 shows the values of resistance, Vin, Vout, and gain that were recorded while testing the instrumentation amplifier circuit.

Table 3: Measured resistance and gain values for the instrumentation amplifier

Resistors	kΩ	Supply voltage (V)	5	7	9
R1	3.81	First stage input (V)	0.0037	0.0052	0.0066
R2	99.4	Stage 1 out (V)	0.1221		
R3	3.81	Stage 2 out	3.21	4.64	5.99
R4	99.4	Actual stage 1 gain	33		
R5	10.01	Theoretical stage 1 gain	37.4		
R6	10.01	Actual stage 2 gain	26.29		
Rg	0.551	Theoretical stage 2 gain	26.09		
		Actual combined gain	867.5676	892	908
		Theoretical combined gain	975.766		

VI. Discussion

We compared our results, for the resistance value for 0°C, during the lecture, after the first part of the lab. Our measurement was nearly 10 kΩ less than the results of the other groups. The rest of our results were comparable to those of the other groups.

If any of the results were to be incorrect, I would have suspected it to be the resistance value for the 0°C measurement. The opening in the top of the bottle was large enough to work with but became blocked by the hand when trying to stick the thermistor inside. The measurement relied on their being enough ice mixed with the water to bring the temperature to 0°C. Either of these could have led to human error. There was potential to lose site of the position of the thermistor leading the person testing to assume they were submerging it when there was the possibility they weren't. There could have been too much water added to the mixture causing the temperature to be above 0°C. There had also been mention, during the lab, that there was potential for the temperature of the ice to be much lower than 0°C depending on how long it was in the freezer. If the thermistor was touching the subzero ice there may have been a chance that the reading could have been biased due to the temperature of the ice. Our reading was low in comparison to the others, based on the graph depicted in Figure 10 I would estimate the temperature we measured to be closer to 10°C.

From Figure 11 it is clear the voltage reading at 0°C, for the 56kΩ and 4.7kΩ resistor circuit, is not in line with the rest of the measurements. This measurement error is again likely due to issues with the measurement setup and the difficulties of ensuring the ice water was at the correct temperature. When comparing the measured voltage values to the calculated values graphed in Figure 12 the calculated curve for the 15kΩ and 1kΩ resistor circuit is quite low in comparison to the measured values. This is likely due to the inaccuracy of the excel generated Equation 11 for the best fit curve for the measured data. It is however interesting to note how seemingly accurate it is for the 39kΩ and 3.3kΩ resistor circuit and the 56kΩ and 4.7kΩ resistor circuit.

We had other concerns with our measurements as well. We were sharing the equipment with two other groups. This meant we were also required to share the calibration apparatus (ice water, boiling water) to try to keep from taking too long while others were waiting. This caused the measurements to be somewhat rushed which most likely led to some offset in the measurements. Due to the rush the measurements might not have been left long enough for the thermistor to reach its steady state reading. It was noticed that the thermistor would oscillate for quite a while due to the demand for the equipment there wasn't one measurement we took where we waited for it to stop completely.

If we were to do this experiment again, we would ensure we got a spot with our own equipment. We would use a thermometer to check our calibration apparatus for the expected temperature to increase the precision of our measurement data. We would take our time and complete the measurements more than once to check for errors. It was also noted during the class that stirring the fluid would keep the temperature more uniform throughout the mixture. Still fluid in a poorly insulated container can have a temperature gradient created by the heat transfer at the container walls which can throw off the measurements.

In saying all of this. After completing some work with the formulas, it became quite interesting to see how adjusting the resistance values in our circuit would alter our output. I decided to see how the circuit would be affected if I held R1 constant at 60 kΩ and changed the value of R2 only. Figure 13 shows clearly that as R2 is increased the linearized portion of the graph becomes less steep and moves to the left and therefore becomes more useful for lower temperatures. As it is increased the linear portion moves to the right and becomes steeper. This indicates it will become useful for higher temperatures but over a shorter range due to the increase in slope.

