Thermoelectric Energy Harvesting

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Abstract

Temperature gradients and heat flow are omnipresent in natural and human-made settings and offer the opportunity to harvest energy from the environment. Thermoelectric energy harvesting (or energy scavenging) may one day eliminate the need for replacing batteries in applications such as remote sensor networks or mobile devices. Particularly attractive is the ability to generate electricity from body heat that could power medical devices or implants, personal wireless networks or other consumer devices. This talk will discuss the design principles for thermoelectric generators in energy harvesting applications, and the various thermoelectric generators available or in development. Such design principles provide good estimates of the power that could be produced and the size and complexity of the thermoelectric generator that would be required.

Harvesting Heat

Environments that naturally contain temperature gradients and heat flow have the potential to generate electrical power using thermal to electric energy conversion. The temperature difference provides the potential for efficient energy conversion, while heat flow provides the power. Even with Large heat flow, however, the extractable power is typically low due to low Carnot and material efficiencies. In addition, limited heat availability will also limit the power produced. Nevertheless, for systems with exceptionally low power requirements, such as remote wireless sensors, thermoelectric energy harvesting has shown to be a viable technology and promise to become more prevalent as the power requirements for such applications drop [1].

A good example of thermoelectric energy harvesting is the thermoelectric wristwatch which converts body heat into the electrical power that drives the watch. At least two models have been built, one by Seiko and another by Citizen. The Seiko watch [2] under normal operation produces 22 μW of electrical power. With only a 1.5 K temperature drop across the intricately-machined thermoelectric modules, the open circuit voltage is 300 mV, and thermal to electric efficiency is about 0.1%.

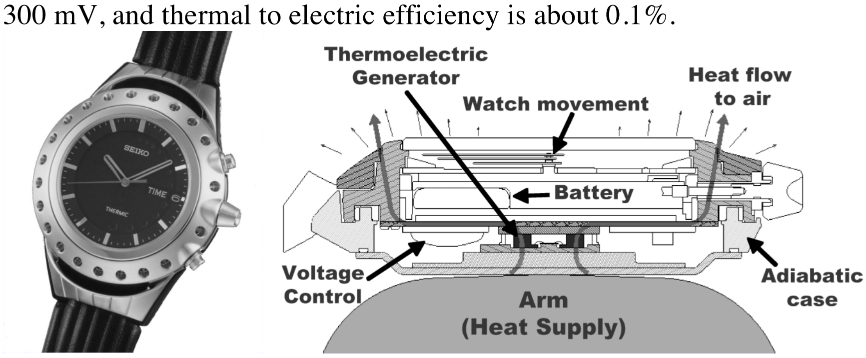

Figure 1. Seiko Thermic, a wristwatch powered by body heat using a thermoelectric energy harvester. (left) the watch, (right) cross-sectional diagram. Copyright by Seiko Instruments Inc., reprinted with permission.

Thermoelectric Generators

Thermoelectric generators are solid state devices with no moving parts. They are silent, reliable, and scalable, making them ideal for small, distributed power generation and energy harvesting.

The thermoelectric effects arise because charge carriers in metals and semiconductors are free to move much like gas molecules while carrying charge as well as heat.[3] When a temperature gradient is applied to a material, the mobile charge carriers at the hot end preferentially diffuse to the cold end. The build-up of charge carriers results in a net charge (negative for electrons, e^-, positive for holes, h^+) at the cold end, producing an electrostatic potential (voltage). An equilibrium is thus reached between the chemical potential for diffusion and the electrostatic repulsion due to the build-up of charge. This property, known as the Seebeck effect, is the basis of thermoelectric power generation.

Thermoelectric devices contain many thermoelectric couples (Fig. 2a) consisting of n-type (containing free electrons) and p-type (containing free holes) thermoelectric elements wired electrically in series and thermally in parallel (Fig. 2b). The best thermoelectric materials are heavily doped semiconductors.

