MCE380: Measurements and Instrumentation Lab

Chapter 6: Temperature Measurements

Topics:
Temperature Scales
Ideal Gas Thermometers
Temperature Measurement by Mechanical Effects
Temperature Measurement by Electrical Effects
Holman, Ch. 8; Copies from Doebelin in ECR

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Thermodynamic Temperature Scale

- Before the discovery of the absolute zero (Lord Kelvin, 1848), temperature was thought to be a relative quantity, with a value dependent of the scale used.
- Kelvin established the existence of a “true” zero temperature correspoding to a state of minimum vibrational energy of molecules.
- The International Practical Temperature Scale was first established in 1968. It provided primary and secondary points that attach a value to certain states of selected substances. For example, it assigned -259.194° C to the triple point of Hydrogen at normalized atmospheric pressure.
- See Holman, Tables 2.1 thru 2.4 for more recent definitions.

Celsius and Fahrenheit Scales

The Celsius and Fahrenheit scales match the freezing and boiling temperatures of water given by the thermodynamic scale.
The Celsius scale divides the freezing-to-boiling range in 100 equal parts, while the Fahrenheit scale uses 180 divisions. For this reason

$$\Delta F = \frac{180}{100}\Delta C = \frac{9}{5}\Delta C$$

When the Celsius scale is shifted by +273.16 or the Fahrenheit scale by +459.69, the resulting scales are the *Kelvin* and *Rankine* scales, respectively. These scales approximate the waypoints of the thermodynamic scale closely.
The conversion btw F and C is well-known:

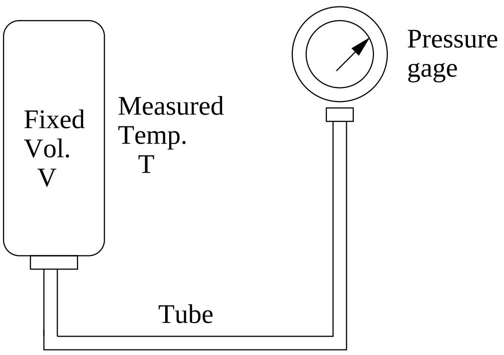
$$F = 32 + \frac{9}{5}C$$

The Ideal Gas Thermometer

The ideal gas thermometer is based in the equation of state for the ideal gas:

$$pV = mRT$$

A fixed-volume canister containing a gas of known mass and R constant is used as the temperature-sensing element. The pressure of the gas is read using a pressure gage.



The Ideal Gas Thermometer

Although it is possible to calculate T knowing p, m and R, there could be uncertainty in the values of m and R.
Instead, we recognize that under constant volume and mass we must have

$$\frac{T_1}{T_2} = \frac{p_1}{p_2}$$

So making a calibration measurement using a known $T_2 = T_{\text{ref}}$ and reading the corresponding $p_2 = p_{\text{ref}}$, we have

$$T = T_{\text{ref}} \frac{p}{p_{\text{ref}}}$$

Thermometers of this type can read temperatures approaching 1° K.

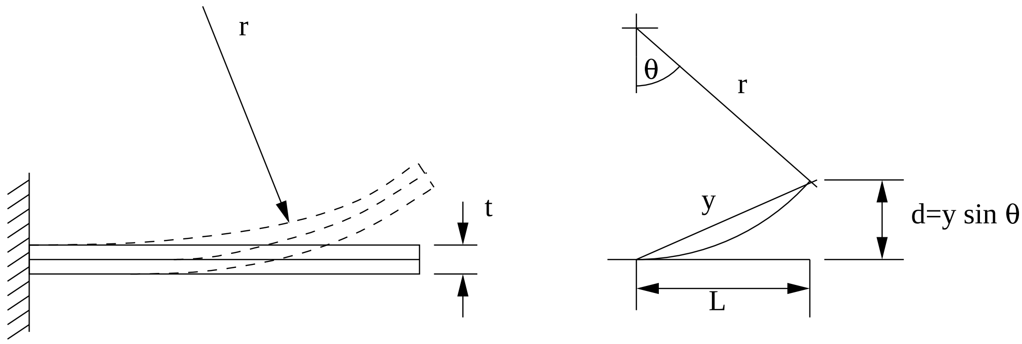
Mechanical Measurement of Temperature

Thermal expansion is used as the working principle of various temperature-measuring devices.
Mercury-in-glass thermometers can be made to read temperatures above -37.8° C (freezing point of Mercury) up to 500° C. Higher temperatures require filling the capillary tube with a gas to increase the pressure and therefore the boiling point.

