Experiment 5: Thermocouples

(tbc 1/14/2007, revised 3/16/2007, 3/22,2007, 2/23/2009, 3/13/2011)

Objective: To implement a thermocouple circuit for temperature sensing.

I. Introduction to Thermocouples

A. Fundamental laws

1. Seebeck Voltage

When two dissimilar metals are joined at one end, an electrical potential called the "Seebeck voltage" is generated, which changes proportionally to changes in the temperature at the joint.

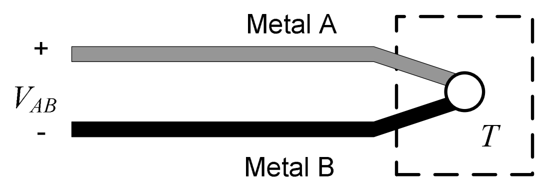

Figure 1.

$$dV_{AB} = \alpha_{AB}(T)\, dT \tag{1}$$

where α_{AB} is called the Seebeck coefficient which is, in general, a nonlinear function of temperature.

2. Law of Intermediate Metals

The introduction of a third metal (Metal C) between two other dissimilar metals (Metal A and B) will yield the same Seebeck voltage, V_{AB}, obtained by removing Metal C, if all the joints are at the same temperature.

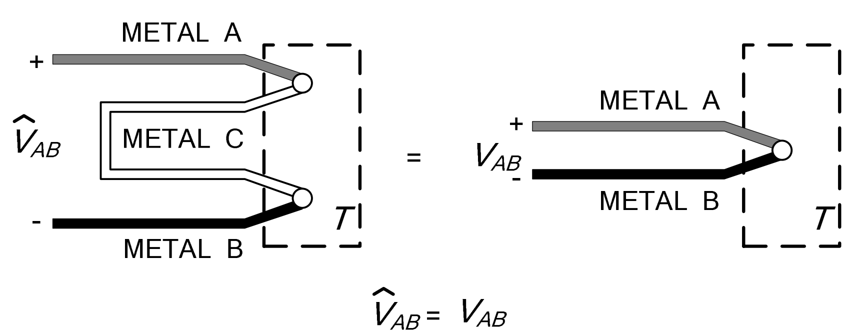

Figure 2.

B. Sensor Configuration

The simplified cold-junction configuration is given in Figure 3.

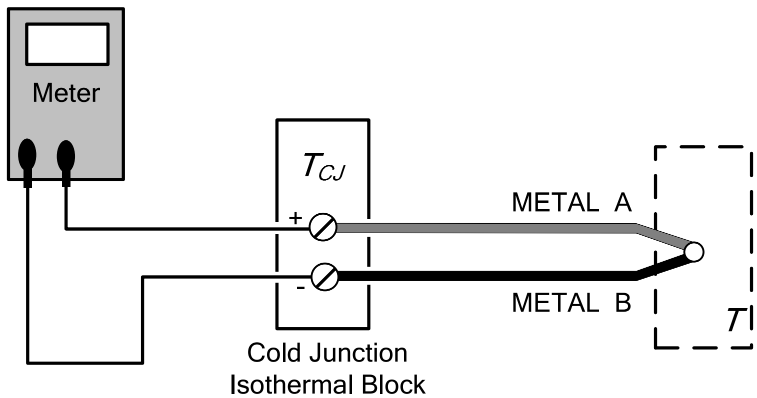

Figure 3.

Let the meter reading be V (in millivolts) and T_{CJ} (cold junction temperature) be measured in ^{o}C. Then the temperature T can be found by using the following equations:

$$\begin{aligned} x &= (5.0412 \times 10^{-2} T_{CJ} + 2.939 \times 10^{-5} T_{CJ}^2 - 7.291 \times 10^{-8} T_{CJ}^3 \\ &\quad +6.509 \times 10^{-11} T_{CJ}^4) + V \\ T &= 19.798\,x - 0.20334\,x^2 + 0.010202\,x^3 - 1.8956 \times 10^{-4} x^4 \end{aligned} \tag{2}$$

The details are given in Appendix A.