A thermoelectric generator utilizes heat flow across a temperature gradient to power an electric load through the external circuit. The temperature difference provides the voltage ($V = \alpha \Delta T$) from the Seebeck effect (Seebeck coefficient α) while the heat flow drives the electrical current, which therefore determines the power output. The rejected heat must be removed through a heat sink. The thermoelectric *figure of merit* of the materials (zT) depends on the Seebeck coefficient (α), absolute temperature (T), electrical resistivity (ρ), and thermal conductivity (κ) of the material:

$$zT = \frac{\alpha^2 T}{\rho \kappa} \quad (1)$$

The maximum efficiency of a thermoelectric device is determined by its figure of merit (ZT), which is largely an average of the component materials' zT values.

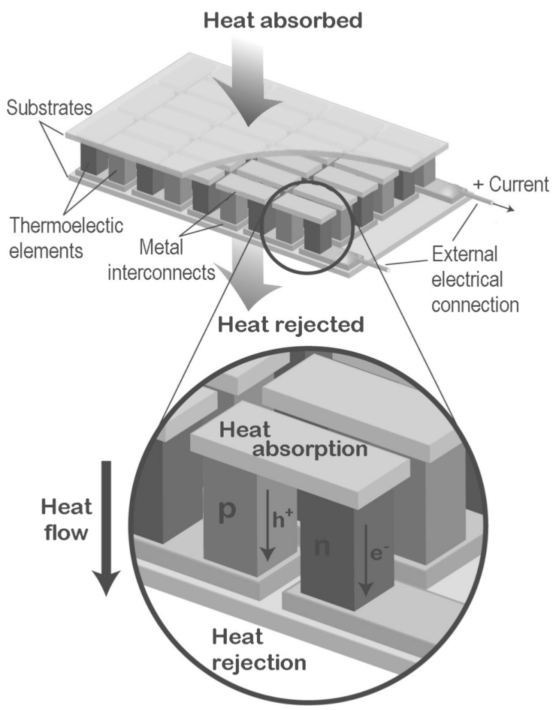

Figure 2. Schematic of a thermoelectric generator. Many thermoelectric couples (inset bottom) of n-type and p-type thermoelectric materials are connected electrically in series and thermally in parallel to make a thermoelectric module (top) or thermopile. The height of the thermoelectric elements and the area of the substrates are used to determine the thermal resistance of the module (see equation 14). Copyright Nature Publishing Group [3], reprinted with permission.

For the past 40 years, solid-state thermoelectric generators have reliably provided power in remote terrestrial and extraterrestrial locations, most notably on deep space probes such as *Voyager*. One key advantage of thermoelectrics is their scalability to small sizes, making them the most appropriate thermal-to-electric technology for energy harvesting.

Design of a Thermoelectric Energy Harvester

Energy harvesting systems, by their nature of using natural chemical-potential gradients, are best designed for their particular environment and are typically not amenable to a one-size-fits-all solution. This is in stark contrast to batteries where the chemical-potential gradient is known, stable, and well regulated as it is an integral part of the power source. Thus a battery can supply similar voltage and power in many different environments, but the power output of an energy harvester could vary by orders of magnitude depending on its location and use.

General Considerations

Viable energy harvesting systems need to outperform a battery solution in terms of energy density, power density, and/or cost. Typically the niche for energy harvesting is in long lived applications where energy density is critical and routine maintenance (replacing batteries) is not an option. A likely scenario for use of an energy harvester is as a means of recharging a battery. In this case the battery supplies high power (mW or W) during a short period of time (e.g. sensing and communications for few seconds or ms), while the majority of the time the energy harvester trickle charges the battery (μW).

While heat is a form of energy, the useful work content of heat is limited by the Carnot factor,

$$\eta_{Carnot} = \frac{\Delta T}{T_h} \tag{2}$$

where $\Delta T = T_h - T_c$ is the temperature difference across the thermoelectric. This puts thermoelectric energy harvesting at a distinct disadvantage compared to other forms of energy harvesting that are not Carnot limited. Visible light, for example has high useful work content that enables photovoltaics to outperform thermoelectrics when sunlight or bright lighting is available. Photovoltaics can produce 100 mW/cm^2 in direct sunlight and about 100 μW/cm^2 in a typically illuminated office—significantly more than the wristwatch in Fig. 1.

