Chapter 2: Temperature Measurements

Chapter 2. Temperature Measurements (5 Weeks) Thermocouples, thermistors, infrared detectors, pyrometers. Calibration of thermal sensors. Errors related to thermal sensors. Sensor selection. Automatic data acquisition and acquisition boards.

II.1 Introduction

Temperature is one of the most fundamental and commonly measured physical quantities in science and engineering. It plays a crucial role in various fields such as meteorology, medicine, manufacturing, and environmental monitoring. Accurate temperature measurements are essential for controlling processes, ensuring safety, and maintaining the quality of products and services. In this lesson, we will explore the principles behind temperature measurement, the different types of temperature sensors, and the methods used to collect and interpret temperature data. Understanding these concepts is key to applying temperature control in real-world applications.

II.2 Temperature

Temperature is the measurement of the hotness and coldness of a body. It is measured with the help of a device called thermometer. The three units in which temperature is measured are Celsius, Fahrenheit, and Kelvin. Hence, there are three different scales for measuring temperature. Every unit can be converted to another unit with the help of a conversion formula that we are going to study in this lesson.

II.2.1 Temperature Scales Conversion

Using conversion formulas, temperatures can be converted from one scale to another. In temperature conversion the value of temperature changes from one unit to another. The three main conversions of temperature are:

- Between Celsius and Kelvin.
- Between Fahrenheit and Kelvin.
- Between Celsius and Fahrenheit.

The following table shows the conversion formulas of the different units of temperature:

Conversion of Temperature From	Formulas
Celsius to Kelvin	$K = C + 273.15$
Kelvin to Celcius	$C = K - 273.15$
Fahrenheit to Celsius	$C = (F - 32)\frac{5}{9}$
Celsius to Fahrenheit	$F = C\frac{9}{5} + 32$
Fahrenheit to Kelvin	$K = (F - 32)\frac{5}{9} + 273.15$
Kelvin to Fahrenheit	$F = (K - 273.15)\frac{9}{5} + 32$

Important Notes:

- Temperature is simply an average measure of the kinetic energy for particles of matter.
- The Celsius scale is generally used for most temperature measuring purposes.
- The Fahrenheit (°F) temperature scale is used in the United States.

II.2.2 Examples on Temperature

Example 1: Noah knows that one-degree Celsius is equal to 273.15 Kelvin. He wants to calculate 30°C in Kelvin. How much is 30°C in Kelvin?

Solution: Given, One-degree Celsius is equal to 273.15 Kelvin. From the temperature conversion formula, we can convert Celsius to Kelvin that is, K = C + 273.15. Putting the value: K = 30 + 273.15K = 303.15 K. Therefore, **30°C in Kelvin is 303.15 K**

Example 2: Isabella knows the body temperature is generally 37ºC. Now she wants to know the body temperature in Fahrenheit. Can you help her?

Solution: Given, the body temperature on the Celcius scale is 37ºC. Using the formula of conversion from Celsius to Fahrenheit is **F = (C×9/5) +32**

Substituting the value, we get **F=37∘C×9/5+32 → F=98.6**

Therefore, the body temperature in Fahrenheit is 98.6F.

Example 3: Joseph knows that the freezing point of water on the kelvin scale is 273.15K. He wants to know the freezing point of water on the Fahrenheit scale. Can you help him find the answer? **Solution:** Given, the freezing point of water on the Kelvin scale is 273.15K. We know that

$$F = (K-273.15)9/5+32$$

So, by substituting the value of K, the freezing point of water on the Fahrenheit scale is 32°F.

II.3 Thermocouple

A **thermocouple** is a temperature measurement device consisting of two different conductors or semiconductors that are joined together at two junctions. When there is a temperature difference between the junctions, an electromotive force (emf) is generated, which can be measured and related to the temperature difference. Thermocouples are widely used for temperature measurement in various industrial, scientific, and engineering applications due to their simplicity, wide temperature range, and versatility.

Figure II.1: Thermocouple.