The glass may expand noticeably, shifting the scale relative to the mercury. High-accuracy thermometers ($\pm 0.05°C$) have a mark designating the proper immersion level.

Bimetallic Strips

The bimetallic strip is a widely-used device. It is made by bonding two strips of materials having different thermal expansion coefficients. The bond is made at a reference temperature, with both strips having equal length.



When the temperature changes, the materials experience different elongations. Since they must stay bonded, a curved shape is adopted.

Bimetallic Strip Calculations

The radius of curvature can be calculated with

$$r = \frac{t\{3(1+m)^2 + (1+mn)[m^2 + \frac{1}{mn}]\}}{6(\alpha_2 - \alpha_1)(T - T_0)(1+m^2)}$$

where t is the total thickness; m is the thickness ratio btw. low- and high-expansion materials; n is the ratio of elastic moduli btw. low- and high-expansion materials; α_1 and α_2 are the lower and higher coefficients of expansion ($^\circ C^{-1}$); T is the measured temperature and T_0 is the initial bonding temperature (both in $^\circ C$).

The deflection can be calculated as shown in the figure (see Holman Ex. 8.1).

Example

Solve Prob. 8.5 from Holman.

Temp. Measurement by Electrical Effects

The Resistance Temperature Detector (or RTD) is based on changes in resistivity with temperature.
The temperature coefficient of resistance is defined as

$$\alpha = \frac{R_2 - R_1}{R_1(T_2 - T_1)}$$

where R_1 and R_2 are the resistances of the material at temperatures T_1 and T_2.
See Holman, Table 8.2 for values.
The above linear relationship is valid for narrow ranges only. A quadratic fit of the form

$$R = R_0(1 + aT + bT^2)$$

is frequently used for wider ranges. The values of a and b must be determined from calibration experiments. These are known as *Callender coefficients*.
RTD's usually have platinum sensing elements (the one used in the lab is of this type). The platinum is coated with another material to protect against environmental effects and mechanical damage.

RTD Signal Conditioning

Nonlinearity, connecting wire resistance and self-heating effects are the main sources of error.
Nonlinearity arises from using the RTD over wide temperature ranges, where the quadratic equation applies. The length and gage of the connecting wires is uncertain. Special bridge circuits (see Holman Fig. 8.7) are used to compensate for connecting leads.
The RTD is subject to heating according to the i^2R power law. This can produce false readings.

The signal conditioner used in the lab contains specialized circuits that guarantee linearity over the whole range of operation, in addition to amplifying and biasing the output to desired levels.

Thermistors

As explained earlier, a thermistor is a semiconductor that *decreases* its resistivity with increasing temperature. This is the opposite behavior of metals. The resistance-temperature behavior is exponential:

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

where R_0 is the resistance at a reference temperature T_0 and β is a constant that varies from device to device.
Observe Fig. 8.8 in Holman (compare to platinum).

Think about a way to obtain β if R_0, T_0 and data points for R and T are available experimentally.

