ENERGY HARVESTING FOR WIRELESS SENSORS

SYNERGISTIC ANALYSIS OF THERMOELECTRIC DEVICES, HEAT SINKS, AND ASSOCIATED ELECTRONICS FOR OPTIMIZED ENERGY HARVESTING SYSTEMS

By Robin McCarty, Ph.D.
Marlow Industries, Inc.

marlow industries, inc

A thermoelectric energy harvesting system is comprised of a thermoelectric generator (TEG), heat sink(s) to direct the heat through the TEG, a DC-DC converter to step-up the voltage to a usable value, and energy storage such as a rechargeable battery or super-capacitor. Utilizing all of these components enables a maintenance-free, renewable energy source that can produce between hundreds of µW's to several mW's of power for a variety of sensors and transmitters. This paper will explore the fundamental interactions between the TEG, heat sink, and DC-DC converters for thermoelectric power sources designed to power wireless sensors.

TEG DEVICE BASICS

To start this exploration, we need to define a few essential terms for a typical TEG and surrounding thermal system. A TEG is made of many TE elements consisting of p-type and n-type material. Each p-type and n-type pair is called a couple. A TEG contains N, number of couples, where each couple is made of a pair of elements of length, L, and cross-sectional area, A. The ratio between element length and cross sectional area of each element, λ, will determine both the thermal and electrical characteristics of the device which will have implications for our TE energy harvesting system. Equation 1 gives the definition of λ.

$$\lambda = \frac{L}{A} \quad (1)$$

Figure 1 shows a typical TEG and thermal system for an energy harvesting application. In this example, the TEG is mounted directly to the heat source at T_{source}. The thermal resistance between the hot side of the TE element, T_H, and the source temperature, T_{source}, is the hot side thermal resistance, HSR. Similarly, CSR is the thermal resistance between the cold side of the TE element, T_C, and ambient, T_{Amb}.

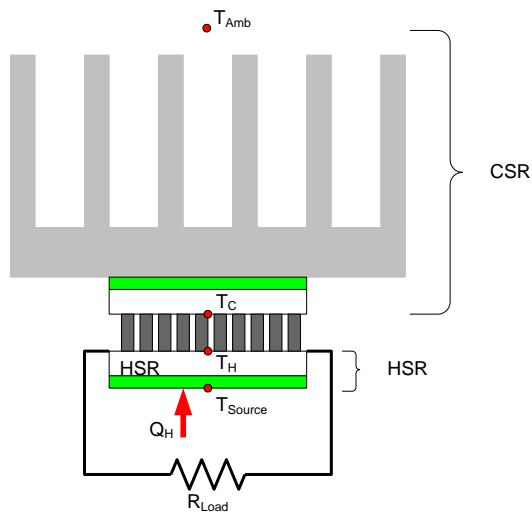## THERMAL CONSIDERATIONS

Most TE energy harvesting applications will require at least one heat sink to help direct heat through the TEG, and most often, this will be a natural convection heat sink. Although a natural convection heat sink has higher thermal resistance than a forced convection heat sink, it requires no additional power for a fan which reduces the power demands of the TEG. When designing a thermal system, most engineers will start by designing the best heat sink for a given mass, volume, or cost constraints. The lower the thermal resistance of the heat sink, the more heat will be directed through the TEG and converted into electrical power.

An important factor is the ratio between the TEG thermal resistance, $R_{TEG,th}$, and the rest of the system thermal resistance including, HSR and CSR. This thermal resistance ratio is given by Equation 2.

$$m = \frac{R_{TEG,th}}{HSR + CSR} \quad (2)$$

Some applications will have an infinite heat source relative to the TEG assembly, and in this case the engineer can assume that the hot side temperature remains constant regardless of the TEG and heat sink thermal resistance. But in other instances, this heat source is more finite causing the hot side temperature to drop when a lower thermal resistance TEG and heat sink assembly is utilized. And in another set of cases, the TEG and heat sink assembly is in a heat path that can be bypassed if the thermal resistance is too great. The lesson here is to experimentally verify your source temperature with the TEG and heat sink thermal resistance prior to final design.

