Thermoelectric Power Generator Design and Selection from TE Cooling Module Specifications

Richard J. Buist and Paul G. Lau
TE Technology, Inc., 1590 Keane Drive, Traverse City, MI 49686 USA
Phone: (616) 929-3966, FAX: (616) 929-4163, E-mail: <cool@tetech.com>

Abstract

There are many applications where theromelectric (TE) coolers can be used effectively as power generators. In fact, where temperatures are less than 500K, TE cooling modules are the best choice for power generation, whether it be from a cost or performance standpoint. The literature available on this subject is scarce and very limited in scope. This paper describes the configuration, limitations and performance of TE coolers to be used as power generators. Also presented are performance curves generated using a new finite element thermoelectric model [1]. This enables the user to design the optimum TE module and select the nearest TE module (normally used for cooling) for this power generation application. A simple process is presented which provides detailed power generation specification (temperatures, watts in, current and voltage out) using the TE module's cooling specifications ΔTmax, Imax, Vmax, and Qmax).

Introduction

Generation of electrical power via thermoelectric devices has been a subject of interest for decades. Basically, thermoelectric power generation is a solid state means of converting heat flow directly into electrical power via the Seebeck effect. High temperature energy sources have historically been utilized because of the inherent higher efficiency at high temperature differences, ΔT's.

However, there are many low level energy sources plentiful in nature which are candidates for thermoelectric conversion. For example: ocean thermals, solar energy, steam and various forms of waste heat. TE modules normally designed for cooling are the best choice for these applications because they are manufactured from materials of highest efficiency at these nominal temperatures. As such, they represent the highest efficiency devices possible for use as thermoelectric power generators for low intensity energy sources.

This paper discusses some of the unique features of these versatile devices together with some limitations and precautions. Finally, design curves are presented enabling one to design or select the TE module to convert heat flow to DC power with the highest level of performance thermoelectrics can provide.

Theory of Operation

A thermoelectric cooler consists of several N & P pellets connected electrically in series and thermally in parallel sandwiched between two ceramic plates as illustrated in Figure 1. The bottom plate is bonded to a heat sink and, with the application of DC current of proper polarity, heat is pumped from the top plate to the bottom plate and into the heat sink, where it is dissipated to ambient. The resultant is that the top surface becomes cold. The top surface can also supply heat by simply reversing DC polarity.

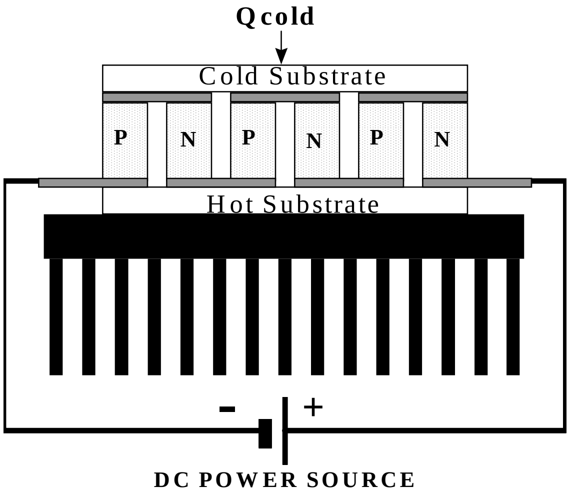

Figure 1. TE module in cooling mode.

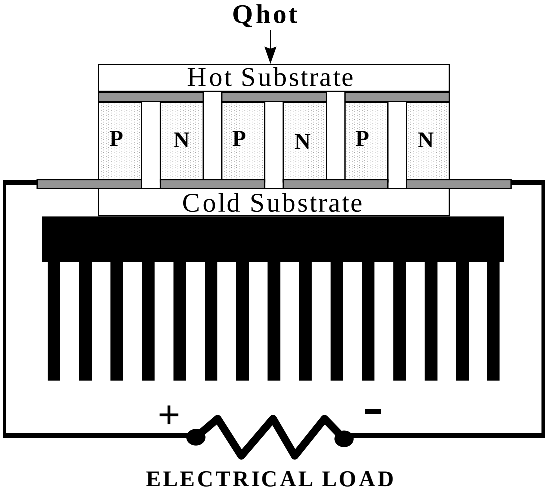

Figure 2. TE module in power generation mode.