Peltier-Seebeck Effect: Modern Explanation for Thermoco

Old notion:

When two distinct metals are joined together, a voltage appears between endpoints. New notion (mid-90's):

A temperature gradient in a material gives rise to a voltage. *We can observe this voltage even in a **single** material having a thermal gradient.*

The *absolute Seebeck coefficient* is defined as:

$$\sigma(T) = \frac{dE_\sigma}{dT}$$

where E_σ is the voltage. Note that $\sigma(T)$ is not a constant, but a function of temperature. Integrating btw T_1 and T_2:

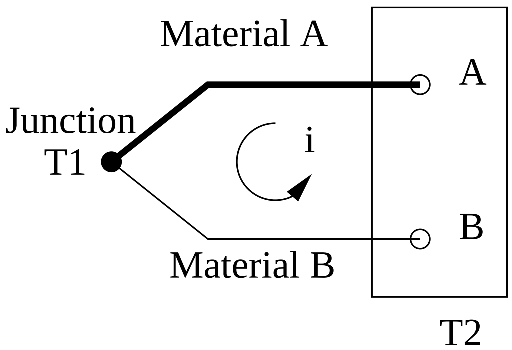
$$E_\sigma = \int_{T_1}^{T_2} \sigma(T)dT = \int_0^{T_2} \sigma(T)dT - \int_0^{T_1} \sigma(T)dT = E_\sigma(T_2) - E_\sigma(T_1)$$

The generated voltage depends only on the values of E_σ at the endpoints.

Relative Seebeck coefficient

Distinct metals will have different values of $\sigma(T)$. Thus, in a back-to-back arrangement (a thermocouple), the two voltages must be subtracted:

$$E = \int_{T_1}^{T_2} \sigma_A(T)dT - \int_{T_1}^{T_2} \sigma_A(T)dT = \int_{T_1}^{T_2} \sigma_A(T) - \sigma_B(T)dT = \int_{T_1}^{T_2} \sigma_{AB}(T)dT$$



σ_{AB} is the *relative Seebeck coefficient*. Note that one of the temperatures must be known in order to find the other from measured voltage.

Thomson and Peltier (Side-) Effects

If we pass a current through a single material, a thermal gradient is estabished. This is called the *Thomson effect*.
If two distinct materials are put in contact and a current is established, there will be heat transfer from one of the materials to the other. One materials heats up, while the other cools down. This phenomenon is known as the *Peltier effect*. Any real thermocouple connected to a measuring device will exhibit a combination of the three effects.
The Peltier-Seebeck effect is the one that determines the measured voltage for the most part, if the current flowing through the junction is kept small.

Recall the concept of input impedance of a meter: it must be high to keep the current small!

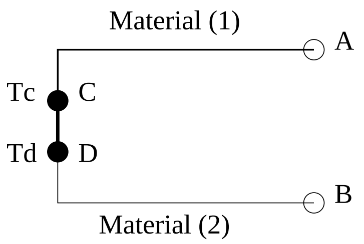
Issues with connecting cables

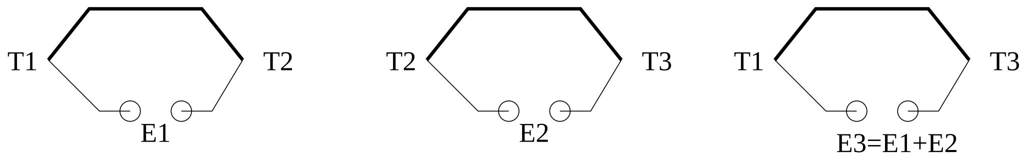
The connection between the metals and the cables creates two additional junctions subject to the Peltier-Seebeck effect. The total output voltage will then depend on the temperature of these extra junctions, which are not intended to act as temperature sensors and only introduce uncertainty.
A reference temperature will be required at the extra junctions.

Two thermocouple interconnection laws will help us analyze various thermocouple circuits.

Thermocouple Laws

<u>Law of intermediate metals:</u>
If a third metal is inserted as shown below, the net voltage of the circuit is unaffected, provided the insert is kept at a uniform temperature ($T_c = T_d$).
<u>Law of intermediate temperatures:</u>
If two junctions are created and operated at different temperatures, the generated voltages follow an additive law as shown below.





