Direct Energy Conversion: Thermoelectric Conversion

References:

Direct Energy Conversion *by Stanley W. Angrist, Allyn and Beacon, 1982.*

Direct Energy Conversion *by Reiner Decher, Oxford University press, 1997.*
Direct Energy Conversion

The best achievable thermal efficiency for electricity generation with conventional methods is about 50%.

In general when a process can occur directly rather than passing through several intermediate steps, it is reasonable to expect that it may take place more efficiently.

Fuel cells (a mode of direct energy conversion) have already demonstrated a capability of producing small quantities of electrical energy with considerable efficiency.

The ability to convert primary energy directly into the required form at its point of use would be of great use in many systems (distributed power, space exploration, satellites, remote weather stations etc.).
Thermoelectric Effect

One of the ways to directly convert the thermal power to electric power is through thermoelectric generators.

In metals and semiconductors, electrons are free to move in the conduction band. They respond to electric fields, which establish a flux of charges or current. These electrons can also respond to a gradient of temperature so as to accommodate a flow of heat.

The motion of the electrons transports both their charge and their energy. At junctions of dissimilar materials the electrons flow across a discontinuity in the energy levels of the conduction bands. If the spectrum of electron quantum states is different in the two materials, the crossing of negatively charged electrons or positively charged holes will not preserve the statistical distribution of electrons around the Fermi level.

\[
f(E) = \frac{1}{\frac{E - \mu_i}{e kT} + 1}
\]

Where \( E \) is the electron energy and \( k \) is the Boltzmann’s constant. The maintenance of the current may require addition or removal of heat (thermoelectric generator) or heating the junction will increase or decrease the electric current.
Seebeck Experiment

Seebeck Coefficient: When two ends of a conductor of material \( a \) are maintained at different temperatures, say \( \Delta T = T_1 - T_2 \), Seebeck observed in 1822 that a voltage \( V \) (varies with \( \Delta T \)) can be measured when the current is zero. The *Seebeck coefficient* is then defined as

\[
\alpha_{ab} \equiv \lim_{\Delta T \to 0} \frac{\Delta V}{\Delta T}
\]

\[
V = \int_{T_1}^{T_2} \alpha_{ab} dT
\]

This equation can be interpreted as that the electrons will acquire an electric potential as they are transported from region of varying thermal energies. Energies are measured by their temperatures.
# Seebeck Coefficient

<table>
<thead>
<tr>
<th>Material</th>
<th>$\alpha$ (µV/K)</th>
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<tbody>
<tr>
<td>Al</td>
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<tr>
<td>Constantan</td>
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<td>Cu</td>
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<tr>
<td>Si</td>
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Peltier Experiment

Peltier Coefficient: Consider two bars of material $a$ and $b$ that are joined with a current source as shown in the figure below. Peltier observed in 1844 that the current flow results in the evolution of heat in an amount proportional to the current and the heat is absorbed when the current is reversed, known as Peltier effect. It is quantified through a proportionality constant associated with a particular junction of materials. The Peltier coefficient is defined as the ratio of heat evolved to current flowing:

$$\pi_{ab} = \frac{Q}{I}$$
Junction of two Dissimilar Materials

The rate at which heat must be removed from the junction in order to maintain the temperature constant:

\[ q_j = I^2 R_j + I(\pi_{T(A)} - \pi_{T(B)}) \text{ watts} \]

\[ q_j = I^2 R_j + IT(\alpha_A - \alpha_B) \text{ watts} \]

The rate at which electrical work is done on the junction with resistance \( R_j \) is the current times the potential drop across the junction

\[ IV_{A,B} = I^2 R_j \]
Thomson Effect: Lord Kelvin (William Thomson) in 1854 realized that a relation between Seebeck and Peltier effects should exist and derived a relationship from thermodynamic arguments. This third thermoelectric effect, now known as Thomson effect is a lateral heating or cooling effect that takes place in a homogeneous conductor when an electric current passes in the direction of a temperature gradient.

A unit length of bar with temperature gradient evolves heat in excess of joule dissipation ($I^2R$) when current flows as represented in the figure below. The Thomson coefficient is given by

$$\gamma \equiv \lim_{\Delta T \to 0} \frac{\frac{1}{I} \frac{\Delta Q}{\Delta T}}{T_2 - T_1}$$

$$Q = \int_{T_1}^{T_2} \gamma dT$$
Heat developed is greater or less than $I^2R$ depending upon the magnitude and direction of the current.