II. Experimental Setup

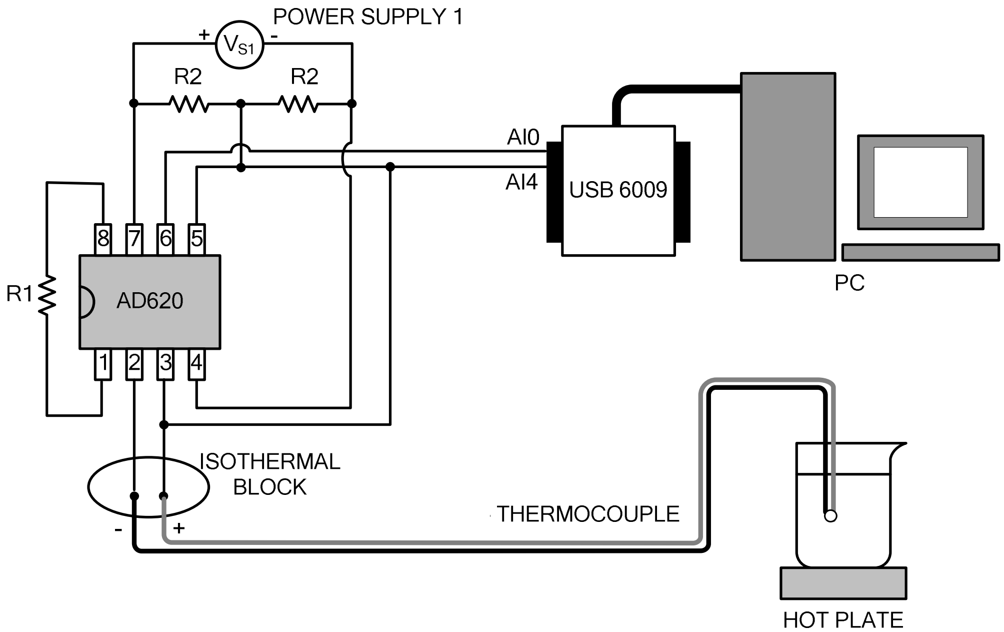

Figure 4.

Table 1.

R_1	47 Ω
R_2	10 kΩ
V_{S1}	12.0 volts

Remarks:

i) For information purposes, the complete data sheet of the Analog Devices AD620 amplifier can be found through the link:

http://www.analog.com/UploadedFiles/Data_Sheets/37793330023930AD620_e.pdf

ii) The theoretical gain G of AD620 can be chosen by setting the value of the resistor R_1 (in ohms),

$$G = \frac{49.4 \times 10^3 \Omega}{R_1} + 1 \tag{3}$$

III. Labview Setup

Thermocouple VI

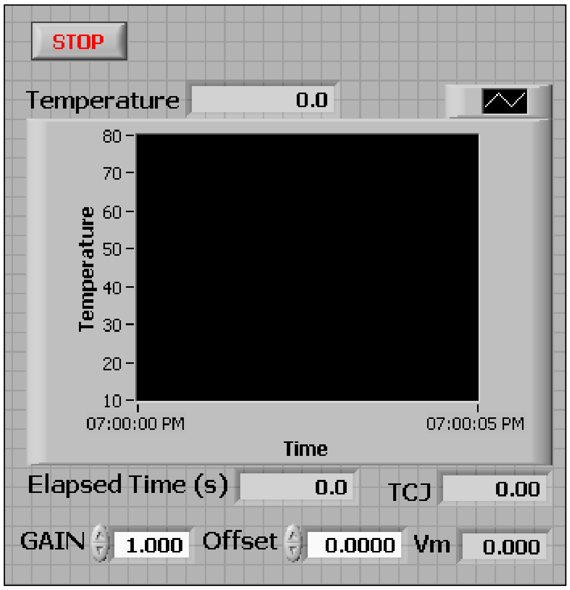

Figure 5a.

