Direct Energy Convertion: Thermoelectricity

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Electric energy is produced in four ways: electrochemical, electromagnetic, electrostatic, and direct conversion. The product of electrochemical energy conversion is batteries. Electromagnetic conversion tools are generators called alternators or dynamos and are the most widely used electricity generation method today. Electrostatic electricity generation is of two types, friction generators, and triboelectric generators. Friction generators are useful when high voltage low current is needed. Triboelectric generators have become one of the wearable technologies and it is an issue on which a lot of work has been done today. The direct generation of electrical energy without any moving parts is called direct energy conversion. The tools that convert light energy into electrical energy are called photovoltaic cells. The conversion of heat energy into electrical energy is called the thermoelectric effect, and the conversion of sound and vibration energy into electrical energy is called the piezoelectric effect.

Thermoelectric Effect

Thermoelectricity is an environmentally friendly, low-cost, pollutant-free energy conversion technology that involves the conversion of heat energy directly into electrical energy or electrical energy into a heat pump through thermoelectric materials. Thermoelectric devices have no moving parts, so they provide noiseless, reliable and maintenance-free operation. These materials have various applications in temperature sensors, local cooling units, power generation designed for special purposes and waste heat recovery.

Although it is stated in many sources that it was discovered by Thomas Johann Seebeck in 1821, Alessandro Volta observed the thermoelectric phenomenon for the first time. While working on the phenomenon Luigi Galvani called animal electricity, he thought that electrical energy could be caused by temperature, but he did not investigate the effect of temperature because the work shifted to electrochemical interaction (Saini et al., 2021). Seebeck put a compass inside the closed system of copper and bismuth plates and observed that when he heated one of the connection points, the compass needle deviated and this was called the thermomagnetic effect. He mistakenly concluded that this interaction was a magnetic phenomenon and tried to relate the temperature difference between the equator and the poles to the earth's magnetic field.

Hans Christian Ørsted explained that the phenomenon Seebeck observed was not magnetic but electric, and he called this phenomenon the thermoelectric effect (Poudel, 2007). Later, Seebeck, who repeated this event using a large number of materials, some of which we know as semiconductors, arranged the “S.σ” products of these materials in his study and published them in 1823 (Poudel, 2007; Rowe, 1995). Here, “S” is the Seebeck coefficient and “σ” is the electrical conductivity coefficient. 12 years after Seebeck’s discovery, Jean Charles Athanase Peltier discovered a complementary effect. Realizing that when current is passed through a circuit consisting of two dissimilar metals, there is a temperature change around the points where the metals join, Peltier tried to use the Seebeck effect as an electric generator that produces weak current, but failed to explain the basic nature of his observations or relate them to Seebeck’s findings. The true nature of the Peltier effect was explained by Heinrich Friedrich Emil Lenz in 1838. Lenz concluded that this phenomenon was dependent on the direction of the current, and proved with a simple experiment that in an arrangement consisting of two conductive junctions, heat is absorbed at one of the junctions and produced at the other. In this experiment, he observed that after turning the water into ice at one of the intersections, the ice began to melt when the current changed its direction. In 1851, William Thomson (Lord Kelvin) established a relationship between the Seebeck and Peltier coefficients and revealed the existence of a third thermoelectric phenomenon. This phenomenon, called the Thomson effect, was later observed experimentally. In 1885, although John William Strutt Rayleigh calculated the efficiency of the thermoelectric generator incorrectly, he suggested the possibility of using the thermoelectric phenomenon for electricity generation (Rowe, 1995). Edmund Altenkirch presented a very satisfactory theory for the thermoelectric generator and refrigeration. In his work, he showed that a good thermoelectric material should have a low thermal conductivity (κ) and low electrical resistivity (ρ) together with a high Seebeck coefficient (S) to minimize Joule heating and retain heat at junctions (Polozine et al., 2014).

