ENERGY TRANSPORT AND CONVERSION AT THE NANOSCALE

Thermoelectrics and Renewable Energy Applications

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Abstract

Solar radiation is the most readily available source of renewable energy, and harnessing it is crucial in meeting our energy needs without having negative consequences on our environment. Using thermoelectric devices, we can utilize the heat from solar energy and industrial waste to convert directly to electricity. We will discuss thermoelectrics (TE) and the underlying principles of energy generation. Then we will discuss TE modules and their use in Solar Thermal Energy Generators, as well as methods to increase efficiency of thermoelectrics.

1 Introduction

Thermoelectric (TE) devices use heat gradients to create a voltage through the Seebeck effect (see section 2.1). This voltage thus creates a current which can be used for a source of electricity. Figure 1 shows a thermoelectric device schematic, which is further discussed in section 2.2.

One very important aspect of thermoelectrics is the figure of merit, ZT, of the device. See equation 1, where $S$ is the Seebeck coefficient, $\sigma$ is the electrical conductivity, $k$ is the thermal conductivity, and $T$ is the temperature. The larger the figure of merit, the more efficient a device is in energy generation. The typical value for ZT is currently around 1.

$$ZT = \frac{S^2 \sigma}{k T}$$

One of the main issues with increasing the figure of merit is the inverse relationship between $\sigma$ and $S$. For example, metals tend to have high electrical conductivity but low Seebeck coefficients, while the opposite is true of semiconductors. Optimizing ZT is thus not trivial; however, there are a few ways to increase electrical output and make TE devices more efficient.

2 Background Information

2.1 Seebeck Effect

Equation 2 shows the Seebeck effect, where $V$ is the voltage created by $\Delta T$, the temperature gradient across the device. $S$ is the Seebeck coefficient, which is a property of material used.

$$\Delta V = S \Delta T$$

Because of this phenomenon, the larger the temperature gradient, the larger the voltage created. Due to Ohm’s Law, larger voltages will increase electrical generation as well.

Figure 1: Thermoelectric device.
2.2 Thermoelectric Module Structure

As shown in Figure 1, a thermoelectric device uses a temperature gradient across two legs to create a current used for electrical output. The p leg is made of p-type material, meaning that the charge carriers are positive holes. The other leg is n-type, meaning that the charge carriers are negative electrons. Upon creating a temperature difference between the heat source and heat sink, the charge carriers move toward the heat sink, creating a net flux of charge and therefore leading to current flow.

3 Why Thermoelectrics?

Technologies like photovoltaics (PV) already offer a way to harness solar thermal energy, and the current efficiency of these devices is significantly higher than thermoelectrics. A typical efficiency value for PV arrays is roughly 30%, while current solar thermal energy generators have an efficiency of around 4%. However, there are two main reasons why we are interested in developing thermoelectrics.

Firstly, thermoelectrics do not rely solely on solar energy sources. Because TE devices only need a temperature gradient, they are much more versatile than PV arrays. Figure 2 shows the difference in the ranges of the solar spectrum in which each type of system can operate. This also means that TE devices can take advantage of waste heat sources, while PV cannot. Energy losses contribute 15% of energy consumption in industrial sectors, so making use of the waste heat created could generate a significant amount of energy.

Secondly, increases in the figure of merit in the near future promise large increases in the efficiency of TE devices that would make said devices practical. Section 5 describes two main methods of increasing electrical output.

4 Solar Thermal Electric Generators

Solar Thermal Electric Generators (STEGs) utilize thermoelectrics to convert heat from concentrated solar energy to electricity. See figure 3. The incident sunlight is concentrated on a thermal absorber, which acts as the heat source. A TE module is placed between this heat source and a cooling system, which acts as the heat sink. The system is encapsulated in a vacuum in order to reduce losses from convection, due to the lack of medium through which convection can travel. This
allows for a maximized temperature gradient by limiting heat losses to the environment caused by high temperature of concentrated light compared to ambient temperature.

It is possible to introduce tracking systems to capture more direct sunlight, but since low power STEGs are typically preferred, they can have a static concentrator; this means that there are no moving parts in the system. This limits the concentration ratio (the ratio of the optical concentration area to the absorber area upon which light is focused), but lowers overall cost. Overall efficiency would be lowered without the tracking aspect, but because TE devices only require the heat from sunlight, it does not matter whether said heat is from direct or diffuse light for full operation.