Thermoelectric Efficiency

A thermoelectric generator converts heat (Q) into electrical power (P) with efficiency η.

$$P = \eta Q \tag{3}$$

The maximum efficiency of a thermoelectric converter depends heavily on the temperature difference ΔT_{TE} across the device. This is because the thermoelectric generator, like all heat engines, can not have an efficiency greater than that of a Carnot cycle (Eq. 2).

$$\eta = \Delta T_{TE} \frac{\eta_r}{T_h} \tag{4}$$

Here η_r is the reduced efficiency, the efficiency relative to the Carnot efficiency.

While the exact thermoelectric materials' efficiency is complex [4], the constant properties approximation (Seebeck coefficient, electrical conductivity, and thermal conductivity independent of temperature) leads to a simple expression for efficiency:

$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h} \tag{5}$$

Here ZT is the thermoelectric *device figure of merit*. Figure 3 shows this is quite a good approximation for a typical commercial thermoelectric device made from bismuth telluride alloys. The efficiency of an actual thermoelectric device should be about 90% of this value due to losses from electrical interconnects, thermal and electrical contact resistances, and other thermal losses.

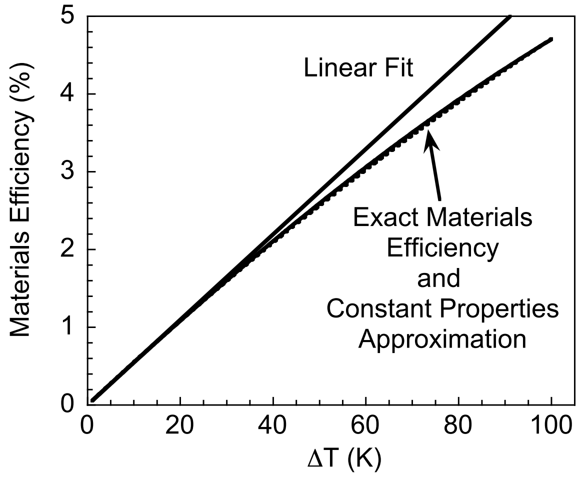

Figure 3. Efficiency of a bismuth telluride based thermoelectric module (cold side at 300K, assuming no additional losses).

The efficiency of a thermoelectric generator increases nearly linearly with temperature difference (Fig. 3), indicating η_r/T_h (Eqn. 4) is fairly constant. In energy harvesting applications where the temperature difference ΔT is small the efficiency is, to a good approximation, directly proportional to the ΔT across the thermoelectric. For good bismuth telluride devices the efficiency is approximately 0.04% for each 1 K of ΔT.

$$\begin{aligned} \eta &= \eta_1 \cdot \Delta T \\ \eta_1 &\approx 0.05\% / K \end{aligned} \tag{6}$$

Matched Thermal Resistance

If the temperature across the thermoelectric, ΔT_{TE}, could truly be kept constant, the power output, P, could be made arbitrarily large by engineering the harvester to conduct more heat. Unfortunately, most real heat sources can not supply arbitrarily large heat fluxes without loss of temperature difference (the heat exchange to the thermoelectric has non-zero thermal impedance).

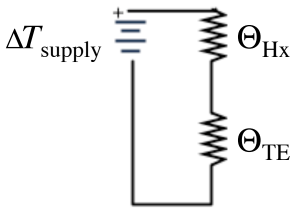

Figure 4. Typical thermal circuit in a thermoelectric energy harvesting device, .

Figure 4 shows a simple thermal model of a thermoelectric energy harvester. $\Delta T_{\mathrm{supply}}$ is the temperature difference between the heat source and the cold bath, Θ_{TE} is the thermal resistance of the thermoelectric, and Θ_{Hx} is the combined thermal resistance (impedance) of the hot and cold side heat exchangers in series with the thermoelectric. Heat exchangers used as sinks and sources are often well characterized by a thermal resistance Θ_{Hx}, according to:

$$\Delta T_{Hx} = Q\Theta_{Hx} \tag{7}$$

Notice that this implies that the heat supplied to the thermoelectric is proportional to the temperature drop across the heat exchanger.