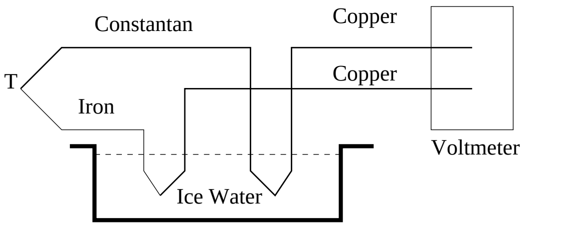
Thermocouple Laws

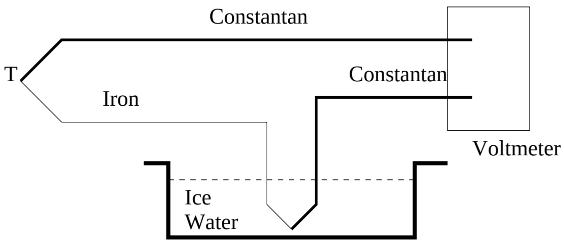
<u>Independence of intermediate temperatures:</u>
The voltage generated by each branch of the thermocouple is independent of intermediate temperatures if each material is homogeneous.
This law is an immediate consequence of the formula we saw earlier:

$$E_\sigma = E_\sigma(T_2) - E_\sigma(T_1)$$

Traditional Temperature Referencing Method

At least two junctions are created by connecting the ends of the metals to instrumentation cables. These junctions can be at the same or at different temperatures, leading to the methods shown below. *Note that the second arrangement works because of the law of independence of intermediate temperatures for homogeneous materials.*





Standard Thermoelectric Potentials

Standardized voltage data for cold junctions referenced at 0°C is available for various material pairs.

T type: Copper-Constantan

E type: Chromel-Constantan

J type: Iron-Constantan

K type: Chromel-Alumel

S type: Platinum-Platinum Rhodium

N type: Nicosil-Nisil

Observe Table 8.3a in Holman for temperature ranges and thermoelectric voltages.

A J-type thermocouple should generate -6.5 μV at -150°C and +69 μV at +1200°C.

The voltage-temperature data follows a power law

$$E = AT + \frac{1}{2}BT^2 + \frac{1}{3}CT^3$$

High-Order Polynomial Fit

NIST has published coefficient data and accuracies for several thermocouple materials. A 9th-order polynomial has been used to fit the temperature-voltage data:

$$T = a_0 + a_1 x + a_2 x^2 + ... + a_9 x^9$$

where x is in volts (reference junction at 0°C) and T is in °C. An excerpt of the NIST data appears in Holman, Table 8.5.

The sensitivity in volts per degree may be obtained by differentiation of the cubic polynomial or by differentiation of the 9th-order polynomial and reciprocation.

Practical "Cold Junction Compensation"

It is inconvenient to keep the connecting junctions at the reference temperature at all times. Two methods are used in practice. Both use an additional temperature sensor (thermistor or RTD) to measure the temperature of the connection junctions.

In *hardware compensation*, a specially-designed circuit utilizes the thermistor voltage to cancel out the effect of connecting junction temperature.

In *software compensation*, the thermistor voltage is digitized and a micro-processor calculates the true temperature. The advantage of this method is that the characteristics of the thermocouple being used are not hard-wired in the compensating circuit, and can thus be re-programmed.

Basic Calculation

The voltage generated by a thermocouple depends on the difference between the sensing and connecting junction temperatures. Usually, both binding posts at the voltage-measuring instrument are at the same temperature.

If the connecting junction were at 0°C, we would read the generated voltage directly from Table 8.3a.

When the connecting junction is at a different temperature, the intermediate temperature law tells us that we must *subtract* the voltage generated by the connecting junction from that generated by the sensing junction.

Examine Example 8.4 and then solve Prob. 8.12.

Thermopiles

Thermopiles are series connections of the same thermocouple pairs (see Fig. 8.19). Thermopiles are used to obtain larger voltage readouts (more sensitivity). The net voltage will depend on the difference of temperatures between sensing and connecting junction and will obey the law of intermediate temperatures.

Examine Example 8.5 (first part).