ELECTRICAL CONSIDERATIONS

The electrical resistance of a single couple is a function of λ as given in Equation 3.

$$R_{TEG,el} = \lambda(\rho_p + \rho_n) \quad (3)$$

where ρ is the electrical resistance of the TE material for the p-type and n-type element respectively. In Figure 1, R_{Load} is the external electrical resistance connected to the TEG in series. The ratio between this external load resistance and the internal electrical resistance of the TEG is the load resistance ratio and is defined by Equation 4.

$$n = \frac{R_{Load}}{N \, R_{TEG,el}} \quad (4)$$

In most energy harvesting applications, the TEG output voltage will be directed through a DC-DC converter. These converters will present an apparent electrical load resistance to the TEG. Also, each converter will require a minimum threshold voltage, V_{min}, from the TEG in order to kick-start the converter operation. The magnitude of the TEG voltage entering the DC-DC converter will affect the overall converter efficiency or transconductance, G_m, which is the ratio of converter short circuit current output to TEG input voltage.

TEG THERMAL RESISTANCE AS A FUNCTION OF LOAD RESISTANCE RATIO

It is important to recognize that the thermal resistance of a TEG is not only a function of geometry, N, and λ. It is also a function of the load resistance of the electronics wired in series with the TEG. The passive thermal resistance of a single TEG couple when a temperature difference is applied across the device but current is not allowed to flow (i.e. open circuit conditions), is given in Equation 5:

$$R_{TEG,th,o} = \frac{\lambda}{(k_p + k_n)} \tag{5}$$

where k is the thermal conductivity of the TE material for the p-type and n-type element respectively.

As current is permitted to flow through the TEG while a temperature difference is imposed across the TEG, the heat flow through the TEG increases thus reducing the apparent thermal resistance of the TEG. The heat flow through a TEG as a function of current flow is given by Equation 6:

$$Q_H = N\bar{\alpha}IT_H + \frac{N}{R_{TEG,th,o}}\Delta T_{TEG} - \frac{1}{2}NI^2R_{TEG,el} \tag{6}$$

where $\bar{\alpha} = \alpha_p - \alpha_n$, and α is the Seebeck coefficient of the TE material for the p-type and n-type elements respectively, and ΔT_{TEG} is the temperature difference across the TEG.

The current induced by a temperature difference across the TEG is a function of the electrical resistance of a couple and the electrical load resistance ratio and is given by Equation 7.

$$I = \frac{\bar{\alpha}\Delta T_{TEG}}{R_{TEG,el}}\left[\frac{1}{n+1}\right] \tag{7}$$

Substituting Equation 7 into 6 yields the heat flow into a TEG as a function of load resistance ratio given by Equation 8.

$$Q_H = N\Delta T_{TEG}\left(\frac{\frac{2\bar{\alpha}^2 T_H(n+1) - \bar{\alpha}^2 T_H + \bar{\alpha}^2 T_C}{2(n+1)^2 R_{TEG,el}}}{+\frac{1}{R_{TEG,th,o}}}\right) \tag{8}$$

If the temperature difference across the TEG is small ($T_H \approx T_C$), then Equation 8 reduces to Equation 9.

$$Q_H = N\Delta T_{TEG}\left(\frac{\bar{\alpha}^2 T_H}{(n+1)R_{TEG,el}} + \frac{1}{R_{TEG,th,o}}\right) \tag{9}$$

Assuming that the TEG efficiency is small such that the heat leaving the TEG is approximately equal to the heat entering the TEG, the basic heat transfer equation, $\Delta T = QR$, can be used to find the thermal resistance of a TEG. From Equation 9, everything on the right had side of the equation that is multiplied by ΔT_{TEG} becomes thermal resistance of a TEG as a function of electrical load resistance ratio and is given by Equation 10.