If all the available ΔT is across the thermoelectric with no ΔT across the heat exchangers ($\Delta T_{\mathrm{Hx}} = 0$), the heat exchangers supply no heat ($Q = \Delta T_{\mathrm{Hx}}/\Theta_{\mathrm{Hx}}$) and therefore no power is produced. As the ΔT across the heat exchanger increases, the heat flux supplied increases, increasing the power output, but the temperature drop across the thermoelectric generator will decrease (ΔT_{TE} = $\Delta T_{\mathrm{supply}}$ - ΔT_{Hx}), reducing efficiency. Even if the heat source has low thermal impedance, the same consideration applies to the colds side heat sink. Invariably, some of the ΔT will be needed to transport heat through the heat exchangers to the heat source and/or sink which will reduce ΔT_{TE} to less than $\Delta T_{\mathrm{supply}}$.

For maximum power, it can be shown (see below) that the thermal resistance of the heat source and sink should be designed to match [5]. If either the heat source or heat sink has a large thermal resistance, the thermoelectric must have a large thermal resistance to build a significant ΔT_{TE} across the thermoelectric. If both the heat source and sink have low thermal resistance, then low thermal resistance for the thermoelectric will enable large heat flow and therefore high power.

From this thermal circuit, one can show that the temperature difference across the thermoelectric is given by

$$\Delta T_{TE} = \Delta T_{\mathrm{supply}} \frac{\Theta_{TE}}{\Theta_{Hx} + \Theta_{TE}} \tag{8}$$

and the heat flow through the circuit is given by

$$Q = \frac{\Delta T_{\mathrm{supply}}}{\Theta_{Hx} + \Theta_{TE}} \tag{9}$$

Combining these with the linear relationship between efficiency and ΔT_{TE} (Eq. 6) gives power*:*

$$P = \eta_1 \Delta T_{\mathrm{supply}}^2 \frac{\Theta_{TE}}{\left(\Theta_{Hx} + \Theta_{TE}\right)^2} \tag{10}$$

From this analysis it is clear that larger heat sinks (with smaller heat sink impedance, Θ_{Hx}) provide higher power.

Once the largest heat sink viable for a particular application has been selected (Θ_{Hx} now a constant), the highest power is provided when the thermal resistance of the thermoelectric is designed to match that of the heat exchangers ($\Theta_{Hx} = \Theta_{TE}$) [6].

$$P_{\max} = \frac{\eta_1 \Delta T_{\mathrm{supply}}^2}{4\Theta_{Hx}} \tag{11}$$

Under the matched condition, the temperature difference across the thermoelectric is exactly half of the total temperature difference across the cold and hot heat baths.

$$\Delta T_{TE} \approx \frac{\Delta T_{\text{supply}}}{2} \tag{12}$$
$$\eta \approx \frac{\eta_1 \Delta T_{\text{supply}}}{2}$$

From this simple analysis, the efficiency (and even the number of couples needed for a particular voltage) can be estimated for a given application with only the knowledge of ΔT_{supply}.

Thus, to at least a first approximation, the thermal resistance of the thermoelectric should be designed to be equal to that of the heat exchangers. This is particularly true in energy harvesting where power and size is more important than efficiency, and heat exchangers typically limit size.

Heat Flux

Typically power and size are the primary concerns in energy harvesting. Obviously a bigger device that utilizes more heat Q will produce more power P. Similarly, the use of twice as many power converters will naturally produce twice the power and consume twice the heat.

Thus, without a specific application in mind, it is natural to focus on power per unit harvested area (P/A) produced and heat flux (Q/A) rather than absolute power and heat consumed. This is particularly convenient for thermoelectric power generation because the systems are so easily scalable: a large system can simply be an array of smaller systems.

$$\frac{P}{A} = \eta \frac{Q}{A} \tag{13}$$

For maximum power flux (P/A), it is necessary to maximize both heat flux (Q/A) and efficiency.