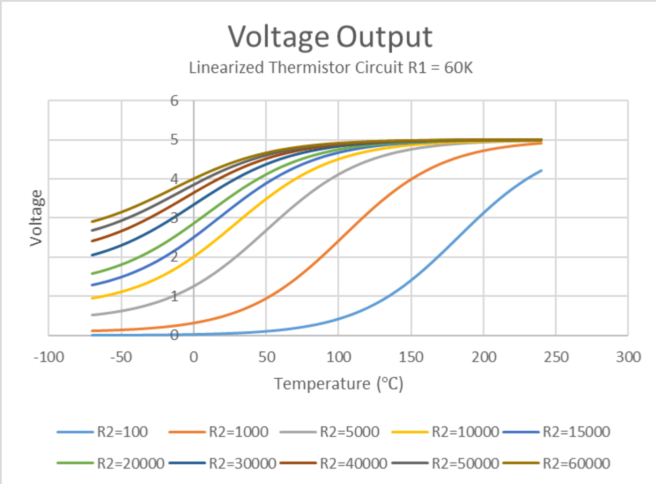


Figure 13: Voltage curves calculated using for a fixed value of R1 using Equation 9

Not nearly as interesting an outcome but just as worthy to investigate was holding the value of R2 fixed at 60 kΩ and allowing R1 to vary. It can bee seen in Figure 14 that as the value for R1 is increased it pulls the left side of the graph down. The slope is not steep so this may prove useful for lower temperatures if the slope is found to be approximately linear over some range.

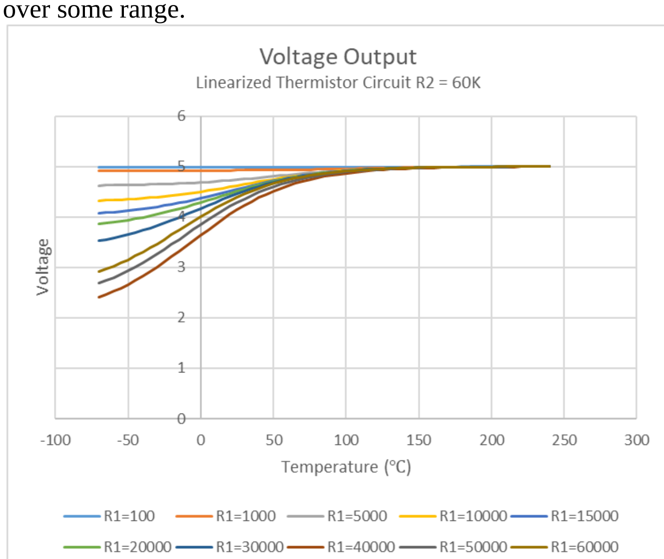


Figure 14: Voltage curves calculated using for a fixed value of R2 using Equation 9

The rest of this lab turned into a test of patience and persistence. We were fortunate enough to get the instrumentation amplifier working on the bread board and to find the loose connection.

We also found the interesting result of the increase in gain with increase in voltage supply across the op amp, seen in Table 3. After some discussion in class and some discussion with my group we determined that we were unaware of how the op amps in the first stage of the amplifier were sharing the voltage. Due to this there was a good possibility that at the lower voltage supply of one or even both op amps may have had a saturated output which could have pulled down the overall gain. After a discussion with the professor during the second day in the lab we were also made aware that the common mode voltage could also play havoc with the gain. However, when looking at the increase in gain with increase in supply voltage it appears more likely that the first stage may have been saturated at the lower voltage. The common mode voltage may have been a component of the remaining gain offset that we were noticing.

VII. Conclusions

As expected, we found that the change in resistance with temperature of the thermistor was quite large but non-linear. We were able to successfully linearize its output over a small range of temperatures. Through the calculations we were able to show that we could manipulate the linearized portion of the curve to situate over a temperature range that might be of interest.

It was interesting to see that these tests can be carried out using readily available methods for calibration such as the ice water and the boiling water.

While constructing the instrumentation amplifier it was found that things do not work out on the bench as easily as they work on paper. We ran into many difficulties with wiring the circuit and sizing the resistors incorrectly. This caused us a lot of grief while trying to get the amplifier working correctly. The main take away from this experience was to ensure your planning is correct and your schematics are easy to follow. The bread boards are small and become cluttered quickly if the wiring is not carefully constructed. This leads to the circuit being difficult to troubleshoot.

The gain achievable using the instrumentation amplifiers is incredible. However, it is susceptible to the common mode reduction ratio (CMRR) in which the common mode voltages that are not suppressed can cause the output gain to be less than expected.

References

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