

# Thermocouple: Facts and Theories

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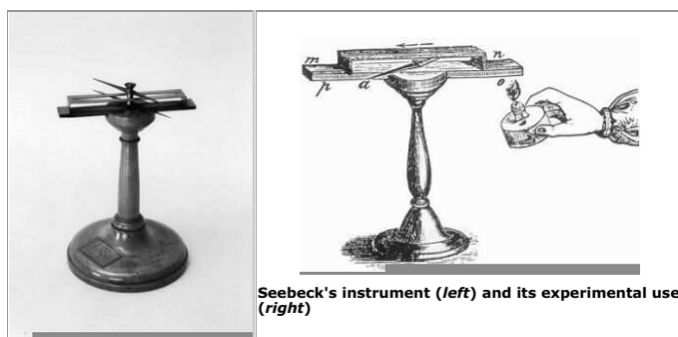
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**Abstract :** *In reality, thermocouples are extremely versatile and rugged. They are primarily simple devices and can be made to very small dimensions to convert heat into electricity. They are capable of operating over a wide range of temperatures. In addition, they are low in cost and are readily interchanged or replaced. However they do need to be tacit, so that they will measure the quantity that is desired with the precision that is required. In this context, the article presents an explanation about the thermocouple.*

**Keywords:** Thermocouple, temperature gradient, Seebeck effect, Peltier effect, Thomson effect.

## 1. BACKGROUND

It was amazing and implausible thing at the time of little world of physics to think about thermocouple and inter-conversion of heat & electricity. All things came in reality through the enthusiastic and innovative mind of the scientists. In 1821 Thomas Johann Seebeck (1770-1831), Estonian-German physicist, joined copper and bismuth wires to form a closed loop to study magnetic property and then accidentally discovered the thermocouple (Dataforth corporation, an106.pdf) since he had already learned of Oersted's discovery of electromagnetism. When he heated one junction to a high temperature and another junction remained at a cooler temperature than he observed magnetic field around the loop having temperature gradient. For his discovery he used the term thermo-magnetic currents or thermo-magnetism (Hunt, 1964; Molki, 2010 and Biography of Seebeck). And later he described the observation as "the magnetic polarization of metals and ores produced by a temperature difference" and explained the earth's magnetic field as per the temperature different between the two poles and the equator.



Seebeck's instrument (left) and its experimental use (right)

Figure 1 Seebeck's experimental set up [Courtesy: <http://chem.ch.huji.ac.il/~eugeniik/history/seebeck.html>]

Even though he explained his discovery incorrectly, in fact

his discovery was genuine to reveal the thermocouple and thermoelectricity, he was credited with the discovery of the thermoelectric effect (Biography of Seebeck) and it is known as Seebeck effect after his name to honor him.

Leopoldo Nobili, an Italian physicist, collaborated with Macedonio Melloni, another physicist, to develop a thermoelectric battery/thermopile, in 1826, coupled with galvanometer to measure radiation. For his excellent work some people credit Nobili as inventor of the thermocouple as it is known today, or at least the archetype (Thermocouple History, wiki).

## 2. INTRODUCTION

A series combination of two dissimilar conducting wires (i.e., metal/alloy/semiconductor materials) to form a closed loop which usually generates electricity due to temperature gradient is known as thermocouple as shown in figure 2 and the phenomenon is known as thermoelectric effect. It was introduced first by Seebeck in 1821. Thermocouple has two connecting points/ends called junctions where one is used to sense the radiation or to come in contact with hot body is termed as active or hot junction and another end is usually kept at constant lower temperature is reference or cold junction. Thermoelectric effect is intimately associated with thermocouple. Today, thermocouple is one of the most popular and cost effective temperature sensors. But some people credit Nobili as inventor of the thermocouple due to his incredible work with thermocouples.