Seebeck Effect

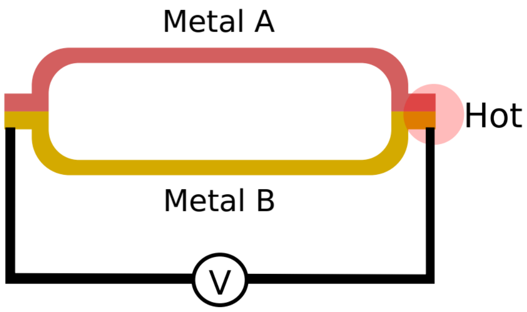

Figure 1. Seebeck Experiment

When two different metal sheets are joined as shown in the Figure 1 and one of the connection points is heated, a potential difference occurs between the junction points. The resulting voltage can be given by the following equation.

$$V=S_{AB}.(T_{Hot}-T_{Cold})$$

“S” is given as the Seebeck coefficient. Valence electrons in the hot region move towards the cold region with the effect of thermal energy. Electrons in the cold region slide towards the warm region. However, since the average momentum of the electrons in the hot region will be higher than in the cold region, a negative charge will occur in the cold region. S_{AB} is the relative Seebeck coefficient of metals with respect to each other.

$$S_{AB}=S_{B}-S_{A}$$

S_A and S_B are the Seebeck coefficients of each metal, with the platinum metal being the reference metal. The Seebeck coefficient is not a fixed value, but changes depending on the average temperature value. The average temperature is the arithmetic average of the temperature of the hot and cold zone. Seebeck coefficients for some metals at room temperature are given in the table below (Lasance, 2006).

Table 1. Seebeck Coefficient of Some Metals (Moffat, 1997).

Metals	Seebeck Coefficient (μV/K)	Metals	Seebeck Coefficient (μV/K)
Antimony	47	Aluminum	3,5
Molibdenum	10	Platinum	0
Tungsten, Cadmium	7,5	Sodium	-2
Copper, Gold, Silver	6,5	Potassium	-9
Rhodium	6,5	Nickel	-15
Tantalum	4,5	Bismuth	-72

Peltier Effect

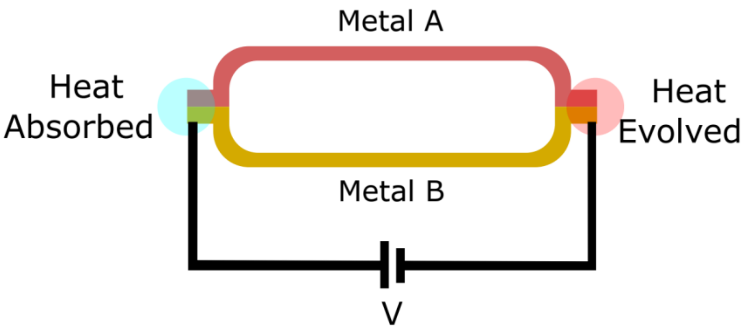

Figure 2. Peltier Circuit

When two different metal sheets are joined as shown in the Figure 2 and voltage is applied between the junctions of metal plates, as shown in the figure, heat is absorbed in one of the connections, while heat is released in the other. Depending on the direction of the current, heat is given or absorbed by the metal pairs. The heat transferred through the metal can be given by the following equation.

$$Q=\pi_{AB}.I$$

“Π” is given as the relative peltier coefficient of metal pairs. The Peltier effect is an inverse process of the Seebeck effect.