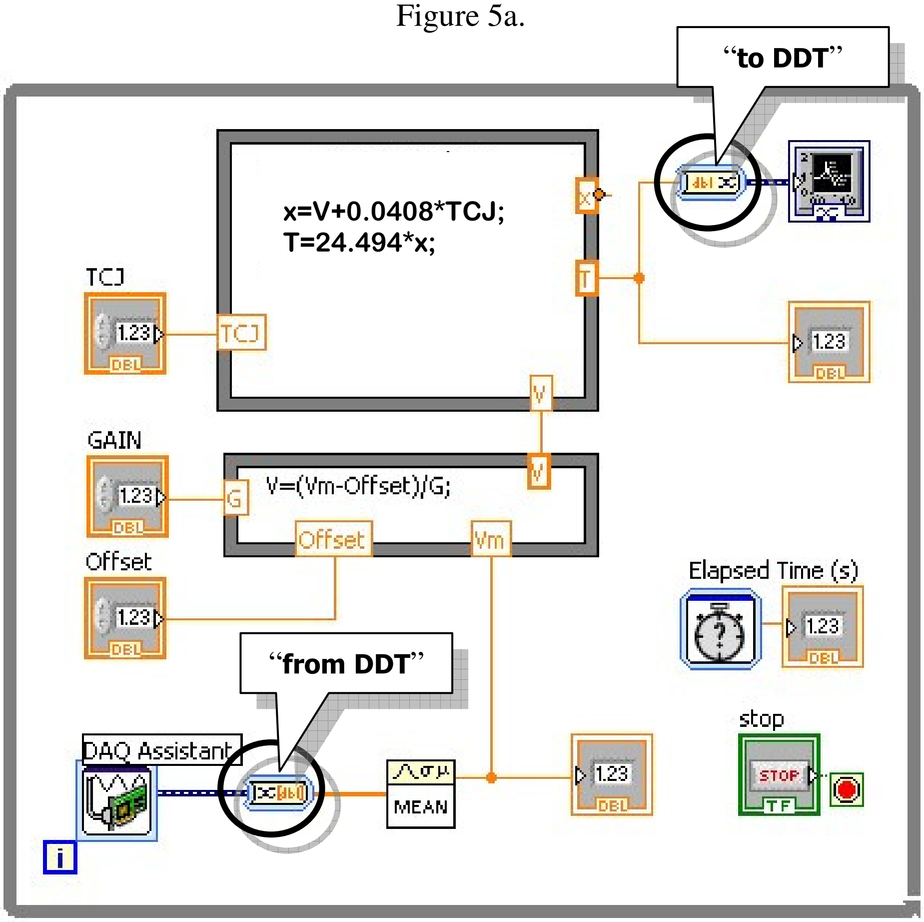

Figure 5b.

Remarks:

a) From “Functions Paletter”, **[Express]→[Input]** subdirectory, select **[DAQ Assistant]** and select **[Analog Input]→[Voltage]** then select **[ai0]**

b) The “**mean**” function block can be found in the “Functions Palette”, [**Mathematics**]→[**Probability and Statistics**] subdirectory.

c) For the “from DDT” block, go to properties and select [**1D array of scalars, single channel**] resulting data type.

d) For the “to DDT” block, go to properties and select [**Single scalar**] input data type.

III. Procedure

1. Prepare the experimental setup shown in Figure 4 and the **Thermocouple VI** in Figure 5.
2. Record the steady-state voltage readings in [**Vm**] indicator, corresponding to $0°C$ and $100°C$.
3. Modify the values of **G** and **Offset** in the **Thermocouple VI** using the values found for Gain and Offset in the spreadsheet.
4. Test the **Thermocouple VI**.

Appendix A.

From "Ice-Water Bath" Configuration To "Simplified Cold-Junction" Configuration.

A1. Ice-water Bath Configuration

The classical thermocouple configuration is one that uses an ice-water bath to set the reference temperature as shown in Figure A1. Points 1 and 2 are kept at the same temperature by using an "isothermal block", which is an insulator used to make sure that both points are at the same temperature T_{CJ}, often referred to as the "cold-junction" temperature.

Most standard tables for the value of V_{std} for different thermocouples are obtained using this configuration (where we include the subscript "std" to denote that this voltage is specific to this standard configuration).