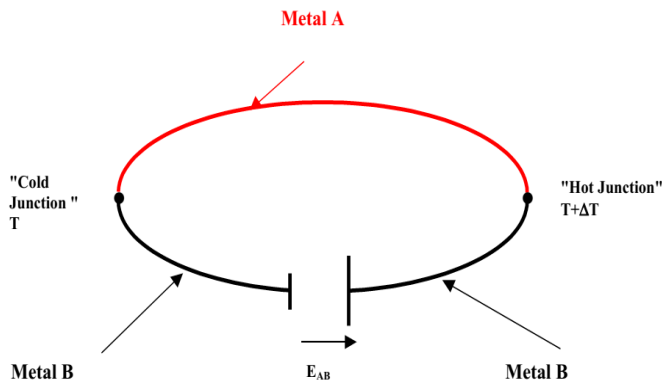


Figure 2 Thermocouple [Courtesy: Weckmann S., 1997]

Randomly chosen any pair of dissimilar wires (or thermocouple) can also produce some thermoelectric outputs as thermo-emf or potential when it is subjected to temperature gradient. In order to produce desirable signal and use for specific purpose one should have to design a thermocouple with taking consideration of range of temperatures over which the device is to be used, expected service life, stability in use, compatibility with various operating environments and their cost.

Selection and types of thermocouple are associated with the useable temperature range, sensitivity and accuracy. For correct compatibility and suitability in use of thermocouple one should be known their types and features. Among the different thermocouples some standard types (Park, Marlin Course) of them are introduced below along with their some important features.

1. Base metal types: In base type thermocouple the material used are mostly copper, iron, and their alloys. These are cheap in cost, operates at lower temperatures, and they have non-magnetic and magnetic response.

Type E, Chromel (nickel-10% chromium) (+) vs. Constantan (nickel-45% copper) (-): Suitable for use in oxidizing or inert atmosphere to  $900^{\circ}\text{C}$  ( $1600^{\circ}\text{F}$ ), for low temperature up to  $-230^{\circ}\text{C}$  ( $-380^{\circ}\text{F}$ ), and develops the highest output emf of any standardized type.

Type J, Iron (+) vs. Constantan (nickel-45% copper) (-): Suitable for use in vacuum, air, oxidizing atmospheres to  $760^{\circ}\text{C}$  ( $1400^{\circ}\text{F}$ ) in the heavier gage sizes. Rapid oxidation of the iron wire at temperatures above  $540^{\circ}\text{C}$  ( $1004^{\circ}\text{F}$ ) limits the expected service life. The positive leg is magnetic and negative is non-magnetic.

Type K, Chromel (nickel-10% chromium) (+) vs. Alumel (nickel-5% aluminum and silicon) (-): Suitable for use in

oxidizing or inert atmospheres at temperatures up to  $1260^{\circ}\text{C}$  ( $2300^{\circ}\text{F}$ ), the positive leg is non-magnetic, while the negative one shows a moderately magnetic response.

Type N, Nicrosil (nickel-14% chromium, silicon) (+) vs. Nisil (nickel-4% silicon, magnesium) (-): Suitable for use to temperature above about  $1000^{\circ}\text{C}$  ( $1832^{\circ}\text{F}$ ), should not be used in vacuum or reducing atmospheres and both are non-magnetic.

Type T, Copper (+) vs. Constantan (nickel-45% copper) (-): Moisture resistant, very stable, both non-magnetic legs and useful to  $-200^{\circ}\text{C}$  ( $-328^{\circ}\text{F}$ ) to  $370^{\circ}\text{C}$  ( $698^{\circ}\text{F}$ ) in air.

2. Noble Metal types: In this case materials used are noble metal platinum and its alloys mostly with rhodium. They are more costly, operates at higher temperatures, recover a significant portion of their initial cost, and have non-magnetic response.

Type S, Platinum-10% rhodium (+) vs. Platinum (-): Recommended for continuous use in air or inert atmospheres in the temperature range  $0$  to  $1480^{\circ}\text{C}$  ( $32$  to  $2696^{\circ}\text{F}$ ), quite stable and capable of long operating life.

Type R, Platinum-13% rhodium (+) vs. Platinum (-): Recommended for continuous use in air or inert atmospheres in the temperature range  $0$  to  $1480^{\circ}\text{C}$  ( $32$  to  $2696^{\circ}\text{F}$ ), quite stable and capable of long operating life.

Type B, Platinum-30% rhodium (+) vs. Platinum- 6% rhodium (-): Recommended for use in clean air at temperatures from  $870$  to  $1700^{\circ}\text{C}$  ( $1598$  to  $3092^{\circ}\text{F}$ ), may be used for brief periods in vacuum, but should not be used in reducing atmospheres nor where exposed to nonmetallic or metallic vapors.

