Marking Sheet for MecE 301 Reports

Student Name: Alex Diep

Marking Category	Inadequate (0-2 points)	Adequate (3-4 points)	Superior Work (5 points)	Grade (0-5)	Weight Factor	Total (%)
Title Page	Missing information.	All required information is given.	All required information is given. Appropriate title.		x1	
Introduction	Poorly defined problem or lacking motivation.	Explains the problem and why the work was done.	"Adequate" + motivates interest.		x1	
Procedure	Lists equipment used.	Describes procedure used so that reader could repeat experiments.	"Adequate" + organized in a logical fashion.		x2	
Discussion	Results were simply stated or information was missing.	Results were stated and interpreted.	Discussion shows in-depth interpretation of the results.		x3	
Conclusions/ Recommendations	Summarizes results.	Discusses objectives and how they were met.	Conclusions and recommendations provide insightful solutions.		x2	
Appendices	Missing data and calculations are not explained.	Data is given, calculations are explained.	Data and calculations are put into context.		x2	
Engineering Analysis	Major errors in calculations and analysis.	Minor errors in calculations and analysis.	No errors in calculations and analysis.		x4	
Data Presentation (Figures/Tables /Symbols)	Several errors in data presentation.	A few minor errors in data presentation.	Figures, tables, and symbols are presented to course standard.		x3	
Grammar, spelling, layout.	Several errors.	A few minor errors.	No grammar/spelling errors. Logical layout.		x2	
					Total:	

MEC E 301
Lab 6: Temperature Measurement Devices

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Section: D21

Contents

1 Introduction

The objective of this lab was to investigate the accuracy, resolution, and time constant of a thermistor and thermocouple. The thermistor and thermocouple was calibrated using water baths at different temperatures. Next, the step response of the thermistor and thermocouple were investigated by placing them in a heater and then removing them to room temperature air and water.

2 Procedure

2.1 Equipment

The following equipment was used to perform the experiment: Arduino Uno, MEC E 301 Shield, laptop, USB cable, breadboard, jumper wires, 5110 Ω resistor, ANOVA sous vide precision cooker, large container for water bath, heater, petri dish, 4-wire platinum RTD, Type K thermocouple, Adafruit-AD8495 K-type thermocouple amplifier, and Honeywell TD5A thermistor.

2.2 Setup

The circuit shown in Figures A.1 and A.2 were built on a breadboard. The example code *ReadAnalog-Voltage* was modified to read the voltage from the thermistor and thermocouple. The equation for the thermocouple, found on the underside of the Adafruit AD8495, was used to convert the voltage to temperature.

Three water baths were prepared. The first water bath was filled with room temperature water. The second and third water baths were filled with water with the ANOVA sous vide precision cooker set to 40 °C and 60 °C, respectively. Time was given for the water baths to reach their steady-state temperature, about half an hour.

2.3 Calibration

The calibration of the both the thermistor and thermocouple were performed by placing the devices in the water baths and allowing them to reach equilibrium. Fifty temperature and voltage measurements were recorded at equilibrium for each water bath.

2.4 Transient Response

The thermistor and thermocouple were placed in the heater until they reached equilibrium, about five minutes. The devices were then removed from the heater and allowed to cool to room temperature in air. The temperature, voltage, and timestamps were recorded every second.

Again, the thermistor and thermocouple were placed in the heater until they reached equilibrium. Water was poured into a petri dish. The devices were then removed from the heater and submerged in the water in the petri dish. The temperature, voltage, and timestamps were recorded every ten milliseconds.

3 Results and Discussion

3.1 Calibration

Table 1: Accuracy, repeatability, and resolution of the thermistor and thermocouple.

	Thermistor	Thermocouple	Thermocouple with Linear Fit
Accuracy	2.2 °C	1.8 °C	0.8 °C
Repeatability	3.3 °C	1.3 °C	1.4 °C
Resolution	1.1 °C	0.6 °C	0.6 °C

The thermistor was the worst performing device in terms of accuracy and repeatability. There are several ways to improve the resolution of the thermistor. The equation for resolution is given by

$$\text{Resolution} = \frac{\Delta \mathrm{V_{fs}}}{2^{\mathrm{n}} \times \text{Sensitivity}} \tag{1}$$

where $\Delta \mathrm{V_{fs}}$ is the full-scale voltage and n is the number of bits.

