3.9 SEEBECK AND PELTIER EFFECTS

In 1821, Thomas Johann Seebeck (1770-1831), an Estonian born and Berlin and Göttingen educated physician, accidentally joined semicircular pieces of bismuth and copper while studying thermal effects on galvanic arrangements [20]. A nearby compass indicated a magnetic disturbance (Fig. 3-9.1). Seebeck experimented repeatedly with different metal combinations at various temperatures, noting related magnetic field strengths. Curiously, he did not believe that an electric current was flowing, and preferred to describe that effect as "thermomagnetism" [21].

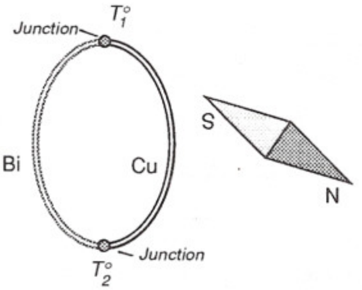

Fig. 3-9.1 Seebeck experimet

If we take a conductor a and place one end of it into a cold place and the other end into a warm place, energy will flow from the warm to cold part. The energy takes the form of heat. The intensity of the heat flow is proportional to the thermal conductivity of the conductor. Besides, the thermal gradient sets an electric field inside the conductor (this directly relates to Thompson effect[1]). The field results in incremental voltage

$$dV_a = \alpha_a \frac{dT}{dx} dx \quad , \tag{3.9.1}$$

where dT is the temperature gradient across small length, dx and α_a is the *absolute* Seebeck coefficient of the material [22]. If the material is homogeneous, α_a is not a function of length and (3.9.1) reduces to

$$dV_a = \alpha_a dT \quad . \tag{3.9.2}$$

To observe the electric current we must form a closed loop with a meter connected in series with the wire (Fig. 3-9.2A). If the loop is made of a uniform material, say cooper, then no current will be observed. Electric fields in the left and right arms of the loop produce equal currents $i_a = i_b$ which cancel one another resulting in zero net current [23]. In order to observe *thermoelectricity*, it

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[1] A Thompson effect was discovered by William Thompson around 1850. It consists of absorption or liberation of heat by passing current through a homogeneous conductor which has a temperature gradient across its length. The heat is linearly proportional to current. Heat is absorbed when current and heat flow in opposite directions, and heat is produced when they flow in the same direction.

is in fact necessary to have a circuit composed of two different materials[1], and we can then measure the net difference between their thermoelectric properties. Fig. 3-9.2B shows a loop of two dissimilar metals which produces net current $\Delta i = i_a - i_b$. The actual current depends on many factors, including the shape and size of the conductors. If, on the other hand, instead of current we measure the net voltage across the broken conductor, the potential will depend only on the materials and the temperature difference. It does not depend on any other factors. A thermally induced potential difference is called the *Seebeck potential*.

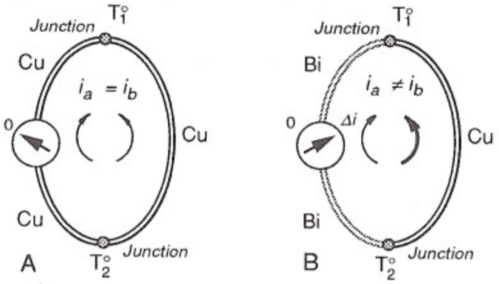

Fig. 3-9.2 Thermoelectric loop
A: joints of identical metals produce zero net current at any temperature difference;
B: joints of dissimilar metals produce a net current Δi

What happens when two conductors are joined together? Free electrons in metal may behave as an ideal gas. Kinetic energy of electrons is a function of the material temperature. However, in different materials, energies and densities of free electrons are not the same. When two dissimilar materials at the same temperature are brought into a contact, free electrons diffuse through the junction [22]. The electric potential of the material accepting electrons becomes more negative at the interface, while the material emitting electrons becomes more positive. Different electronic concentrations across the junction sets up an electric field which balances the diffusion process and the equilibrium is established. If the loop is formed and both junctions are at the same temperature, the electric fields at both junctions cancel each other, which is not the case when the junctions are at different temperatures.