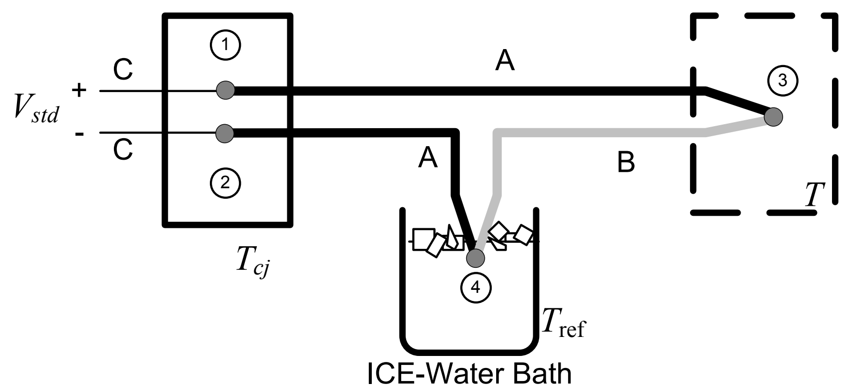

Figure A1.

The voltages across points 1, 2, 3 and 4 in Figure A1 are given by Seebeck voltages V_1, V_2, V_3 and V_4, respectively. Note that $V_1 = -V_2$, since points 1 and 2 are at the same temperature but the metals are polarized in opposite directions. Further, points 3 and 4 also involve the same pair of metals but polarized in the opposite directions, i.e. $\alpha_{AB} = -\alpha_{BA}$. Applying Kirchoff's law and Seebeck's law given in equation (1),

$$
\begin{gathered}
V_{std} = V_1 + V_2 + V_3 + V_4 \\
V_{std} = V_3 + V_4 = \int_{T_o}^{T} \alpha_{AB}(T)\,dT + \int_{T_o}^{T_{ref}} \alpha_{BA}(T)\,dT \\
V_{std}(T) = \int_{T_{ref}}^{T} \alpha_{AB}(T)\,dT
\end{gathered}
\tag{4}
$$

(where T_o is the absolute zero temperature)

A2. Simplified Cold-Junction Configuration

The configuration given in Figure A1 is not convenient in most practical applications because of the burden of maintaining the ice-water condition of the bath. As an alternative, one could change the reference to be $T_{CJ,}$ the "cold-junction" temperature present in the leads, as shown in Figure A2. This changes equation (A1) to be

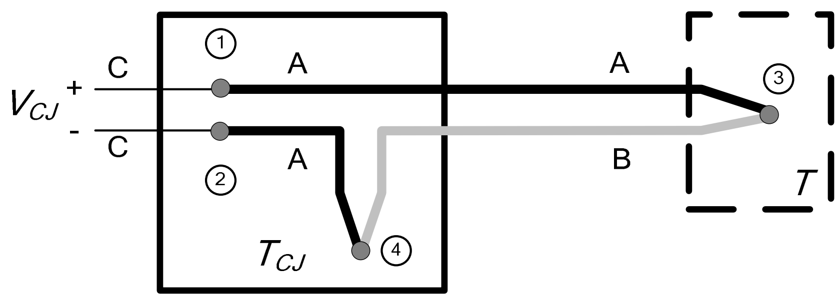

Figure A2.

$$
\begin{aligned}
V_{CJ}(T) &= \int_{T_{CJ}}^{T} \alpha_{AB}(T)\,dT \\
&= \int_{T_{ref}}^{T} \alpha_{AB}(T)\,dT - \int_{T_{ref}}^{T_{CJ}} \alpha_{AB}(T)\,dT \\
&= V_{std}(T) - V_{std}(T_{CJ}) \\
V_{std}(T) &= V_{CJ}(T) + V_{std}(T_{CJ})
\end{aligned}
\tag{5}
$$

The configuration given in Figure A2 can be simplified further by applying the law of intermediate metals (see section I.A.2) in the sub-circuit involving points 2 and 4. Metal A is an intermediate metal between metal C and B. Since points 2 and 4 are the same temperature, the law of intermediate metals state that metal A can be removed while merging points 2 and 4. This is the simplified cold-junction thermocouple configuration shown in Figure A3, where V_{CJ} measured in the configuration given in Figure A3 will be the same V_{CJ} measured as that in Figure A2.