The temperature difference causes the development of a voltage that is approximately proportional to the difference between the temperatures of the two junctions. The voltage can then be interpreted using thermocouple reference tables to calculate the temperature, or the measuring instrument can be calibrated to read temperature directly.

II.3.1 Working Principle of Thermocouple

The working principle of a thermocouple is based on the **Seebeck effect**, which states that when two different metals are connected at two junctions and subjected to a temperature gradient, an electromotive force (emf) is generated. This voltage is proportional to the temperature difference between the junctions, and the relationship between temperature and voltage is material-dependent. When one junction is heated or cooled, the temperature difference between the junctions causes electrons to move, generating an emf. This voltage can then be measured, and by knowing the Seebeck coefficient of the materials involved, the temperature difference can be calculated.

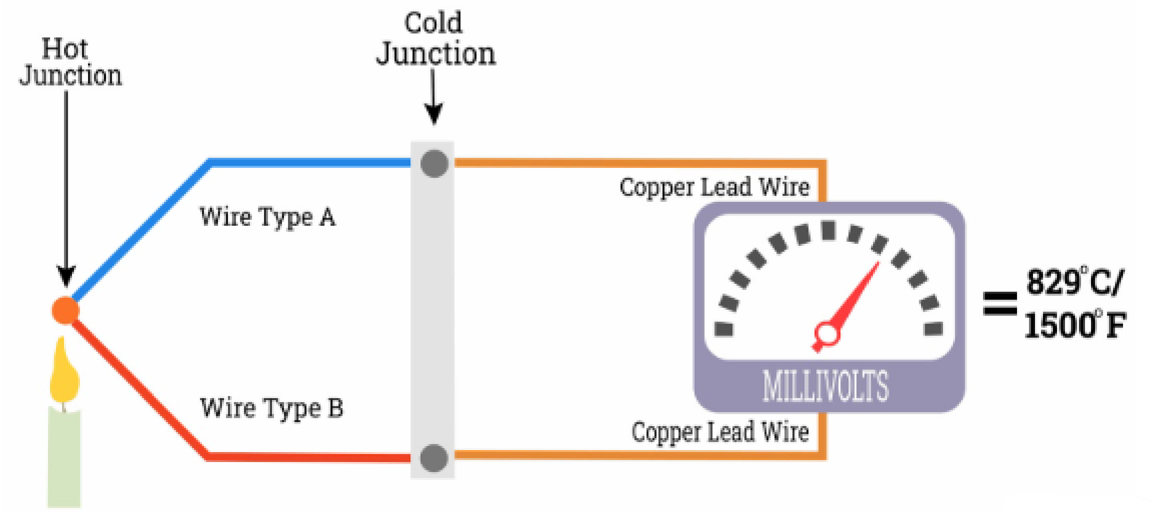

Figure II.2: Principe of Thermocouple.

II.3.2 Thermocouple General Equation

The general equation used for thermocouple voltage $\mathcal{E}$ based on the temperature difference (ΔT) is often approximated using a **polynomial** equation (specific to the thermocouple type):

$$V(T) = a_0 + a_1 T + a_2 T^2 + a_3 T^3 + \cdots + a_n T^n$$

Where:

- **V(T)** is the voltage generated by the thermocouple (in volts).
- ***T*** is the temperature (in °C or K).
- $a_0, a_1, a_2, \ldots, a_n$ are the coefficients determined for a specific thermocouple type (these coefficients vary with the material and the temperature range).

This equation approximates the voltage-temperature relationship for a given thermocouple over a defined temperature range.

II.3.3 Thermocouple Effects

Thermocouples rely on three key thermoelectric effects: **Seebeck**, **Peltier**, and **Thomson**. These effects govern the behavior of charge carriers in different materials when subjected to temperature gradients. Each of these effects contributes in a specific way to the generation and movement of the voltage in thermocouples.

II.3.3.1 Seebeck Effect

The **Seebeck effect** occurs when two dissimilar metals are joined at two junctions, and a temperature difference between the junctions generates an electromotive force (emf). The emf depends on the type of metals used and the temperature gradient between the junctions. This effect is the fundamental principle behind thermocouples, where the difference in temperature at the two junctions induces a voltage that can be measured and related to the temperature.