To realize the thermocouple in present form many other scientists: Leopoldo Nobili (1784-1835), A.C. Becquerel, Jean Charles Athanase Peltier (1785-1845), William Thomson (1824-1907), Edmond Becquerel, Avenarius, P.G. Tait, Gustav Magnus, Abram F. Ioffe, H. Julian Goldsmith, Henry Le Cliatelier (known as father of modern thermocouple), Sir William Roberts-Austen, and Edward Matthey have incomparable contributions (Hunt, 1964 and Pollock, 1991).

Thermocouples, extremely versatile and rugged, are primarily simple devices and can be made to very small dimensions. They are capable of operating over a wide range

of temperatures. In addition, they are low in cost and are readily interchanged or replaced. However they do need to be tacit, so that they will measure the quantity that is desired with the precision that is required (Park, Marlin Course).

### 3. THEORIES

The fundamental principle which governs the thermocouple is the thermoelectric effect or Seebeck effect. It is inherently related to the Peltier and Thomson effects. Thus, these are the related theories of thermocouple, explained below, so that thermocouples are employed in our daily life.

**i) Seebeck Effect:** Few months later the Oersted's discovery, in 1820, of magnetic effect of electric current (i.e., magnetism is an electrical phenomenon) Seebeck announced to the Berlin Academy of Science his discovery, in August 1821, that two different metals forming a closed loop, in the absence of moisture, showed magnetic properties when subjected to a difference in temperature at the point of contact. After various experiments with different thermocouples and with the similar results he published his findings about "thermomagnetism" in 1822-1823 as "Magnetische Plarisation der Matalle und Erze durch Temperatur-Differenz". That is, he described the phenomenon as 'thermo-magnetism', taking objection in later years to the expression thermo-electricity (Hunt, 1964). When there is a temperature gradient along the length of a metallic conductor, electrons start to diffuse from one end to the other end of the conductor (Molki, 2010) and develop an electric potential. This phenomenon of inter-conversion of heat energy into electrical energy (as thermoelectric potential called thermo-emf) in a metallic conductor when subjected to temperature gradient can be termed as thermoelectric effect. The thermo-emf so generated depends upon the temperature different between hot & cold ends and nature of the material, which is expressed in equation (1).

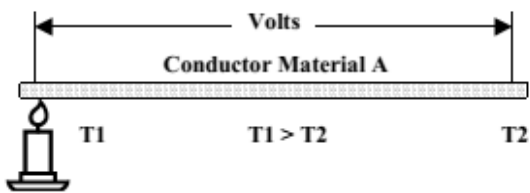


Figure 3 Thermoelectric effect

$$E = S_A (T_1 - T_2) \quad (1)$$

Where E is thermo emf,  $S_A$  is proportional constant called

absolute Seebeck coefficient of material A,  $T_1$  is temperature of the hot end and  $T_2$  is temperature of the cold end. Seebeck coefficient may be positive or negative that depends on nature of the material.

If a thermocouple is subjected to temperature difference, can again be observed thermoelectric effect as long as the junctions are not at same temperature, observed first by Seebeck, is known as Seebeck effect. Seebeck effect is shown in Figure 2. The polarity of the metal A is positive to that of metal B if electron flows from A to B at cold junction (Pollock, 1991). The theory to describe this effect is given in equation 2.

$$E_{AB} = S_A (T_1 - T_2) - S_B (T_1 - T_2) \quad (2)$$

Where  $S_A$  is Seebeck coefficient of metal A,  $S_B$  is Seebeck coefficient of metal B,  $T_1$  is temperature of the hot junction and  $T_2$  is temperature of the cold junction. The electromotive force or emf ( $E_{AB}$ ), that appears in an open circuit is the emf developed by the thermocouple to block the flow of electric current.

$$\text{Or, } E_{AB} = (S_A - S_B) (T_1 - T_2) = S_{AB} (T_1 - T_2)$$

Where,  $S_A - S_B = S_{AB}$  is called relative Seebeck coefficient of thermocouple and its unit is V/K. This coefficient is usually a nonlinear function of temperature.