Thomson Effect

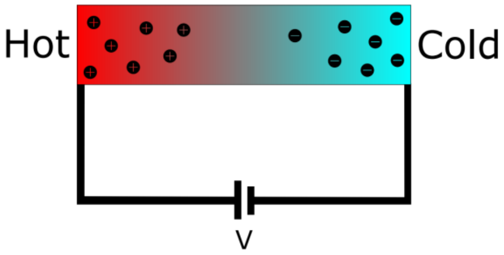

Figure 3. Thomson Experiment

Thomson found that when a current is passed through a wire consisting of a single homogeneous material in which there is a temperature gradient as shown in the figure, the heat must be exchanged with the environment so that the original temperature gradient can be maintained along the wire. As a result of this experiment, he proved that the Peltier effect and the Seebeck effect are interdependent processes. The reversible heat produced in a part of the conductor can be given by the following equation.

$$Q=\rho.I^2-\beta.\Delta T.I$$

Here, in order for ρ to be the resistivity of the material, is the Joule heat, Q is the Thomson heat, ΔT is the temperature difference between the ends of the conductor, I is the current through the conductor, and β is the Thomson coefficient. Interestingly, the total amount of heat produced varies depending on the direction of the current and the type of material. For lead the Thomson heat effect is zero, for copper the hot end exhibits high potential behavior, while for iron the hot end exhibits low potential behavior.

The relationship between the Seebeck coefficient and the Peltier coefficient is given by the following expression.

Figure of Merit and Conversion Efficiency

These desirable traits were represented by Z, which was defined as the quality factor (figure of merit), and was defined as

$$Z=\frac{S^2.\sigma}{k}$$

In this expression obtained by Altenkirch by doing experimental studies, “S” is Seebeck coefficient, “σ” is electrical conductivity and “κ” is thermal conductivity of thermoelectric element. expression is also called power factor. However, according to this definition, the unit of the thermoelectric quality factor (Z) was K^{-1}. For ease of use, the expression was multiplied by the average temperature (T) to become dimensionless ZT (Becker et al., 2008; Bottner et al., 2004).

The maximum efficiency η_{max} for an energy production is given below.

$$\eta_{max} = \frac{\Delta T(\sqrt{ZT+1}-1}{T_H\sqrt{ZT+1}+T_C}$$

Thermoelectric energy conversion is a process that occurs through electron transport and this process accompanies Joule heat and is irreversible. Therefore, the η_{max} expressions in the equation can be reduced to the Carnot efficiency for (Paul, 2013).

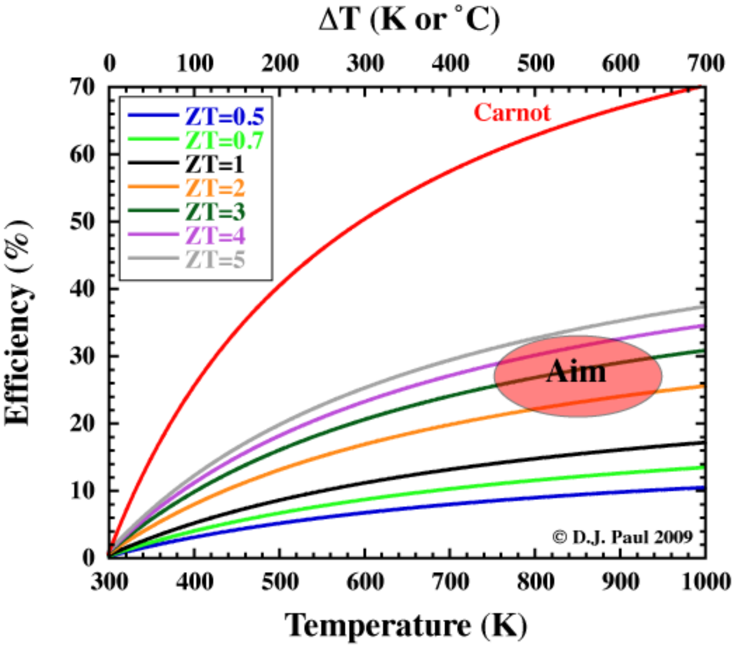

Figure 4. Energy Conversion Efficiency for Some ΔT Values of ZT (Paul, 2013).

According to the graph above, applications where the temperature difference is 600 degrees for a thermoelectric generator with ZT=2 can be commercially preferred.