In general, The **Seebeck effect** is the phenomenon where a voltage is generated in a circuit made of two different materials when there is a temperature difference between the two junctions. The **Seebeck effect** relates the temperature difference between two junctions to the induced electromotive force (emf). The equation for the Seebeck effect is:

$$\mathcal{E} = S \cdot \Delta T$$

$$\Delta T = (T_{\text{hot}} - T_{\text{cold}})$$

Where:

- $\mathcal{E}$ is the electromotive force (emf) generated across the two materials (in volts).
- **S** is the Seebeck coefficient of the material (in µV/∘C).
- **ΔT** is the temperature difference between the two junctions (in °C or K).

The Seebeck coefficient SSS is a material property, and it varies depending on the type of material used for the thermocouple.

II.3.3.2 Peltier Effect

The Peltier effect refers to the heat absorption or release when an electric current flows through a junction of two dissimilar metals. When current passes through the junction, one side absorbs heat (cooling), while the other side releases heat (heating). The Peltier effect is the basis for thermoelectric coolers and heat pumps but is less directly related to the temperature measurement principle of thermocouples, although it is still a key thermoelectric phenomenon.

In general, The **Peltier effect** refers to the heat absorbed or released when an electric current flows through a junction of two dissimilar materials. The effect causes one junction to cool down while the other heats up. The **Peltier effect** describes the heat absorbed or released at the junction between two different conductors when an electric current flows through them. The equation for the Peltier effect is:

$$Q = \Pi \cdot I \cdot \Delta t$$

Where:

- **Q** is the amount of heat absorbed or released (in joules).
- **Π** is the Peltier coefficient (in volts).
- ***I*** is the current flowing through the circuit (in amperes).
- **Δt** is the time interval over which the heat is transferred (in seconds).

The Peltier coefficient **Π** is also a material-dependent property, and it can be related to the Seebeck coefficient.

II.3.3.3 Thomson Effect

The Thomson effect describes the potential difference generated along a conductor when there is a temperature gradient along its length. In other words, if a conductor made of a single material has a temperature gradient along its length, a potential difference will appear. This effect is typically smaller than the Seebeck effect but is still relevant in certain thermoelectric materials.

In general, The **Thomson effect** describes the potential difference that develops along a conductor when there is a temperature gradient along its length. In other words, a voltage is generated along a conductor when its temperature is not uniform. The **Thomson effect** describes the potential difference generated along a conductor when a temperature gradient exists along its length. The equation for the Thomson effect is:

$$V = \alpha \cdot L \cdot \Delta T$$

Where:

- **V** is the potential difference generated (in volts).
- **α** is the Thomson coefficient of the material (in μV/∘C).
- ***L*** is the length of the conductor (in meters).
- **ΔT**is the temperature difference across the length of the conductor (in °C or K).

The Thomson coefficient α\alphaα is also dependent on the material and the temperature.

II.3.4 Types of Thermocouples

Thermocouples come in different types based on the materials used for the two wires (conductors) in the thermocouple. Each type has its own specific characteristics, such as temperature range, sensitivity, and resistance to corrosion. Here are the most common types:

1. **Type K (Chromel-Alumel)**:
   - **Composition**: Chromel (Nickel-Chromium alloy) and Alumel (Nickel-Aluminum alloy)
   - **Temperature Range**: -200°C to 1372°C
   - **Characteristics**: Type K is the most commonly used thermocouple. It is highly sensitive and widely used in general-purpose temperature measurements. It has a relatively high accuracy but is prone to oxidation at higher temperatures.
   - **Applications**: Used in a wide range of industrial applications, including furnaces, engines, and other high-temperature environments.
2. **Type J (Iron-Constantan)**:
   - **Composition**: Iron and Constantan (Copper-Nickel alloy)
   - **Temperature Range**: -40°C to 750°C

- **Characteristics**: Type J is less stable than Type K at higher temperatures and is prone to oxidation, especially at temperatures above 600°C. It has good sensitivity and is best used in lower temperature applications.
- **Applications**: Commonly used in older equipment, food processing, and for general-purpose temperature measurements in environments where moderate temperatures are expected.