From (1), there are three recommendations to increase the resolution of the thermistor. The first is to utilize an A/D with a more bits. The second is to increase the sensitivity of the device by using a different material such as platinum. The third is to decrease the full-scale voltage by using an amplifier. The effects of saturation may need to be taken into consideration with the usage of an amplifier.

The thermocouple voltage data was processed in two ways. First the Adafruit conversion equation was used to convert the voltage to temperature. Second, a linear fit was performed on the calibration data to convert the voltage to temperature. The accuracy, repeatability, and resolution of the thermocouple with the Adafruit conversion equation and the linear fit are shown in Table 1.

The thermocouple with the linear fit has a higher accuracy and repeatability than with the Adafruit conversion equation. This is because the linear fit is based on the calibration data, which is more accurate than the Adafruit conversion equation. Variation in manufacturing of the thermocouple and the Adafruit AD8495 amplifier could contribute to the lower accuracy of the conversion equation.

3.2 Transient Response

The time constant is a function of the rate of heat transfer to/from the sensor. The higher rate of heat transfer, the lower the time constant. Since water has a higher convection coefficient than air, the time constants are expected to be lower in water than in air. This agrees with the experimen-

Table 2: Time constants of the thermistor and thermocouple in air and water.

	Air		Water	
	Thermistor	Thermocouple	Thermistor	Thermocouple
τ	18.698 s	18.027 s	0.374 s	0.225 s

tally determined time constant values where for both the thermistor and thermocouple, the time constants in water are lower than in air by about two orders of magnitude.

Thermistors are made of ceramic-like materials whereas thermocouples are made of metal. Metals have free electrons resulting in higher thermal conductivity than ceramics. Since the time constant decreases with increasing heat transfer, the thermocouple is expected to have a lower time constant than the thermistor. This agrees with the experimentally determined time constant values where the thermocouple has a lower time constant than the thermistor for both air and water.

The first order fit was a good approximation of the experimental data. The first order χ^2 fit was appropriate for the step response to the system. Figures A.5, A.6, A.7, and A.8 show the experimental data and the first order fit.

4 Conclusion

From the calibration, the thermocouple with the linear fit had the best accuracy, repeatability, and resolution. The thermistor had the worst accuracy, repeatability, and resolution. The thermocouple also had a lower time constant than the thermistor in both air and water. The thermocouple with the linear fit performed better than with the Adafruit conversion equation. This was because the linear fit was tailored to the calibration data. Further work on the worse performance of the thermistor could be investigated in future labs.

The results were obtained in the small temperature range of 21.2°C to 54.1°C. The accuracy, repeatability, and resolution may change outside of this range. This report recommends using the thermocouple with the linear fit for temperature measurements.

This lab introduced the concept of temperature sensors, calibration, and step response. The thermistor and thermocouple were calibrated and their step response was measured. Further work into RTD and different thermistor materials could be done to understand the differences between temperature sensors.