Thermoelectric Modules

A modern thermoelectric module consists of ingot-shaped "n" and "p" type thermoelement semiconductors connected in series through conductors between two insulating ceramics (Figure 5). When the temperature difference is created between the surfaces of this module, the electrical power is transferred in an external way and the module works like a generator.

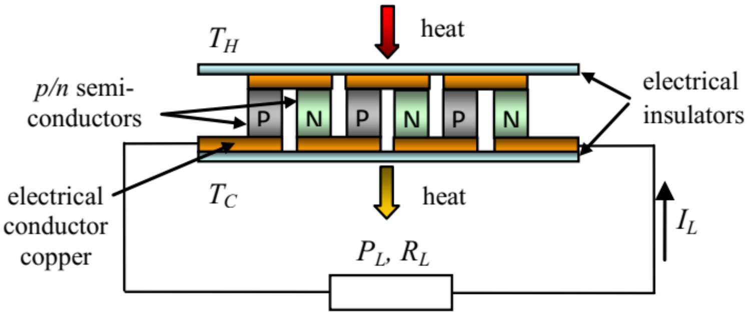

Figure 5. Thermoelectric Modules for Power Generation (Ahiska & Mamur, 2014).

The first commercial thermoelectric generators were produced in 1898 and it have a power of 21 watts. The longest-term use of thermoelectric generators is Radioisotope Thermoelectric Generators used in space probes sent by NASA away from the sun. These devices are closed systems surrounded by many modules with a thermonuclear core in the middle. Many countries continue their research and development activities on these devices, which have been operating for about 20 years without any maintenance and without any change in performance.

References

Ahiska, R., & Mamur, H. (2014). A review: Thermoelectric generators in renewable energy. *International Journal of Renewable Energy Research*, *4*(1), 128–136. https://doi.org/10.20508/ijrer.25996

Becker, T., Kluge, M., Schalk, J., Otterpohl, T., & Hilleringmann, U. (2008). Power management for thermal energy harvesting in aircrafts. *2008 IEEE Sensors*, 681–684. https://doi.org/10.1109/ICSENS.2008.4716533

Bottner, H., Nurnus, J., Gavrikov, A., Kuhner, G., Jagle, M., Kunzel, C., Eberhard, D., Plescher, G., Schubert, A., & Schlereth, K.-H. (2004). New thermoelectric components using microsystem technologies. *Journal of Microelectromechanical Systems*, *13*(3), 414–420. https://doi.org/10.1109/JMEMS.2004.828740

Lasance, C. J. M. (2006). The Seebeck Coefficient. *Electronics Cooling*. http://www.electronics-cooling.com/2006/11/the-seebeck-coefficient/

Moffat, R. J. (1997). Notes on Using Thermocouples. *Electronics Cooling*. https://www.electronics-cooling.com/1997/01/notes-on-using-thermocouples/

Paul, D. J. (2013). *Thermoelectrics*. http://userweb.eng.gla.ac.uk/douglas.paul / thermoelectrics.html

Polozine, A., Sirotinskaya, S., & Schaeffer, L. (2014). History of development of thermoelectric materials for electric power generation and criteria of their quality. *Materials Research*, *17*(5), 1260–1267. https://doi.org/10.1590/1516-1439.272214

Poudel, B. (2007). *A Study On Thermoelectric Properties Of Nanostructured Bulk Materials*. Dissertation, The Graduate School Of Arts And Sciences, Department Of Physics, Boston College.

Rowe, D. M. (1995). *CRC Handbook of Thermoelectrics*. N.Y., CRC press LLC, Boca Raton Florida, USA.

Saini, A., Kumar, R., & Kumar, R. (2021). Introduction and brief history of thermoelectric materials. In *Thermoelectricity and Advanced Thermoelectric Materials* (pp. 1–19). Elsevier. https://doi.org/10.1016/B978-0-12-819984-8.00012-6

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