Comparison of Temperature Measurements using thermometers, thermocouples, thermistors, and RTDs

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A thermometer, RTD, thermistor, and multiple thermocouple configurations are used to find temperature measurements in different situations. By using an RTD to measure different temperatures, we find the temperature constant for the device to be α = 0.0037 K^{-1}. We follow a similar process to get the temperature coefficient of a thermistor, which is β = 3.8193. We also measure a hot junction using a single thermocouple, a cold-junction compensated measurement with a thermocouple and connect multiple thermocouples in series to achieve a thermopile configuration. The thermocouples give you a voltage generation, which are used to find the temperature with the use of a conversion table and several thermocouple principles. The last part of the lab focuses on the time dependence of the thermocouple and we use a software called LabView to log the temperature change with respect to time using a thick and thin thermocouple. We prove a relation involving the radius of the thermocouple, the density and heat capacity of the sensor material, and the heat transfer coefficient of the medium that the thermocouple is inserted into, namely water and air. We end up with the heat transfer coefficients of the water and air and we see sporadic behavior, which may be due to the movement of the thermocouples and the respective mediums.

INTRODUCTION

There are many instruments that have been designed to make more accurate temperature methods, from a simple mercury thermometer to a thermistor, resistance temperature sensor, and thermocouple. In this lab, all of these methods are used and we compare the time dependence of the measurements and the similarity between different devices.

In Figure 1, a mercury glass thermometer like the one used in the lab is shown. The change in density of the mercury in the thermometer is linearly proportional to the temperature ay the metal tip, which changes the height of the mercury in the straight portion of the device and is calibrated so you can read the temperature based on this change in density. It is used to get the room temperature in the lab environment.

Figure 1-2. Mercury Thermometer (left) and Resistance Temperature Sensor (right)

A resistance temperature sensor (RTD) (as shown in Figure 2) works by using the fact that the electrical resistance across materials is temperature dependent. The metal platinum has a high temperature coefficient of electrical resistance so it is used most commonly in RTDs. The platinum wire is wound a ceramic cylinder and placed in a steel protective tube and increases linearly in resistance with an increase in temperature. The change in resistance can be measured using a calibrated Ohmmeter or a Wheatstone bridge to measure the voltage change and use Ohm's law to get the resistance change. Equation 1 relates the initial and final resistance in the wire to change in temperature that the device experiences.

$$R = R_0[1+\alpha(T-T_0)] \qquad [1]$$

A thermistor works similarly to an RTD, but instead of having a metal element as the main part, it uses a semiconductor, which decreases in resistance with an increase in temperature in a nonlinear way. It has a higher sensitivity than RTD's and we can measure this resistance using bridge circuitry and variants of a Wheatstone bridge. Equation 2 gives the relation for a thermistors change in resistance to a change in temperature.

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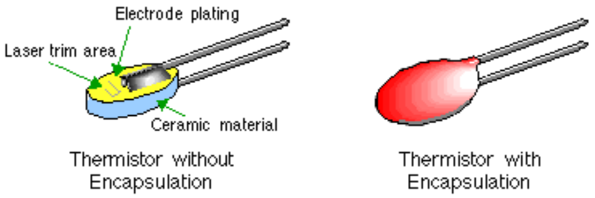

Figure 3. Thermistor Composition

$$R = R_0 \exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \qquad [2]$$

The last device analyzed is a thermocouple, which consists of two dissimilar metals connected at a junction, which produces a potential difference across the wires. The magnitude of the potential difference depends on the temperature that it is in, which is called the Seebeck Effect. The potential difference is also a function of the current that goes across it (Peltier Effect) and the temperature gradient along the wires (Thompson Effect). Thus, in a thermocouple, the current is kept at 0 and the temperature gradient is minimized to eliminate these changes effects on the voltage. The corresponding voltage difference for certain metals in experimentally recorded and provided to check corresponding temperatures with respect to 0°C. To find temperature differences that are not respect to 0°C, the following relationship in Equation 3 is used.

$$emf_{1\text{-}3} = emf_{1\text{-}2} + emf_{2\text{-}3} \qquad [3]$$

In this lab, we use a K type thermocouple (as shown in Figure 4), which provides the widest temperature operating range and resistance to corrosion. It consists of Chromel and Constantan wires.

Like most measurement devices, these devices do not have instantaneous responses to changes in temperature. The time dependent relationship for the thermocouple used is shown in Equation 3, which we have used to predict the value of h, the heat transfer coefficient for the fluid we measured, water.

$$\frac{T - T_\infty}{T_1 - T_\infty} = \exp\left(-\frac{3h}{\rho c_v R}t\right) = \exp\left(-\frac{t}{\tau}\right) \qquad [4]$$

Figure 4. Industrial K-Type Thermocouple.