A Figures

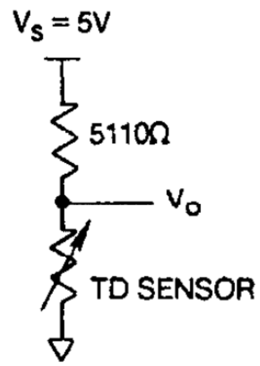

Figure A.1: Schematic of the circuit for the Honeywell TD5A temperature sensor

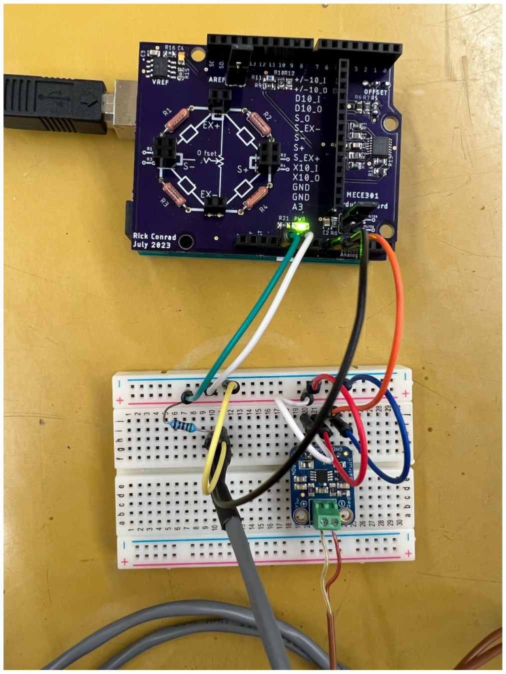

Figure A.2: Built circuit for the Honeywell TD5A temperature sensor

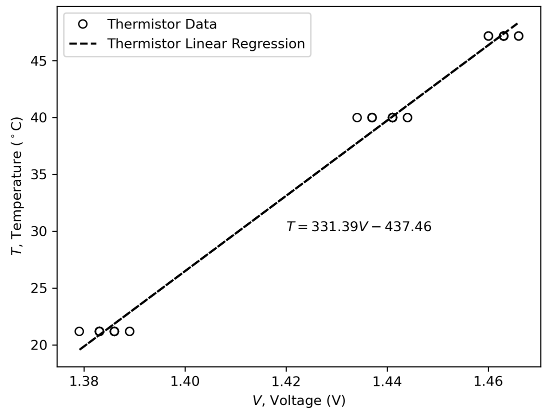

Figure A.3: Linear fit for the thermistor

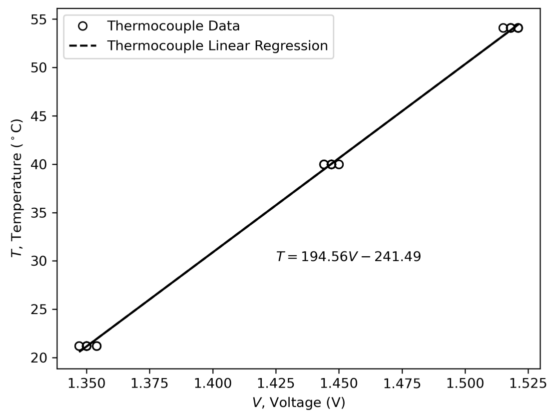

Figure A.4: Linear fit for the thermocouple

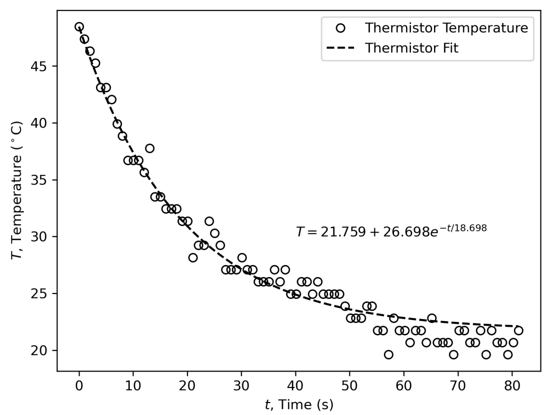

Figure A.5: Transient response of the thermistor in air

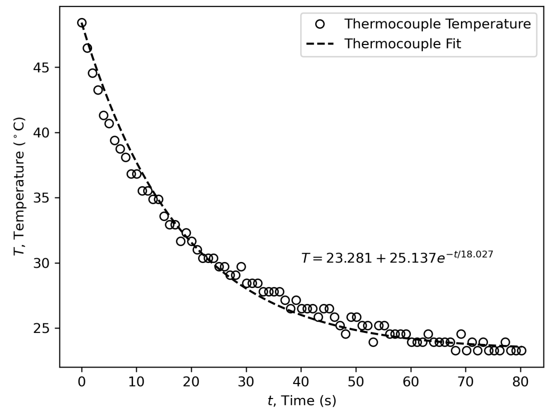

Figure A.6: Transient response of the thermocouple in air

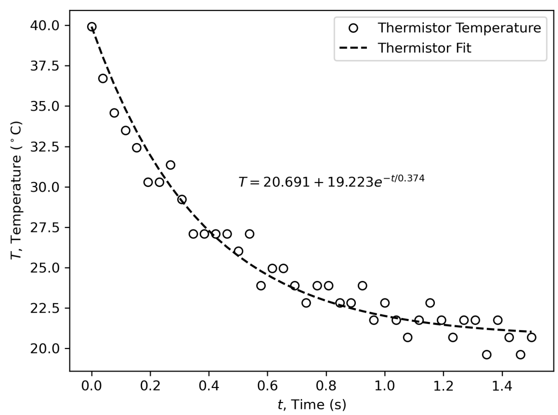

Figure A.7: Transient response of the thermistor in water

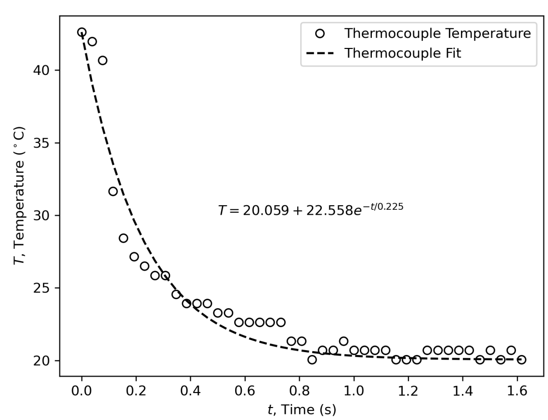

Figure A.8: Transient response of the thermocouple in water

B Tables

Table B.3: Deviation table for the thermistor

Reference Temperature (°C)	Measured Temperature (°C)	(°C)	(°C)	(°C)	(°C)	(°C)		Max Deviation (°C)
21.2	0.6	0.6	0.6	0.6	0.6	0.6	...	3.3
40.0	-1.3	-1.3	-2.2	0.1	0.1	0.1	...	3.3
46.9	0.5	0.5	0.5	-0.5	0.5	0.5	...	2.0

Table B.4: Head of deviation table for the thermocouple using Adafruit conversion equation

Reference Temperature (°C)	Measured Temperature (°C)	(°C)	(°C)	(°C)	(°C)	(°C)		Max Deviation (°C)
21.2	-1.1	-1.1	-1.1	-1.1	-1.1	-1.1	...	1.3