3. **Type T (Copper-Constantan)**:
    - **Composition**: Copper and Constantan (Copper-Nickel alloy)
    - **Temperature Range**: -200°C to 350°C
    - **Characteristics**: Type T is very accurate and stable at low temperatures, making it ideal for cryogenic applications. It is also less susceptible to corrosion compared to other types.
    - **Applications**: Used in low-temperature measurements, refrigeration, and cryogenic systems.
4. **Type E (Chromel-Constantan)**:
    - **Composition**: Chromel (Nickel-Chromium alloy) and Constantan (Copper-Nickel alloy)
    - **Temperature Range**: -200°C to 900°C
    - **Characteristics**: Type E has a higher output voltage (compared to Type K and J) and is more sensitive, but it has a more limited temperature range. It is highly stable and accurate.
    - **Applications**: Used in cryogenic applications, as well as in aerospace and laboratory measurements where high sensitivity is required.
5. **Type N (Nicrosil-Nisil)**:
    - **Composition**: Nicrosil (Nickel-Silicon alloy) and Nisil (Nickel-Silicon alloy)
    - **Temperature Range**: -200°C to 1300°C
    - **Characteristics**: Type N is stable at high temperatures and is resistant to oxidation, making it suitable for use in harsh environments. It has a high resistance to corrosion.
    - **Applications**: Used in high-temperature, high-accuracy applications, particularly in industries such as power generation, steel manufacturing, and research.
6. **Type R (Platinum-Rhodium)**:
    - **Composition**: Platinum (90%) and Rhodium (10%)
    - **Temperature Range**: 0°C to 1700°C
    - **Characteristics**: Type R thermocouples have high accuracy and stability, especially in high-temperature environments. They are less sensitive than base metal thermocouples but can withstand extremely high temperatures without degradation.
    - **Applications**: Commonly used in scientific applications, high-temperature furnaces, and in industries where precise temperature control is essential.
7. **Type S (Platinum-Rhodium)**:

    - **Composition**: Platinum (90%) and Rhodium (10%)
    - **Temperature Range**: 0°C to 1600°C
    - **Characteristics**: Similar to Type R but with a slightly higher temperature range. It has excellent stability and is highly accurate.
    - **Applications**: Used in high-precision applications such as industrial processes, laboratory environments, and calibration equipment.
8. **Type B (Platinum-Rhodium)**:
    - **Composition**: Platinum (70%) and Rhodium (30%)
    - **Temperature Range**: 0°C to 1820°C
    - **Characteristics**: Type B thermocouples are used for very high-temperature measurements. They are less sensitive at lower temperatures but highly accurate at very high temperatures.
    - **Applications**: Used in high-temperature furnace calibration, ceramics, and in processes that require precise temperature control at very high temperatures.
9. **Type C (Tungsten-Rhenium)**:
    - **Composition**: Tungsten and Rhenium (in various combinations)
    - **Temperature Range**: 0°C to 2320°C
    - **Characteristics**: Type C thermocouples are known for their ability to withstand extremely high temperatures, especially in vacuum and inert environments. They are very stable but are typically more expensive.
    - **Applications**: Used in high-temperature applications, such as in materials testing, aerospace, and space research.
10. **Type M (Platinum-Rhodium)**:

- **Composition**: Platinum (87%) and Rhodium (13%)
- **Temperature Range**: 0°C to 1200°C
- **Characteristics**: Type M thermocouples are designed for moderate to high-temperature environments. They are relatively stable and offer good accuracy.
- **Applications**: Used in processes requiring temperature control and precision, such as in chemical industries and laboratory experiments.

Each type of thermocouple is chosen based on factors such as the temperature range, sensitivity, environmental conditions (like corrosion or oxidation resistance), and specific application requirements.