A subsequent investigation has shown the Seebeck effect to be fundamentally electrical in nature. It can be stated that the thermoelectric properties of a conductor are in general just as much bulk properties as are the electrical and thermal conductivities. Coefficient α_a is a unique property of a material. When a combination of two dissimilar materials (A and B) is used, the Seebeck potential is determined from a *differential* Seebeck coefficient

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[2] Or perhaps the same material in two different states, for example, one under strain, the other is not.

$$\alpha_{AB} = \alpha_A - \alpha_B \ , \tag{3.9.3}$$

and the net voltage of the junction is

$$dV_{AB} = \alpha_{AB} dT \ . \tag{3.9.4}$$

The above equation can be used to determine a differential coefficient

$$\alpha_{AB} = \frac{dV_{AB}}{dT} \tag{3.9.5}$$

For example, voltage as function of a temperature gradient for a T-type thermocouple with a high degree of accuracy can be approximated by a second order equation

$$V_{AB} = a_o + a_1 T + a_2 T^2 = -0.0543 + 4.094 \cdot 10^{-2} T + 2.874 \cdot 10^{-5} T^2, \tag{3.9.6}$$

then a differential Seebeck coefficient for the T-type thermocouple is

$$\alpha_{\mathrm{T}} = \frac{dV_{AB}}{dT} = a_1 + 2a_2 T = 4.094 \cdot 10^{-2} + 5.748 10^{-5} T \tag{3.9.7}$$

Table 3-8 Characteristics of some thermocouple types

Junction Materials	*Sensitivity μV/°C (@ 25°C)*	*Temperature Range (°C)*	*Applications*	*Designation*
Copper/Constantan	40.9	-270 to +600	Oxidation, reducing, inert, vacuum. Preferred below 0°C. Moisture resistant	T
Iron/Constantan	51.7	-270 to +1000	Reducing and inert atmosphere. Avoid oxidation and moisture	J
Chromel/Alumel	40.6	-270 to 1300	Oxidation and inert atmospheres	K
Chromel/Constantan	60.9	-200 to 1000		E
Pt (10%)/Rh-Pt	6.0	0 to 1550	Oxidation and inert atmospheres, avoid reducing atmosphere and metallic vapors	S
Pt (13%)/Rh-Pt	6.0	0 to 1600	Oxidation and inert atmospheres, avoid reducing atmosphere and metallic vapors	R

It is seen that the coefficient is a linear function of temperature. Sometimes, it is called the *sensitivity* of a thermocouple junction. A junction which is kept at a cooler temperature is called a *cold junction* and the warmer is a *hot junction*. The Seebeck coefficient does not depend on the nature of the junction: metals may be pressed together, welded, fused, etc. What counts, is the temperature of the junction and the actual metals. In effect, the Seebeck effect is a direct conversion of thermal energy into electric energy.

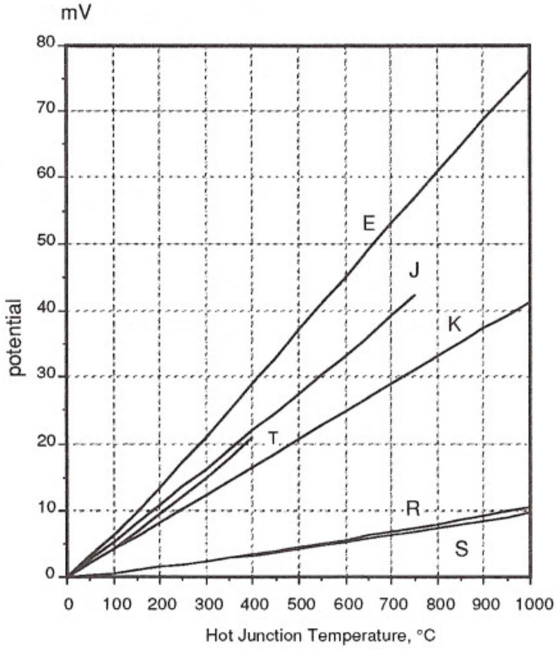

Fig. 3-9.3 Output voltage from standard thermocouples as functions of a cold-hot temperature gradient

In 1826, A. C. Becquerel suggested to use the Seebeck's discovery for temperature measurements. Nevertheless, the first practical thermocouple was constructed by Henry LeChatelier almost 60 years later [24]. He had found that the junction of platinum and platinum-rhodium alloy wires produce "the most useful voltage". Thermoelectric properties of many combinations have been well documented and for many years used for measuring temperature. Table 3-8 gives sensitivities of some thermocouples (@25°C) and Fig. 3-9.3 shows Seebeck voltages for the standard types of thermocouples over a broad temperature range. It should be emphasized that a thermoelectric sensitivity is not constant over the temperature range and it is customary to reference thermocouples at 0°C. Besides the thermocouples, the Seebeck effect also is employed in *thermopiles* which are, in essence, multiple serially connected thermocouples. Nowadays, thermopiles are most extensively used for the detection of thermal radiation (Section 13.7.1). The original thermopile was made of wires and intended for increasing the output voltage. It was invented by James Joule (1818-89) [25].