The rate at which heat must flow out the sides of the rod in order for the temperature at every point in the rod to be maintained constant:

$$q_s = I\Delta V + I\pi_{T(1)} - I\pi_{T(2)} = I[\Delta V + (T + \Delta T)\alpha_1 - T\alpha_2]$$

Since

$$\alpha_1 = \alpha_2 + \frac{d\alpha}{dT}\Delta T$$

$$q_s = I\left(\Delta V + T\frac{d\alpha}{dT}\Delta T + \alpha\Delta T\right)$$

Since the voltage drop across the rod is $\Delta V = IR - \alpha\Delta T$

$$q_s = I^2R + I\left(T\frac{d\alpha}{dT}\Delta T\right)$$

Thomson heat
Thermoelectric Interactions

The three effects and the constants that describe them are related through energy balance that must apply around a circuit. The balance states that the electrical power generated as a result of temperature difference maintained across a junction equals to the heat dissipated at the two junctions and through the two bars.

\[
\int_{T_1}^{T_2} \alpha_{ab} IdT = \left( \pi_{ab_2} - \pi_{ab_1} \right) I + \int_{T_1}^{T_2} \left( \gamma_a - \gamma_b \right) IdT
\]

or

\[
\alpha_{ab} = \frac{d\pi_{ab}}{dT} + (\gamma_a - \gamma_b)
\]

The entropy generated at the two junctions, where the temperatures differ, gives

\[
\Delta s = \left( \frac{\pi_{ab_2}}{T_2} - \frac{\pi_{ab_1}}{T_1} \right) I
\]

\[
\int_{T_1}^{T_2} Id \left( \frac{\pi_{ab}}{T} \right) + \int_{T_1}^{T_2} I \left( \frac{\gamma_a - \gamma_b}{T} \right) dT = 0
\]

\[
\frac{d\pi_{ab}}{dT} - \frac{\pi_{ab}}{T} + (\gamma_a - \gamma_b) = 0
\]

\[
\frac{\pi_{ab}}{T} = \alpha_{ab}
\]
Thermoelectric Generator

- **Heat input**
- **Hot junction**
- **Cold junction**
- **Electrical Power output**
- **p-type**
- **n-type**
- **Heat rejected**
- **$T_H$**
- **$T_C$**
- **$R_o$**
Thermoelectric generators are useful devices for converting heat energy directly into electrical energy.

In a thermoelectric generator a heat flux induces a potential difference across a junction of dissimilar materials.

The output voltage $\Delta V$, and input heat flux, $q$ is given by

$$
\Delta V = \alpha \frac{\Delta T}{T} - R I
$$

$$
q = C \frac{\Delta T}{T} + \alpha I
$$

Where $\Delta T$ is the temperature drop through the device in the direction of the heat flux $q$, $\Delta V$ is the potential rise through the device in the direction of $I$, $\alpha$, $R$ and $C$ are interaction, resistance and conductance coefficients respectively.

Thermoelectric Generator

The $p$ and $n$ legs have thermal and electrical conductivities $k_i$ and $\sigma_i$ respectively ($i$ refers to either $p$ or $n$). The conductance $k$ of a bar of length $l$ and cross sectional area $A$ is given by

$$K_i = k_i \frac{A_i}{l_i}$$

The electrical resistance $R$ of a bar of length $l$ and cross sectional area $A$ is given by

$$R_i = \sigma_i \frac{l_i}{A_i}$$
Thermoelectric Generator

The first equation indicates that the voltage difference measured across the terminals of the device is proportional to the internal resistance and to the temperature difference applied to the generator. In the second equation we see that the heat flux is proportional to the temperature difference and to the current through the device. Thus under open circuit conditions with zero current the ratio $C/T$ represents the internal thermal conductance (the thermal conductivity $\lambda = q/(A\Delta T)$ of the generator $K$:

$$K = \frac{C}{T} = \frac{\lambda_n A_n}{l_n} + \frac{\lambda_p A_p}{l_p} \quad \text{(watts/°K)}$$

and

$$R = \frac{\rho_n l_n}{A_n} + \frac{\rho_p l_p}{A_p} \quad \text{(ohms)}$$

where, $\rho = A\frac{\Delta V}{ll}$

In addition, we define $\alpha$ to be the Peltier coefficient, $\pi_T$, the heat transfer per unit current for the particular combination of materials that make up the generator.

$$\pi_T = \pi_{1n} + \pi_{1p} \quad \text{(watts/amp)}$$

and

$$\alpha_1 = \frac{\alpha}{T} = \frac{\alpha_n + \alpha_p}{T} \quad \text{(volts/degree)}$$
Thermal Efficiency

Where $\alpha_1$ is defined as the Seebeck Coefficient, the voltage rise per unit of temperature for a particular combination of materials for the device.