At a constant temperature difference across the thermoelectric (ΔT_{TE}) the thermal conductance ($K = \kappa A/l$), inverse of thermal resistance) and therefore the heat/area absorbed into the thermoelectric generator can be modified by adjusting its height, l (Fig. 2), and therefore engineered for thermal impedance matching with the heat exchangers.

$$\frac{Q}{A} = \frac{\kappa_{eff} \Delta T_{TE}}{l} \tag{14}$$

This relation holds because, to a good approximation, the thermoelectric device acts as a simple heat conductor. The effective thermal conductivity, κ_{eff},of the thermoelectric module depends not only on the thermal conductivity of the n-type and p-type materials but also on the thermoelectric material filling fraction, parallel heat losses within the module, and Peltier and Thomson effects.

Matching Thermoelectrics to Heat Exchangers

Heat exchangers also scale with size, larger heat exchangers carry more heat and have lower thermal resistance. In this way, the product of thermal resistance times the area, ΘA, is a relatively constant quantity ($\Theta A = 1/h$ where h is the heat transfer coefficient). A low but achievable ΘA value for air cooled heat sinks is 5 K cm^2/W. For a forced fluid heat exchanger a typical value is 0.5 K cm^2/W.

Heat exchangers are likely to be the physically largest component in an energy harvesting system (Figure 5), and thermoelectrics are typically small in comparison. Because of this, even when space is at a premium, it is usually best to size the thermoelectric to achieve the most power from a given allowed size of heat exchanger.

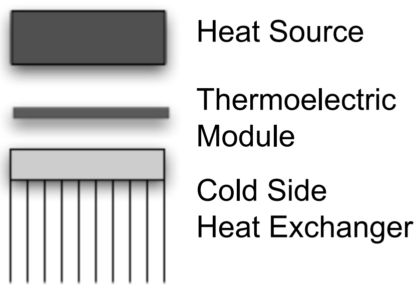

Figure 5. Schematic of a thermoelectric energy harvesting system consisting of a hot and cold side heat exchanger and a thermoelectric module.

Even before the exact size and design of the heat exchanger is selected, the general size and type of thermoelectric module can be determined from available heat flux from the heat exchangers. Specifically, because Θ_{TE} and Θ_{Hx} should be matched for maximum power, the size-independent quantities $\Theta_{\text{TE}}A$ and $\Theta_{\text{Hx}}A$ should also be matched.

The ΘA value for a thermoelectric is derived using the effective thermal conductivity from Eq. 14,

$$\Theta_{TE} A = \frac{\Delta T_{TE}}{Q/A} = \frac{l}{\kappa_{eff} f} \tag{15}$$

but now including a filling factor, f, in case the heat exchangers also act as heat spreaders ($f < 1$). The filling factor is the ratio of the area of the thermoelectric to the area of the heat exchangers. In Fig. 5, $f = 1$.

Matching $\Theta_{TE}A$ and $\Theta_{Hx}A$ for a given type of heat exchanger (*e.g.* natural convection air cooled, forced convection or water cooled) then determines the length, l, of the thermoelectric module. This is because the heat transfer coefficient, $h = 1/\Theta A$, will be relatively constant, which gives

$$l = \frac{\kappa_{eff} f}{h} \tag{16}$$

for an impedance-matched thermoelectric generator.

Typical bulk thermoelectric modules have $0.1 \text{ cm} < l < 0.5 \text{ cm}$. Custom modules and thermopiles can be made outside this range. Thin bulk devices routinely have l as small as 0.02 cm [7], while unicouples and miniature thermopiles [8] can be made with $l > 2$ cm. A typical densely packed thermoelectric module (thermopile) has κ_{eff} of about 0.02 W/cm K. From such values of l and κ_{eff} in available devices, one can map out the available design space (Figure 6) for thermoelectric generators.