In the early 19th century, a French watchmaker turned physicist, Jean Charles Athanase Peltier (1785-1845) discovered that if electric current passes from one substance to another (Fig. 3-9.4), then heat may be given or absorbed at the junction [26]. Heat absorption or production is a function of the current direction

$$dQ_P = \pm pidt \ , \tag{3.9.8}$$

where i is the current and t is time. The coefficient p has a dimension of voltage and represents thermoelectric properties of the material. It should be noted that heat does not depend on temperature at the other junction.

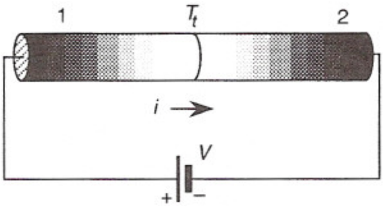

Fig. 3-9.4 Peltier effect

The Peltier effect concerns the reversible absorption of heat which usually takes place when an electric current crosses a junction between two dissimilar metals. The effect takes place whether the current is introduced externally, or is induced by the thermocouple junction itself (due to Seebeck effect).

The Peltier effect is used for two purposes: it can produce heat or "produce" cold, depending on the direction of electric current through the junction. This makes it quite useful for the devices where precision thermal control is required. Apparently, the Peltier effect is of the same nature as the Seebeck effect. It should be well understood that the Peltier heat is different from that of the Joule. The Peltier heat depends *linearly* on the magnitude of the current flow as contrasted to Joule heat[1]. The magnitude and direction of Peltier heat do not depend in any way on the actual nature of the contact. It is purely a function of two different bulk materials which have been brought together to form the junction and each material makes its own contribution depending on its thermoelectric

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[1] Joule heat is produced when electric current passes in any direction through a conductor having finite resistance. Released thermal power of Joule heat is proportional to squared current: $P = i^2/\mathrm{R}$, where R is resistance of a conductor.

properties. The Peltier effect is a basis for operation of thermoelectric coolers which are used for the cooling of photon detectors operating in the far infrared spectral range (Section 13.6) and chilled mirror hygrometers (Fig. 12-9).

In summary, thermoelectric currents may exist whenever the junctions of a circuit formed of at least two dissimilar metals are exposed to different temperatures. This temperature difference is always accompanied by irreversible Fourier heat conduction, while the passage of electric currents is always accompanied by irreversible Joule heating effect. At the same time, the passage of electric current always is accompanied by reversible Peltier heating or cooling effects at the junctions of the dissimilar metals, while the combined temperature difference and passage of electric current always is accompanied by reversible Thomson heating or cooling effects along the conductors. The two reversible heating-cooling effects are manifestations of four distinct e.m.f.s which make up the net Seebeck e.m.f.

$$E_s = p_{AB}|_{T_2} - p_{AB}|_{T_1} + \int_{T_1}^{T_2} \sigma_A dT - \int_{T_1}^{T_2} \sigma_A dT = \int_{T_1}^{T_2} \alpha_{AB} dT \qquad (3.9.9)$$

where σ is a quantity called the Thomson coefficient, which Thomson referred to as the specific heat of electricity, because of an apparent analogy between σ and the usual specific heat c of thermodynamics. The quantity of σ represents the rate at which heat is absorbed, or liberated, per unit temperature difference per unit mass [27, 28].

3.10 MECHANICAL MEASUREMENTS

Mechanical properties of objects were the first ever measured for the engineering purposes, and of all mechanical characteristics, the events of motion were the oldest ever studied. Motion analysis constitutes a part of physics which is known as the *kinematics*. When motion is related to forces, it is studied by *dynamics*. Here we briefly review some fundamental properties both of which can be directly measured by sensors.

Using a vector notation, a *position* of an object with respect to a given system of coordinates can be described by a vector **r** (Fig. 3-10.1A) which mathematically is defined as

$$\mathbf{r} = \mathbf{i}x + \mathbf{j}y \ , \qquad (3.10.1)$$

where **i** and **j** are the unit vectors in x and y directions. This means that a position of an object can be defined by a distance and a direction from a reference point c. When an object moves along a