$$R_{TEG,th} = \left(\frac{N\bar{\alpha}^2 T_H}{(n+1)R_{TEG,el}} + \frac{N}{R_{TEG,th,o}}\right)^{-1} \tag{10}$$

To truly understand this equation, Figure 2 shows a typical plot of TEG thermal resistance as a function of load resistance ratio for a 100 couple device with a λ of 2000 1/m. The thermal resistance of the TEG almost doubles as the load resistance ratio varies from zero to infinity (short circuit to open circuit

conditions). Note that a good thermoelectric design will normally operate near a load resistance ratio of one, but the slope of this curve is fairly steep indicating that thermal resistance is quite sensitive to load resistance ratio in this region. This TEG thermal resistance is used in Equation 2 to define the thermal resistance ratio, m.

Figure 2: Plot of TEG thermal resistance as a function of electrical load resistance ratio

SYSTEM CONSIDERATIONS

With thermal resistance ratio, and electrical load resistance ratio properly defined, we can now discuss the characteristics of an optimal TEG energy harvesting system. It is a common estimation that if you match the internal electrical resistance of the TEG to the electrical load resistance, maximum power is achieved from the TEG or any other power generator [1]. This is commonly referred to as impendence matching.
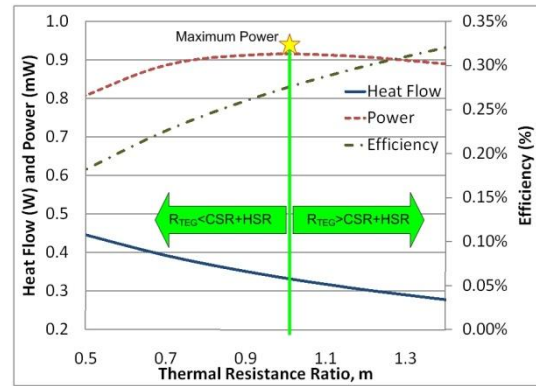

Figure 3: Plot of heat flow, TEG power, and TEG efficiency as a function of thermal resistance ratio.

Previous research has proven that a very similar trend occurs for the thermal resistance of the TEG. To better understand why this occurs, it is helpful to look at two extreme cases. For a given heat sink thermal resistance, if you pair it with a TEG with much lower thermal resistance, more heat would pass through the assembly, but since the efficiency of a TEG is proportional to the temperature difference across the TEG, zero power would be converted into electrical power. Now looking at the other extreme, if the thermal resistance of the TEG is much greater than the heat sink, the temperature drop across the TEG will be significant and therefore efficiency will be higher.

But since the thermal resistance of the TEG is so large, very little heat will pass through the TEG and heat sink assembly, therefore producing zero power. There exists an optimal point where the TEG thermal resistance equals the heat sink thermal resistance which results in the most TEG power output as seen in Figure 3 [2].

To summarize, the optimal TEG design occurs when both the electrical and thermal resistance ratios are equal to 1.0. The most interesting conclusion from this exercise is to recognize that the optimal number of couples, N, in a TEG and the element geometry, or λ, is simply a function of system thermal resistance ($CSR + HSR$) and electrical load resistance, R_{Load}.

ESTIMATED PERFORMANCE EQUATIONS

For TEG energy harvesting system where the TEG is not optimized for the heat sinks or electrical load resistance, performance can be estimated using a few convenient basic equations for a given thermal resistance ratio, m, and electrical load resistance ratio, n. The temperature difference across the TEG is a function of source and ambient temperature as well as thermal resistance ratio and is given by Equation 11.

$$\Delta T_{\text{TEG}} = \frac{T_{\text{Source}} - T_{\text{Amb}}}{1/m + 1} \qquad (11)$$