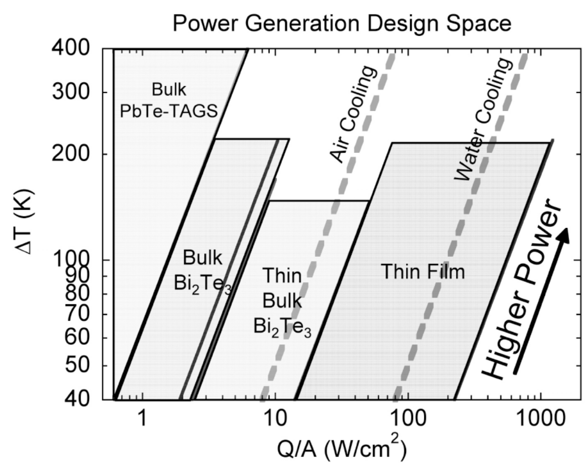

Figure 6. Available design space for energy harvesting from commercial thermoelectric generators. Approximate limits of air cooing and water cooling are shown. Traditional bulk devices are most appropriate for low heat flux (Q/A), passive air-cooled heat exchangers. High performance air-cooled heat exchangers require higher heat flux than is available with thin bulk modules. To utilize the very high heat fluxes at the limit of water cooling, thin film devices are needed. Highest power is achieved from both large heat flux and ΔT, in the upper right corner of the figure.

Thin Film Devices

Recently developed thin film devices have very thin thermoelectric material, ranging from about 0.0005 cm to 0.004 cm. In out-of-plane devices [9-11], this provides a very small value for l, which allows exceptionally high heat fluxes and low thermal resistances. These thin films have the greatest advantage when the heat exchangers are nearly ideal, having very low thermal resistances, such as in forced water cooling (Fig. 6). So far, these devices have lower efficiency due to the larger fraction of electrical and thermal contact resistance losses.

Thin film thermoelectrics used in the in-plane direction have the capability of producing a much greater number of higher thermal impedance couples [12]. The large number of couples produces significantly higher voltage and the higher thermal impedance is more appropriate for low heat flux energy harvesting applications. The inherent disadvantage of in-plane thermoelectrics is that the substrate used to deposit the thermoelectrics acts as a thermal short, reducing the efficiency.

Additional Considerations

Power conditioning of a thermoelectric energy harvester should also be a consideration. Even in steady-state, maximum-power operation, the output voltage of a generator is small due to the low voltage per couple, typically 0.2 mV/K. Modules have many couples in series, but even these may use a DC/DC transformer to achieve the few Volts necessary for most applications (e.g. the Seiko watch in Fig. 1). When the energy harvester is recharging a battery, the power conditioning also protects the battery from overcharging.

When the temperature changes, power conditioning is needed to stabilize the output voltage. If no battery is present then the power conditioning circuitry may itself require a minimum voltage to start, which will be a challenge for a thermoelectric harvester when the temperature difference is small.

Since high power and efficiency of a thermoelectric system require optimizing the thermal impedance of the harvester with respect to the environment, changes in environmental conditions will adversely affect performance. Devices are typically designed for a steady thermal supply. If the heat and temperatures drop dramatically, the power and voltage produced will rapidly fall. Increases in temperatures may damage contacting solders or the thermoelectric materials themselves. Altering the thermal impedance of the harvester or redirecting the heat to only a portion of the thermoelectric generator would increase power, but methods for such thermal switching are not common.

Summary

Natural thermal gradients are omnipresent sources of available energy for powering remote, low power electronics. Thermoelectric generators are the ideal converter for such applications because of their small size and solid-state, maintenance-free operation. The development of several micro-fabrication techniques to build small thermoelectric modules ensures that devices will be available for even the smallest applications.

The most power is provided when the thermal resistance of the thermoelectric device is matched with that of the heat sinks. Under the matched condition, the temperature difference across the thermoelectric is exactly half of the total temperature difference across the cold and hot heat baths. The power output can then be easily estimated using the performance of the available heat exchangers.

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