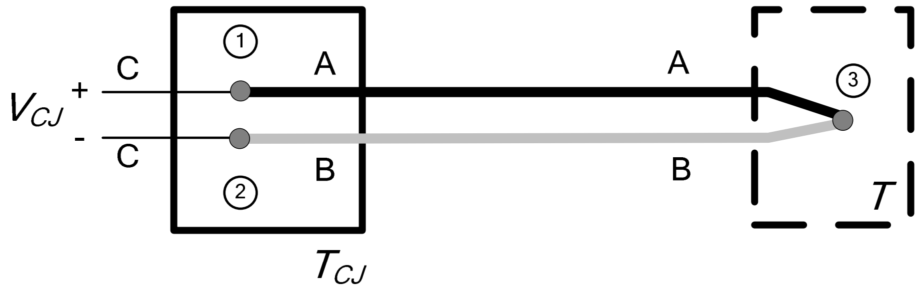

Figure A3.

A3. Temperature measurements

Regardless of the configurations shown above, the main application of thermocouples is to measure the temperature T at point 3. As we had mentioned earlier, the data $V_{std}(T)$ is often available for many commercially available thermocouples. If configuration in Figure A1 is used, we need to just read off the value of T that correspond to the voltage $V=V_{std}$ measured at the leads.

For the simplified cold-junction configuration given in Figure A3, we can use equation (A2) together with available standard V_{std} data (table or function) as follows:

i) Measure the cold junction temperature, T_{CJ}, using a thermistor, IC sensor or other sensors. (Note that thermistors and IC temperature sensors have a limited range, but are usually able to measure the cold junction temperatures.)
ii) Using the available V_{std} data (table or function), obtain the value $V_{std}(T_{CJ})$.
iii) Add $V_{std}(T_{CJ})$ to the measured voltage V_{CJ} to obtain $V_{std}(T)$.
iv) Using the available V_{std} data one more time, find T that corresponds to the calculated $V_{std}(T)$.

In several implementations, the V_{std} data is approximated by a high order polynomial function of temperature, i.e. $V_{std}=p_1(T)$. On the other hand, the final step of finding the unknown temperature value T will involve the inversion of the polynomial $p_1(T)$. A more convenient alternative is to relate temperature T as a function of voltage V_{std} using another polynomial function, $T=p_2(V_{std})$. Thus, assuming polynomials p_1 and p_2 (or other comparable approximations) are available, temperature T can be found as

$$T = p_2\left(V_{CJ} + p_1(T_{CJ})\right) \tag{6}$$

where T_{CJ} and V_{CJ} are the measured cold-junction temperature and voltage, respectively, shown in Figure A3.

For the type K thermocouple, in the range of 0^oC to 100^oC,

$$p_1(T) = 0.0408\,T \; [=] \text{ units in mV}$$
$$p_2(V_{std}) = 24.494\,V_{std} \; [=] \text{ units in } ^\circ C \qquad (7)$$

where V_{std} is in millivolts while T is in $^\circ C$. (Note: do not extrapolate the equations in (A4) for temperatures below 0^oC or above 100^oC. Also, since the voltages are assumed nonnegative, one needs to switch the thermocouple leads in case the voltage readings are negative)

Appendix B. Typical Thermocouples

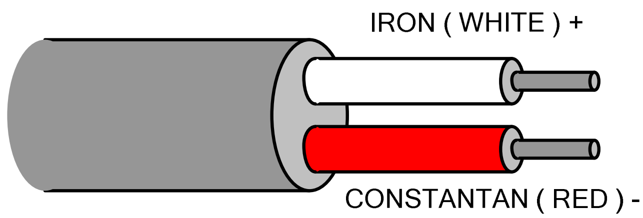

Figure B1. Type J Thermocouple. (Useful range is 95^oC to 760^oC)

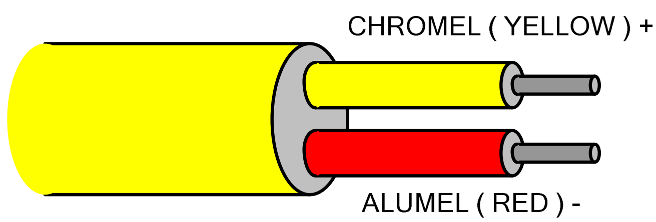

Figure B2. Type K Thermocouple. (Useful range is 95^oC to 1260^oC)

General rules of thumb:

(i) Larger thermocouples if longer life is needed,
smaller thermocouples if sensitivity is needed.

(ii) Length should not be too long.