40.0	-0.6	-0.6	-0.6	-0.6	-0.6	-1.3	...	1.3
53.5	0.7	0.7	0.1	0.7	0.7	0.1	...	1.3

Table B.5: Head of deviation table for the thermocouple using linear fit

Reference Temperature (°C)	Measured Temperature (°C)	(°C)	(°C)	(°C)	(°C)	(°C)		Max Deviation (°C)
21.2	0.0	0.0	0.0	0.0	0.0	0.0	...	1.4
40.0	0.0	0.0	0.0	0.0	0.0	-0.6	...	1.2
53.5	0.3	0.3	-0.3	0.3	0.3	-0.3	...	1.2

Table B.6: Transient response of the thermistor in air

Time (s)	Thermistor (°C)	Thermistor Model (°C)	$(\Delta T_{\text{thermistor}})^2$ (^{c}ircC^2)
0.000	48.457	48.457	0.000
1.003	47.389	47.063	0.106
2.005	46.321	45.742	0.335
3.008	45.253	44.490	0.582
4.010	43.117	43.303	0.035
5.013	43.117	42.179	0.881
6.015	42.049	41.113	0.877

Table B.7: Transient response of the thermocouple in air

Time (s)	Thermocouple (°C)	Thermocouple Model (°C)	$(\Delta T_{\text{thermocouple}})^2$ (°C^2)
0.000	48.418	48.418	0.000
1.003	46.484	47.058	0.330
2.005	44.551	45.772	1.490
3.008	43.262	44.555	1.672
4.010	41.328	43.404	4.311
5.013	40.684	42.316	2.662
6.015	39.395	41.286	3.576

Table B.8: Transient response of the thermistor in water

Time (s)	Thermistor (°C)	Thermistor Model (°C)	$(\Delta T_{thermistor})^2$ (°C^2)
0.000	39.914	39.914	0.000
0.038	36.710	38.032	1.749
0.077	34.574	36.335	3.101
0.115	33.506	34.804	1.684
0.154	32.438	33.422	0.969
0.192	30.302	32.176	3.512