Along with these devices a PC controlled data acquisition system is used with LabView software to capture the analog signal of the voltages for the thermocouples in the time dependent part of the experiment.

In the experiment, we start by getting the room temperature using thermometer and then measure the temperature of an ice bath using a thermocouple, RTD, and thermistor sequentially. We then measure the voltage using a thermocouple connected to a hot and cold junction and next place the cold junction in the ice bath and measure that voltage. We use a combination pump/heater to set the temperature of the water bath to 25.1°C and increase it in steps of 10°C to 55.1°C and make measurements using the thermocouple, RTD, and thermistor. At the last step, the water bath is at 55.1°C, and a thermopile is used along with an RTD and thermistor to measure that steady temperature. Lastly, we measure the temperature with respect to time for a thick and thin thermocouple using the LabView software and analyze the slopes of the graph and Equation 4 to obtain time constants and the heat transfer coefficient.

RESULTS AND DISCUSSION

We assume that the reading of the temperature indicator is the true value. The temperature from the RTD is obtained using Equation 1 and is plotted using that relation to obtain the linear curve shown in Figure 5. As the graph shows, the resistances obtained follows this linear relations and the temperature constant obtained from a linear fit is $\alpha = 0.0037\ K^{-1}$, which is quite close to the given value of $0.00385\ K^{-1}$.

Next, we analyze the resistances obtained from the thermistor and plot them so that the exponential curve is made linear with as shown in Figure 6.

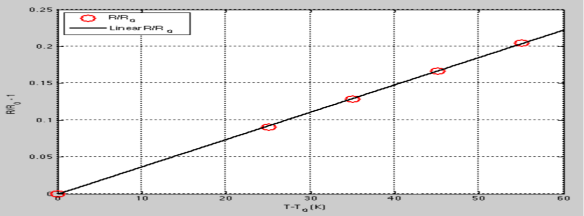

Figure 5. RTD: Temperature Change vs. Resistance Ratio – 1.

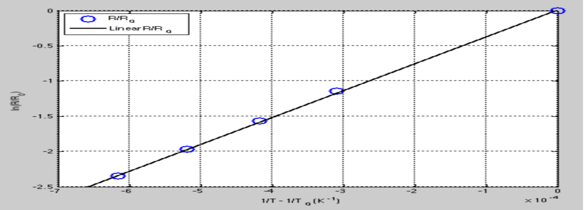

Figure 6. Thermistor: Change in Inverse of Temperature in Kelvin vs. ln(R/R_0).

The temperature constant is obtained by taking a linear fit of this graph, which gives slope of $\beta = 3.8193$. This result is within the limits of the uncertainty given by the manufacturer of the device.

Next, we analyze the thermocouple in three situations: (1) a single thermocouple, (2) a cold-compensated thermocouple at 3 different temperatures, and (3) a thermopile. We use a K-Type thermocouple chart with experimental voltages for a range of temperature referenced at 0°C.

For the single thermocouple the voltage obtained of 2.701 mV corresponds to 66.38°C. The temperatures obtained from the cold compensated thermocouple voltage values agree well with the true temperature, but there seems to be a slight sensitivity error as you can see in Figure 7, where the measured voltage curve slope is lower than the true voltage line's slope.

The thermopile consisted of one room temperature reference junction and one ice-water reference junction. After accounting for the room temperature emf by subtracting it from the measured emf and dividing the resulting emf by 2 to compensate for the 2 junctions measured, the resulting emf turned out to be a bit lower than the expected emf with a 1.69% error. This was not expected, in fact, a higher emf was expected because of the fact that a series thermopile acts as an amplifier. This may be due to an overestimation in room temperature measurement or a deviance in the room temperature from the time the temperature was measured to the time of thermocouple use. Nonetheless, the thermopile proved to be more accurate than the single and cold compensated thermocouples.

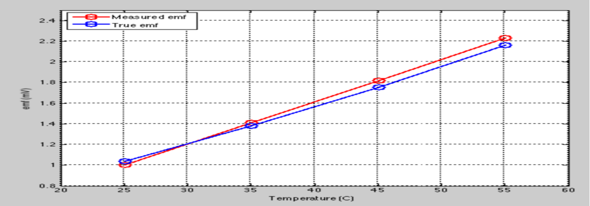

Figure 7. Cold-Compensated Thermocouple.

The last part of the experiment analyzed the time dependence of the thermocouple. The change in temperature for both the thick and thin thermocouples with respect to time is shown in Figure 8.