Note that if the thermal resistance ratio is one, ΔT_{TEG} is one half the total temperature difference across the system. The voltage from the TEG is a function of number of couples, N, the temperature difference across the TEG, ΔT_{TEG}, and electrical load resistance ratio, n, as seen in Equation 12.

$$V_{TEG} = N\bar{\alpha}\Delta T_{\text{TEG}} \left(1 - \frac{1}{n+1}\right) \qquad (12)$$

Note that if both the thermal resistance ratio and electrical load resistance ratio are equal to one, the TEG voltage can be represented by Equation 13.

$$V_{TEG} = \frac{N\bar{\alpha}(T_{\text{Source}} - T_{\text{Amb}})}{4} \qquad (13)$$

To calculate the minimum temperature difference to activate the DC-DC converter, combine Equation 11 and 12, set $V_{TEG} = V_{min}$ of the converter, and solve for the temperature difference from the source to ambient. This minimum temperature is shown in Equation 14:

$$\Delta T_{\text{min}} = \frac{V_{min}}{N\bar{\alpha}} \left(1 - \frac{1}{n+1}\right)^{-1} \left(1/m + 1\right) \qquad (14)$$

where V_{min} is the minimum voltage required by the DC-DC converter. If both the thermal resistance ratio and electrical load resistance ratio are equal to one, this equation simplifies to Equation 15.

$$\Delta T_{\text{min}} = \frac{4V_{min}}{N\bar{\alpha}} \qquad (15)$$

To estimate the current output from the DC-DC converter, Equation 16 can be used which relies on the approximate transconductance of the converter, the minimum threshold input voltage for the converter, and the TEG voltage:

$$I_{out} = G_m(V_{TEG} - V_{min}) \qquad (16)$$

where G_m is the transconductance of the converter. With this estimated current, we can also estimate output power from the converter using Equation 17:

$$P_{out} = EF\, I_{out} V_{out} \qquad (17)$$

where V_{out} is the expected output voltage from the converter, and EF is the efficiency factor of the converter which is typically between 80-90%.

Using the estimation that an optimal design occurs when load resistance ratio and thermal resistance ratio are both 1, these equations allow an engineer to quickly estimate TEG and converter performance for a given heat sink, converter, TEG and source and ambient temperature.

EXAMPLE

Use of these equations to optimize an energy harvesting system is best demonstrated by working through an example. In this example, a TEG is mounted directly to the heat source similar to Figure 1. A typical natural convection heat sink has relatively high thermal resistance. It is common to find 25mm X 25mm cross-sectional area heat sinks with a thermal resistance of 15 K/W for relatively low temperature rise above ambient, so let $HSR = 0\ K/W$ and $CSR = 15\ K/W$ [3]. Also, typical DC-DC converters have electrical load resistances ranging from 2-6 Ω, so for this example let $R_{Load} = 2.25$ Ω [4, 5]. Also, assume the DC-DC converter requires at least 20mV from the TEG before it is activated, so let $V_{min} = 20\ mV$. Table 1 contains other basic information necessary to identify the optimal TEG for this example and includes typical TE Bi₂Te₃ material properties near room temperature.

Table 1 TEG estimated material properties and example source and ambient temperatures

Parameter	Value	Unit
Seebeck Coefficient, $\bar{\alpha}$	0.00043	V/K
Thermal Conductivity, k_p, k_n	1.4	W/mK
Electrical Resistivity, ρ_p, ρ_n	1e-5	Ω-m
Source Temperature, T_{Source}	35	°C
Ambient Temperature, T_{Amb}	25	°C

To select the best matched TEG for this application, we will chose from four standard devices from Marlow Industries. These candidate TEGs, number of couples, N, and element λ are outlined in Table 2.