The dissipation (the difference between the maximum possible work rate and the actual work rate) for the device is given by

$$D = C \left( \frac{\Delta T}{T} \right)^2 + RI^2$$

The dissipation can also be represented as the product of the entropy generation times the absolute temperature.

The thermal efficiency is defined as the ratio of the electrical power output $P_o$ to the thermal input $q_H$ to the hot junction

$$\eta_t = \frac{P_o}{q_H}$$
The thermal input to the hot junction is given by

\[ q_H = K\Delta T + \alpha_1 T_H I - \frac{1}{2} I^2 R \]

and

\[ P_o = I^2 R_o \]

where \( R_o \) is the load resistance. The open circuit voltage is \( \alpha \Delta T \), so the electric current drawn from the generator is

\[ I = \frac{\alpha_1 \Delta T}{R + R_o} \]

The thermal efficiency may be computed from

\[ \eta_t = \frac{I^2 R_o}{K\Delta T + \alpha_1 T_H I - \frac{1}{2} I^2 R} \]
Figure of Merit

Good thermoelectric materials should possess large Seebeck coefficients, high electrical conductivity and low thermal conductivity. A high electrical conductivity is necessary to minimize Joule heating, whilst a low thermal conductivity helps to retain heat at the junctions and maintain a large temperature gradient. These three properties were later embodied in the so-called figure-of-merit, Z. Since Z varies with temperature, a useful dimensionless figure-of-merit can be defined as $ZT$

The figure-of-merit of a thermoelectric material is defined as:

$$Z = \frac{\alpha^2 \sigma}{\lambda}$$

Where $\alpha$ is the Seebeck coefficient of the material (measured in microvolt/K), $\sigma$ is the electrical conductivity of the material and $\lambda$ is the total thermal conductivity of the material.
Thermoelectric Generator

Introduce the ratio of load resistance to the internal resistance \( m' \), in the previous equation

\[
m' = \frac{R_o}{R}
\]

and after some manipulation result in the following

\[
\eta_t = \frac{m' \left( \frac{\Delta T}{T_H} \right)}{(1 + m')^2 + (1 + m') - \frac{1}{2} \frac{\Delta T}{T_H}}
\]

where

\[
Z^* = \frac{\left( |\alpha_{n}| + |\alpha_p| \right)^2}{\left( \rho_n \lambda_n \right)^{\frac{1}{2}} + \left( \rho_p \lambda_p \right)^{\frac{1}{2}}}
\]

\[
T_{av} = \frac{T_c + T_H}{2}
\]
Thermoelectric Generator
Multistage generators

The output voltage for N couples is simply N times the voltage of a single couple, where as the current is the same as for a single couple. The optimal load resistance is n times the optimal load resistance of a single stage device, whereas the electrical power output and thermal input increase linearly with N. thus the thermal efficiency is independent of the number of couples.
Ground Source Thermoelectric Generator

\[ \Delta T \sim 20^\circ - 30^\circ F \]

\[ \eta_{TEG} = 0.15 \eta_{Carnot} \]
Thermopile: A thermopile is made of thermocouple junction pairs connected electrically in series.
Radioisotope Thermoelectric Generators

An RTG basically consists of two parts: a source of heat and a system for converting the heat to electricity. The heat source contains a radioisotope, such as plutonium-238, that becomes physically hot from its own radioactivity decay. This heat is converted to electricity by a thermoelectric converter which uses the Seebeck effect. An electromotive force, or voltage, is produced from the diffusion of electrons across the junction of two different materials (e.g., metals or semiconductors) that have been joined together to form a circuit when the junctions are at different temperatures.

Doping semiconductor materials such as silicon-germanium with small amounts of impurities such as boron or phosphorus produces an excess or deficiency of electrons, and therefore makes the semiconductor a more efficient power converter than metals. The joining of these thermoelectric materials with hot radioisotopes produces a reliable source of power with no moving parts. The temperature difference between the hot and cold junctions is about 700 K (800 deg F).
To generate power, fuel is contiguously burned in a ceramic tube which glows red-hot. The photovoltaic cells which surround the tube receive the infrared (IR) photons from this emitter and convert them to electric power. In effect, "solar" cells are used with a small manmade "sun" created by burning methane. However, because this "sun" is only 1" away from the cell, IR power intensities at the cell are one thousand times higher than the sunlight on the roof of a car. Unlike an internal combustion engine, fuel is burned continuously without periodic explosions. Combustion is complete and clean.