The efficiency of TE devices relies on efficiencies of both the absorber and TE module. These two efficiencies have an inverse relationship, further complicating optimization. Equation 3 shows that TE efficiency increases with an increase in $T_h$. However, the absorber efficiency decreases as a function of $T_h$ because of the dependence of radiative losses on $T_h$. This dependence can be seen in equation 4. As temperature increases, $q_{rad}$ increases, indicating that more heat is lost. As heat is lost to $q_{rad}$, less heat can be utilized by the absorber. See Appendix A for nomenclature.

\[
\eta_{TE} = 1 - \frac{T_c}{T_h} \eta_r \quad (3)
\]

\[
q_{rad} = A_{abs} \pi \int_0^\infty \epsilon_s(E) \frac{2E^3}{c^2 h^3 (e^{\frac{E}{kT}} - 1)} dE \quad (4)
\]

For the purpose of this research, we will focus on increasing the efficiency of the TE module only.

5 Increasing Efficiency

5.1 Increasing $\Delta T$

Equation 2 shows that an increase in $\Delta T$ causes an increase in voltage, and therefore electrical output. Thus, we need to maximize the temperature gradient across the device. However, since every material has an optimal temperature range, increasing $\Delta T$ may be problematic. In order to effectively increase this temperature range, we can segment our materials as shown in figure 4.

In this segmented structure, it is possible to find an ideal ratio between the segment lengths in each the p- and n-leg. This relationship is shown in equation 5, where the $i^{th}$ index represents one of the segments in either the p- or the n-leg. See Appendix A.

\[
\frac{k_i \Delta T_i}{l_i} = \frac{k_{i+1} \Delta T_{i+1}}{l_{i+1}} \quad (5)
\]
Using theoretical values of $T_h=1050^\circ C$ and $ZT=2$, the efficiency of a STEG would be roughly 24%. This value of $T_h$ can be obtained by increasing the concentration ratio (section 4), but this value is currently theoretical.

5.2 Decreasing Thermal Conductivity, $k$

As shown in equation 1, the figure of merit is inversely proportional to the thermal conductivity. Since it is difficult to optimize the numerator of $ZT$ as previously mentioned, we can use geometry to decrease thermal conductivity without needing to change material properties. By nanostructuring the legs of our TE device, we can increase the effect of boundary scattering, therefore limiting the mean free path of our phonons and decreasing the ability to transfer heat from the heat source to the heat sink.

Another way to limit thermal conductivity is by using nanocomposites, which is a method to increase impurities in the material used. Phonon-impurity scattering is thus increased, which decreases thermal conductivity as well.

One problem that each of these methods creates is the high cost of nanofabrication for such a small relative output. Ideally, these TE devices could be manufactured at a lower cost, and with macroscopic qualities in order to produce a product that can be scaled to larger applications (with larger energy outputs). This leads us to consider the limitations of current TE technology.

6 Limitations

As mentioned previously, the optimization of $ZT$ on a macroscopic scale is very difficult due to the inverse relationship between the Seebeck coefficient, $S$, and electrical conductivity, $\sigma$. Thus, nanoscale applications seem to be the only current method of increasing the efficiency of thermoelectric device. This presents another problem, however, as nanoscale applications are both expensive and hard to use in large-scale applications.

In the future, if thermoelectrics are to be used as a practical means for renewable energy generation, we must find methods to increase $ZT$ to a value of roughly 2 without requiring nanostructuring or nanocomposites. With this increase in the figure of merit, thermoelectrics present a method of energy generation with efficiencies on par with photovoltaics, without the need for strictly solar radiation.
7 References


A Nomenclature (in order of appearance)

- $\Delta T$ - Temperature difference across device
- $\Delta V$ - Voltage across device
- $S$ - Seebeck coefficient (material dependent)
- $\eta_{TE}$ - Thermoelectric efficiency
- $\eta_r$ - Reduced efficiency (fraction of $dT/T$)
- $q_{rad}$ - Radiative heat loss from absorber surface
- $A_{abs}$ - Area of absorber surface
- $\epsilon_s(E)$ - Spectral emissivity
- $E$ - Energy
- $k$ - Thermal conductivity
- $l$ - Segment length