Table 2 Candidate TEGs for example

Marlow TEG	N	λ (1/m)
NL1012T	31	4921.3
NL1022T	31	2519.7
NL1025T	39	2519.7
NL1015T	39	4921.3

For each candidate TEG, the number of couples and λ are used to calculate the electrical and thermal resistance ratios by using Equations 2, 3, 4, and 10. Additionally, Equations 11, 12, and 14 can be used to calculate TEG voltage and minimum

temperature. Also, using Equation 18, TEG power can also be estimated.

$$P_{TEG} = \frac{V_{TEG}^2}{R_{Load}} \tag{18}$$

Table 3 shows the electrical and thermal resistance ratios as well as the TEG voltage and power, and the minimum temperature to activate the DC-DC converter.

Table 3 Candidate TEG estimated outputs

Marlow TEG	n	m	V_{TEG} (mV)	P_{TEG} (mW)	ΔT_{min} (°C)
NL1012T	0.737	2.384	39.86	0.71	5.02
NL1022T	1.440	1.366	45.42	0.92	4.40
NL1025T	1.145	1.043	45.71	0.93	4.38
NL1015T	0.586	1.830	40.08	0.71	4.99

From Table 3, you can see that the NL1025T would produce the most power; it also has electrical and thermal resistance ratios near 1.0. The other candidate TEGs which produces less power also had electrical and thermal resistance ratios further away from 1.0. Additionally, the NL1025T also produced the most TEG voltage and it also required the least ΔT to activate the DC-DC converter. Calculating the electrical and thermal resistance ratios is an easy yet effective means to evaluate potential TEGs for your energy harvesting system.

SUMMARY

To optimize a TE energy harvesting system, both the thermal and electrical aspects of the design must be balanced. For most applications a natural convection heat sink is employed to eliminate additional TEG power demands from a fan or pump. This heat sink guides the thermal design of the TEG by defining the optimal number of couples, N, and element length over area ratio, λ needed in order to thermally match the heat sink. A DC-DC converter is also necessary to boost the TEG voltage up to a usable value, and has an associated electrical resistance that can also affect TEG electrical and thermal performance.

REFERENCES

1. James W. Nilsson and Susan A. Riedel, Electric Circuits, 5th Edition, Addison-Wesley Publishing Co., Reading, Massachusetts, (1996).
2. James W. Stevens, Optimal design of small DT thermoelectric generation systems, Energy Conversion and Management, V42, (2001), pg. 709-720.
3. Alpha Novatech, Inc., "LPD Series, Low Pressure Drop Heat Sink," http://www.micforg.co.jp/dxf/LPD.pdf, (2010).
4. Linear Technology, "LTC3108 Ultralow Voltage Step-up Converter and Power Manager," http://cds.linear.com/docs/Datasheet/3108fa.pdf, (2010).
5. EnOcean, "ECT 300 Perpetuum Preliminary Data Sheet," http://www.enocean.com/en/enocean_modules/ect-300-perpetuum-developer-kit/, (2010).
6. Marlow Industries, "NL1025 Technical Data Sheet," http://www.marlow.com/thermoelectric-modules/single-stage/nl1025t.html, (2010)
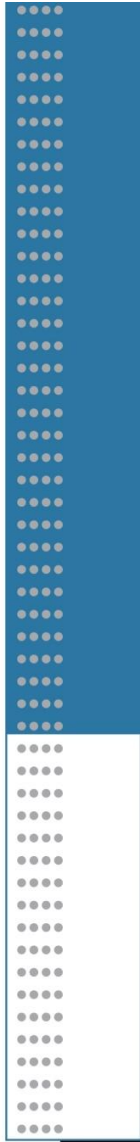
marlow industries, inc

Marlow Industries, a subsidiary of II-VI incorporated, is the world leader in quality thermoelectric cooling technology. For more than 30 years, Marlow Industries has developed and manufactured thermoelectric coolers (TECs) and subsystems for the aerospace, defense, medical, industrial, automotive, power generation and telecommunications markets. Marlow prides itself on providing standard or custom modules and sub-assemblies to meet our customers' exacting needs. Marlow is Telcordia and ISO 9001:2008 compliant and a Malcolm Baldrige National Quality Award winning company.