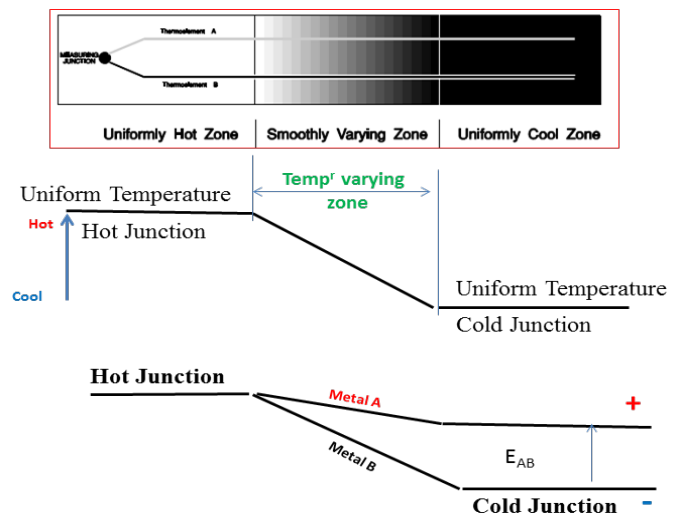


Figure 4 Working of thermocouple: Variation of temperature and emf generation

When both the conductors in thermocouple are made of same material or temperature difference between two junctions does not exist than no thermoelectric/Seebeck effect is observed. Moreover, the relationship between thermo-emf ( $E_{AB}$ ) and temperature of hot junctions is linear up to certain

temperature called neutral temperature but the relation is non linear above that temperature.

Anticipated mechanism of the temperature variation in the thermocouple and hence generation of thermoelectric emf are shown systematically in figure 4. It is clear that, no potential difference between the conductor exists anywhere within the uniform hot zone and within the uniformly cool zone. So, all thermoelectric activity takes place in the middle zone of smoothly decreasing temperature of two metals of different chemical makeup. These dissimilarities will cause each element to respond external stimuli (here, a temperature change) in a different way (Park, Marlin Course).

The electrical potential/emf along any conducting material/thermoelement will change as the local temperature changes. Thus, the small net difference in emf change between two dissimilar conductors/thermoelements constitutes a thermocouple output signal.

It should also be noted that the thermocouple electromotive force (emf) is developed from the measuring junction rather than by that junction.

ii) Peltier Effect: In 1834, thirteen years after Seebeck discovery, Peltier, a French watchmaker cum physicist, discovered that when an electric current flows across a junction of a thermocouple, heat is liberated or absorbed at the junction as shown figure 5. This phenomenon is known as Peltier effect.

The rate of heat liberated or absorbed  $P$  (W) is proportional to the electric current  $I$  (A) flowing in the conductor, that is  $P = P_{AB} I$  (3)

Where  $P_{AB}$  is relative Peltier coefficient in V. This effect is the foundation of thermoelectric refrigeration or heating.

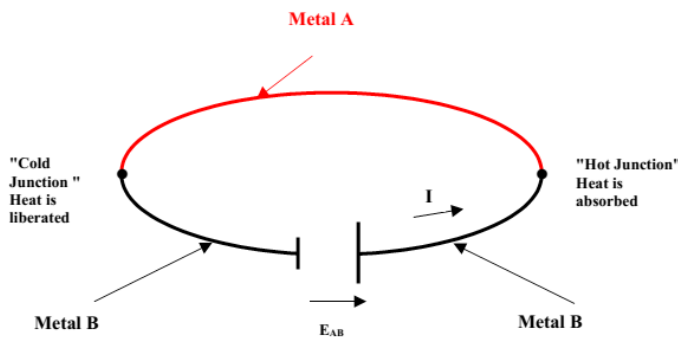


Figure 5. Peltier Effect [Courtesy: Weckmann S., 1997]

iii) Thomson Effect: In 1852, William Thomson discovered that if electric current flows along a single conductor with

temperature gradient than power is either absorbed or rejected, depending on the relative direction of the current and heat flow. This phenomenon is known as Thomson Effect.