Table B.9: Transient response of the thermocouple in water

Time (s)	Thermocouple (°C)	Thermocouple Model (°C)	$(\Delta T_{thermocouple})^2$ (°C^2)
0.000	42.617	42.617	0.000
0.038	41.973	39.071	8.419
0.077	40.684	36.083	21.168
0.115	31.660	33.565	3.627
0.154	28.437	31.442	9.029
0.192	27.148	29.653	6.274

Table B.10: Steady state temperature and time constant for the thermistor and thermocouple in air and water

	Air		Water	
	Thermistor	Thermocouple	Thermistor	Thermocouple
T_0	48.457 °C	48.418 °C	39.914 °C	42.617 °C
T_∞	21.759 °C	23.281 °C	20.691 °C	20.059 °C
τ	18.698 s	18.027 s	0.374 s	0.225 s
SS	122.338 °C	46.266 °C	35.745 °C	69.888 °C

C Appendix: Thermistor and Thermocouple Calibration

For the thermistor, a linear fit was obtained using Excel's `LINEST` function. The fit is shown in Figure A.3 The fit equation is

$$T = 331.39V - 437.46 \tag{2}$$

A deviation table was generated using the fit equation to map the thermistor voltage to temperature. The head of the table is shown in Table B.3. The full table is available in the Excel file submitted with this report.

Deviation was determined by

$$\Delta T = T_{meas} - T_{ref}$$

For the thermistor first measurement at 21.2°C, the deviation was

$$\Delta T = 21.8 - 21.2 = 0.6\,^{\circ}C$$

The accuracy of the thermistor was determined by taking the maximum absolute deviation from the reference temperature across all measurements. The accuracy was determined to be

$$\text{Accuracy} = \max(|\{\Delta T_{i,j}, \forall i, j\}|) = 2.2\,^{\circ}C$$

where $\Delta T_{i,j}$ is the deviation of the jth measurement at the ith reference temperature.

Repeatability was determined by taking the maximum absolute deviation at each reference temperature. The repeatability was determined to be

$$\text{Repeatibility} = \max(|\{\Delta T_j, \forall j\}|) = 1.0\,^{\circ}C$$

where ΔT_j is the maximum deviation of the ith reference temperature.

Lastly resolution was determined by

$$\begin{aligned}\text{Resolution} &= \frac{\Delta V_{fs}}{2^n \times \text{Sensitivity}} \\ &= \frac{3.3}{2^{10}} \times 331.39 \\ &= 1.1\,^{\circ}C\end{aligned}$$

The accuracy, repeatability, and resolution of the thermocouple were determined in the same manner as the thermistor. The deviation table is shown in Table B.4 for the Adafruit conversion equation and Table B.5 for the linear fit. The fit equation was determined to be

$$T = 194.56V - 241.49 \tag{3}$$

D Appendix: Thermistor and Thermocouple Transient Response

The first order response of the system is

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

A modelled response was generated using t, T_0, and T_∞ as inputs. A guess of $\tau = 1$ was used.

From Table B.6, the thermistor in air at t = 1 s, $T_\infty = 21.759\,°C$, and $T_0 = 48.457\,°C$ had a modelled temperature response of

$$T = 21.759 + (48.457 - 21.759)e^{-1/1} = 31.555\,°C$$

The ΔT^2 was calculated by

$$\Delta T^2 = (T_{meas} - T_{model})^2$$

Continuing with the example above, the ΔT^2 was

$$\Delta T^2 = (47.389 - 31.555)^2 = 250.701\,°C^2$$

The sum of ΔT^2, or the sum of squared error, was calculated by summing all the ΔT^2 values. For the thermistor in air, with the parameters above, the sum of squared error was 5881.626 $°C^2$.

Excel's `Solver` was used to minimize the sum of squared error by varying τ to find the best fit. The best fit was found to be $\tau = 18.698$ s with a sum of squared error of 122.338 $°C^2$. The same procedure was used for the thermocouple in air, thermometer in water, and thermocouple in water.