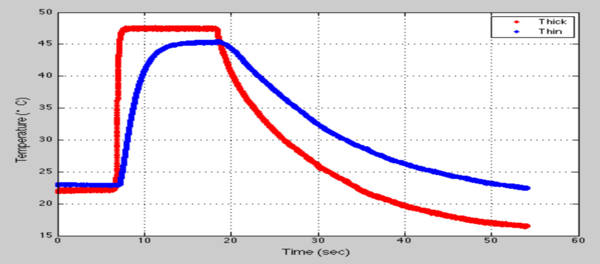

Figure 8. Temperature vs. Time for dunking of a thin (red) and thick (blue) thermocouples.

By using Equation 4, we analyze the time dependence of the temperature change both before and after the temperature reaches steady state. Using the equation we obtain time constants and use them to calculate heat transfer coefficients for water and air using the two exponential parts of the curve in Figure 8. By taking the natural log of the magnitude ratio of the temperature, we find a linear curve fit whose slope corresponds to $-1/\tau$. Figure 9 shows the linear curve fit for the thick and thin thermocouples for dunking of the water which will give h_{water} and Figure 10 shows that of undunking, which will give h_{air}. The values of the time constants and calculate h values are shown in Table 1.

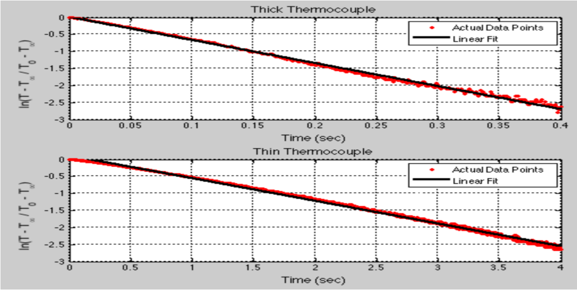

Figure 9. Log Scale of Temp. Ratio for dunking of Thick & Thin Thermocouples in Water

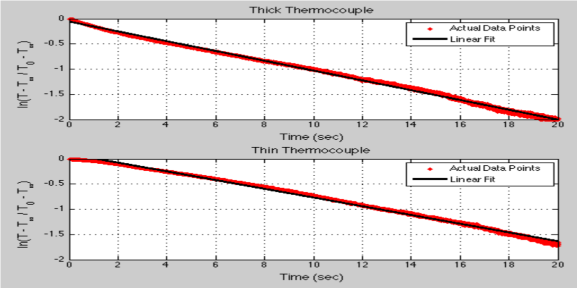

Figure 10. Log Scale of Temp. Ratio for removal of Thick & Thin Thermocouples to Air

The resultant heat transfer coefficients came out to be quite different from the actual values as shown in Table 1. This is most likely because when dunking the thermocouples in the water, the movement of the water causes a faster heat transfer rate because moving fluids transfer heat faster than stationary fluids. Also, the thermocouple temperature was likely still rising while it is still being inserted into the water. This caused the fluctuation of results that were seen. The thin thermocouple had a lower heat transfer coefficient for air which may have been due to the droplets of water that stayed on the thermocouple, while the the thick thermocouple had a higher than actual heat transfer coefficient for air which may have been due to the quick transition into the air and the movement in the air.

Table 1. Heat Capacity Results

Process	τ (s)	h Measured (W/m^2K)	h Actual (W/m^2K)
In (water)		h_{in}	h_{in}
Thick TC	0.1477	16,238	9,058
Thin TC	1.5008	803.8409	
Out (air)		h_{out}	h_{out}
Thick TC	10.2747	233.3617	114.5
Thin TC	11.5382	104.5572	

The response time of the RTD was quite slow, as we saw the reading on the Ohmmeter take a long time, respectively, to settle to stable value. The thermistor, in turn had a relatively fast output, similar or even faster than the thermocouple. The mercury thermometer proved to have the slowest response time of all the temperature devices.

CONCLUSIONS

In this lab, we saw the benefits of certain temperature measurement devices over others and proved the validity of the equations used to calculate those temperatures by comparing a given temperature. All the devices were very accurate in getting the temperature in different situations. The RTD proved to have the best accuracy sensitivity, while the thermistor had the best sensitivity. We showed how a thermocouple can be made more sensitive by using multiples of them in series. We showed how the thermocouple measured temperature difference, while the RTD and thermistor measure absolute temperature. Also the RTD seemed to be more stable than the thermocouple.

We proved the theory of RTDs, thermistors, thermocouples, and thermopiles in this lab. The last part of the experiment analyzed the time response of the devices, mainly the thermocouple. We saw that we can use this temperature data and find the time constant of it by using Equation 4 and also calculate the heat transfer coefficient using this value. Although, these heat transfer coefficient results were not exactly as expected, we can conclude that there are a lot of factors that affect the rate at which heat is transferred to a thermocouple, including thermocouple size and the procedure used to inserted and remove it from a fluid.

REFERENCES

[1] Gere, J.M., Mechanics of Materials, 5th ed, Chapman and Hall, London, 2000.