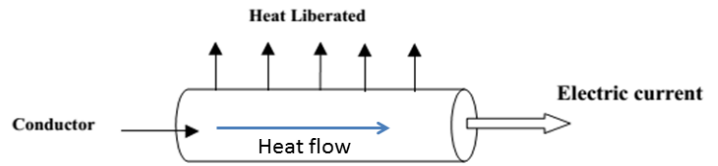


Figure 6 Thomson Effect

The power  $P'$  absorbed or rejected per unit length (W/m) is proportional to the product of the electric current  $I$  (A) and the temperature gradient i.e.

$$P' = \sigma I (\Delta T / \Delta x) \quad (4)$$

Where  $\sigma$  is Thomson coefficient in V/K. It has positive and negative value. When heat is liberated if an electric current flows in the same direction as the heat flows; then this type of material has positive Thomson effect. In metals such as cobalt, nickel, and iron, which have a cooler end at a higher potential and a hotter end at a lower potential, when current moves from the hotter end to the colder end, it is moving from a low to a high potential, there is absorption of energy. When it moves from the colder to the hotter end, there is an energy evolution. This is called the negative Thomson effect (Pollock, 1990 and Thermoelectric effect - Wikipedia).

iv) Thermodynamics of Thermoelectricity: If the emf generated in the thermocouple circuit is  $E_{AB}$  (V), the thermoelectric power is defined as the change in emf per degree Kelvin,  $dE_{AB}/dT$  (V/K), such that the electrical voltage is given by

$$E_{AB} = (dE_{AB}/dT)\Delta T \quad (5)$$

Here,  $dE_{AB}/dT$  is called the thermoelectric power where its dimensions are not power but volts per Kelvin (V/K) so it is called Seebeck coefficient.

Taking into account Peltier effects & Thomson effects along with the conservation of energy in the system, considered as a reversible heat engine, in which a current  $I$  (A) flows, can be written as:

$$(dE_{AB}/dT)\Delta T I = P_{AB} (T + \Delta T) I - P_{AB} (T) I + (\sigma_B - \sigma_A) \Delta T I \quad (6)$$

Where  $P_{AB} (T + \Delta T) I$  is the heat absorbed per second at the hot junction,  $P_{AB} (T) I$  is the heat liberated/sec at the cold junction,  $\sigma_B \Delta T I$  (W) is the heat absorbed/sec in conductor B, and  $\sigma_A \Delta T I$  the heat liberated/sec in conductor A.

Equation (5) reduces into,

$$dE_{AB}/dT = (dP_{AB}/dT) + (\sigma_B - \sigma_A) \quad (7)$$

Thus, electrical Seebeck effect is the result of both the thermal Peltier and Thomson effects. This also proves the relationship among the three effects (Pollock, 1971 and Weckmann, 1997).

#### 4. APPLICATIONS OF THERMOCOUPLES

Thermocouples are working under the principle of Seebeck, Peltier and Thomson effects. Based upon these principles thermocouples are used in various purposes they are given below:

1. Based on thermoelectric effect or Seebeck Effect thermocouple are used as temperature sensors such as in kilns, gas turbine exhaust, diesel engines, other industrial processes and fog machines, thermistor, silicon bandgap temperature sensors and resistance thermometers.
2. Based on the thermoelectric effect, the thermopile (series combination of thermocouples) can be used as a heat sensor in pyranometer to measure solar/thermal radiation.
3. Based on Peltier effect thermocouple can occasionally be used for air conditioning and refrigeration units. But commercial exploitation of the Peltier effect has generally been limited to areas where quick heat and refrigeration is needed and where efficiency is not of utmost importance (Weckmann, 1997).
4. Practical applications of the Thomson effect are few.

#### 5. CONCLUSIONS

Thermocouples, extremely versatile and rugged, are primarily simple devices and can be made to very small dimensions. They are capable of operating over a wide range of temperatures. In addition, they are low in cost and are readily interchanged or replaced. However they do need to be tacit, so that they will measure the quantity that is desired with the precision that is required. To realize the thermocouple in present form many other scientists: Leopoldo Nobili, A.C. Becquerel, Jean Charles Athanase Peltier, William Thomson, Edmond Becquerel, Avenarius, P.G. Tait, Gustav Magnus, Abram F. Iofee, H. Julian Goldsmith, Henry Le Clatelier, Sir William Roberts-Austen, and Edward Matthey have incomparable contributions.

Based upon working principles of thermocouples they are

used in various purposes as: to measure temperature, solar and thermal radiation, air conditioning, refrigeration units etc.

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