Thermoelectric Laws and Thermocouple Applications

Thermocouple:
A junction of two dissimilar metals
- If two junctions are at different temperatures, a voltage develops across the junction
  - Charged carriers diffuse from hot to cold
  - Carriers leave behind opposite charge
    → Voltage
- Voltage is a function of $\Delta T$
- No external power required!

Thermoelectric Laws
- Let’s consider what does and does not affect the operation of a thermocouple
- For example, must we account for the EMF created by another junction that connects the thermocouple to an amplifier or to a data logger?

Law of Homogeneous Materials (#1)
- The thermal EMF of a thermocouple is unaffected by temperatures elsewhere in the circuit if the two metals of the thermocouple are homogeneous
- This law allows us to make the thermocouple leads out of the thermocouple material
- For example, the lead wires can be copper and constantan (a type T thermocouple)
Law of Homogeneous Materials (#1)

In other words, temperature changes in the wiring between the input and output do not affect the output voltage, provided the wire is made of a thermocouple alloy.

Law of Intermediate Materials (#2)

- If a third metal is inserted in either wire A or B and if the two new junctions are at the same temperature, there will be no net voltage generated by the new metal.
- This allows us to connect a thermocouple to an amplifier or to a voltmeter.
- Without this property, a thermocouple would be useless!

Law of Intermediate Materials (#2)

- The insertion of an intermediate material into a thermocouple circuit will not affect the EMF voltage output as long as the two new junctions are at the same temperature. This is commonly termed an __________.

Law of Intermediate Materials (#3)

- If metal C is inserted into the junction AB, no net voltage is generated as long as junction AC and BC are at the same temperature.
- This allows us to use a third metal (e.g., solder) to electrically and physically bond the two thermocouple metals.

An example of an isothermal block

The EMF is the same with or without the solder as long as the junctions are electrically sound.

Thermocouple voltages of two metals A and B with respect to a third metal C may be added to form thermocouple voltages with respect to each other. This allows us to calibrate new thermocouple metal combinations given known standards.

\[ V_{AB} = V_{AC} + V_{CB} \]

If a thermocouple produces a voltage \( \Delta V_a \) for junction temperatures \( T_1 \) and \( T_2 \), and if the same thermocouple produces a voltage \( \Delta V_b \) for junction temperatures \( T_2 \) and \( T_3 \), then the thermocouple will produce a voltage \( \Delta V_a + \Delta V_b \) for junction temperatures \( T_1 \) and \( T_3 \).

How do we determine temperature?

- Thermocouples measure temperature differences.
- We need to know one of the junction temperatures to be able to calculate the other.
- How do we accomplish this?
  - Place one junction in an ice bath (0°C)
  - Place one junction in a temperature controlled chamber (oven)
  - Use a secondary temperature measurement
  - Use an electronic substitute for a reference

Ice-Point Compensator:

Junction temperature errors are typically less than ±0.2°C.

\( R_1 \) is adjusted such that the bridge circuit acts as the second junction placed in an ice bath at 0°C.
Question: Why don’t we use the reference transducer (e.g., thermistor, platinum RTD, semiconductor, etc.) to measure the temperature in the first place?

Answer:
- Other transducers have a limited range compared with a thermocouple.
- Other transducers lack properties necessary for high-temperature and/or physically demanding applications.
- Thermocouples are rugged, high-temperature transducers that are often subjected to harsh environments with conditions that far exceed what other transducers can withstand.


Temperature vs. voltage and Seebeck coefficient for various thermocouple types

Source: Agilent Technologies, Application Note 290

Amplifying a weak signal

\[ V_3 = G(V_1 - V_2) \]

Determining the correct gain

- We want to measure the temperature using a copper-constantan thermocouple such that:
  - Range: –15°C to 35°C
  - \( T_2 = 0°C \)
  - Output: –5 V < \( V_3 \) < 5 V

Problems with large gain:
- Potentially expensive
- Susceptible to noise

Characteristics of thermocouples

- Good points
  - Very small
  - Inexpensive
  - Fast response
  - Reliable
  - Accurate
  - Simple to use

- Drawbacks
  - Small output signal
  - Need known reference
  - Metal corrosion
  - Poor sensitivity
  - Metal fatigue
  - Some residual non-linearity
Thermocouple applications

- Micrometeorology
  - High-speed measurements
  - Turbulence
  - Plant physiology

Thermopile applications

- Soil moisture – Campbell Scientific 229-L

A thermopile is made by connecting multiple thermocouples in series or in parallel

- Pyranometer
- Radioisotope thermoelectric generator