The same unit can be made into a thermoelectric power generator by simply replacing the DC source with the load, or item to receive power, and apply heat to the top surface of the TE modules as illustrated in Figure 2. Note that the polarity of the power delivered is opposite the polarity for cooling. Electrical power is derived from the movement of electrical carriers brought on by heat flow through the TE pellets. Holes, or positive carriers, move to the heat sink side of the P-type pellet making that junction electrically positive. Similarly, electron flow in the N-type pellets results in a net negative charge at the heat sink side of the N-type pellet.

Coolers versus Generators

Technologically, most commercial TE power generators have little in common with TE coolers. Coolers have maximum COP or cooling "efficiency" at small ΔT's, whereas, generators have maximum efficiency at large ΔT's. The resulting high operating temperatures of TE generators demand different assembly technologies than for typical coolers, and different materials such as PbTe and Si/Ge alloys.

TE coolers are composed of alloys of Bi, Sb, Te, and Se optimized for operation in the temperature range of 180K to 500K. These materials have the highest thermoelectric efficiency in this range. Moreover, they have the highest efficiency regardless of whether the devices are used for cooling, heat pumping or for power generation. Consequently, devices normally designed for cooling are theoretically the most efficient TE generators to convert relatively low intensity energy sources with maximum temperatures of 550K.

Limitations and Precautions

There are some important practical considerations that should be made before attempting to use TE coolers in the power generation mode. Perhaps the most important consideration is the question of survivability of the module at the anticipated maximum temperature. Many standard TE cooling modules are fabricated with eutectic Bi/Sn solder which melts at approximately 138°C. However, there are some coolers being offered employing higher temperature solders designed for operation at temperatures of 200°C, even approaching 300°C.

In any case, consideration should be given to operational lifetime of a TE module exposed to high temperatures. Contaminants or even constituents of the solder can rapidly diffuse into the TE material at high temperatures and degrade performance and, in extreme cases, can cause catastrophic failure. This process can be controlled by the application of a diffusion barrier onto the TE material. However, some manufactures of TE coolers employ no barrier material at all between the solder and the TE material. Although application of a barrier material is generally standard on the "high temperature" TE cooling modules manufactured, they are mostly intended for only short-term survivability and may or may not provide adequate MTBF's (Mean Time Between Failures) at elevated temperatures. In summary, if one expects to operate a TE cooling module in the power generation mode, qualification testing should be done to assure long-term operation at the maximum expected operating temperature.

Performance Calculations

The finite element thermal model for a power generator developed by Lau[1] was used to calculate the maximum efficiency conditions of a TE module as a function of Tcold for selected constant values of Thot. This thermal model was especially effective for these calculations because, although the temperature gradient can be quite linear over a fairly large temperature difference, ΔT, the kinetic TE properties are not linear with temperature. Thus, these data are a marked improvement over those developed from equations using "temperature averaged" TE material parameters. The calculations produced from this model were the maximum efficiency, E; the voltage, V; and the current, I; of an arbitrarily chosen TE module at this maximum efficiency point. Of course, E is non-dimensional and, therefore, applies to all TE modules fabricated from the TE materials whose temperature dependent properties were used in the calculations. To normalize (and generalize) V and I, these values were divided by Vmax and Imax which are the voltage and current where maximum cooling ΔT would be achieved in a vacuum with the base plate held at a constant 300K. This condition is the usual performance specification by most, if not all, TE cooling module manufacturers of the world. It is for this reason why the power generation values V and I where normalized to V/Vmax and I/Imax. That is, not only does it generalize the results for all TE modules with a ΔT_{max} of approximately 67°C, it allows for easy identification of the TE module (or set of modules) needed to meet the desired power output from the generator. The final results of these calculations are illustrated in Figures 3, 4 and 5. Figure 3 is the maximum efficiency, E, obtainable from typical thermoelectric "cooling" modules with boundary temperatures Tcold and Thot. The corresponding optimum values of V/Vmax and I/Imax for each combination of Tcold and Thot are shown in Figures 4 and 5.

These curves provide a simple graphical method to design or analyze TE power generators given only these boundary temperatures as shown in Figure 2. That is, the optimum variable set E, V/Vmax, and I/Imax is determinable by reading from the figures given only Thot and Tcold. TE module specifications, Imax and Vmax are subsequently determinable from these graphically determined ratio parameters using the user-desired power generator output current (I) and voltage (V).

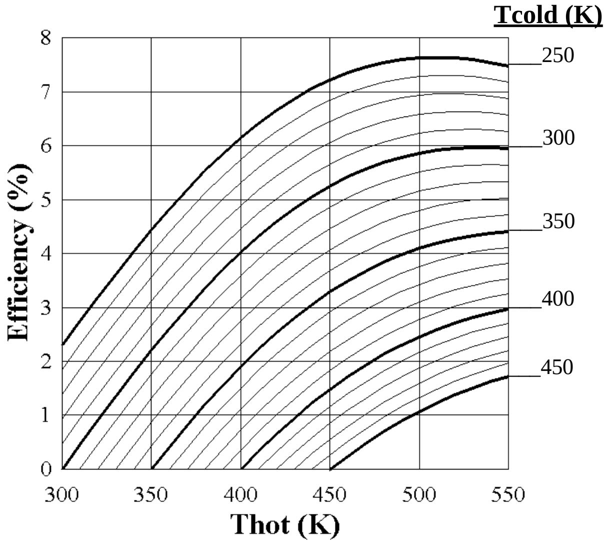

Figure 3. Maximum efficiency of a thermoelectric module as a function of junction temperatures.

The amount of applied heat (Qhot) required at the hot side of the module is determinable from the formula for efficiency:

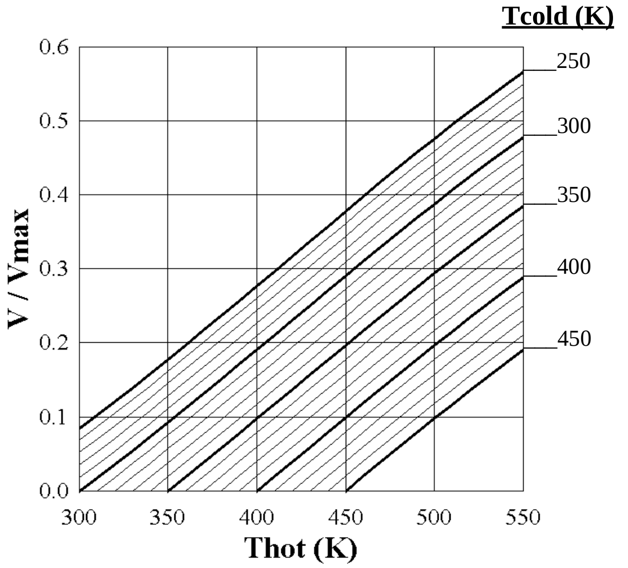

Figure 4. V/Vmax of a thermoelectric module as a function of junction temperatures.

$$E = I * V / Qhot \qquad (1)$$

Electrical power is derived from energy flow, not just high temperature. Therefore, no TE generation system is complete without some means of heat sinking or dissipating the waste heat from the cold side (See Fig. 2). The overall performance of the heat sink is characterized by the heat sink resistance (HSR). This value is a measure of the temperature rise of the heat sink (Tcold) above ambient temperature (Ta) per watt of heat dissipated. This heat is essentially the applied heat (Qhot) at the hot side less the heat converted to electricity:

$$HSR = (Tcold - Ta) / (Qhot - IV) \qquad (2)$$

Examples

Two examples will be presented to provide an understanding of the use of the performance curves for two types of typical power generation applications.

Example 1: A thermoelectric power generator is to be used to supply power to a small sensing electronic system in a remote section of a processing plant using waste heat. The following conditions are given:

KNOWN
a) Thot = 440K
b) Tcold = 350K
c) V = 1.5 volts
d) I = 0.6 amps
e) Ta = 300K

UNKNOWN
f) E
g) Vmax
h) Imax
i) HSR
j) TE Module

STEP	FUNCTION	RESULT
1	Read E from Fig. 3	E = 3.0%
2	Read V/Vmax from Fig. 4	V/Vmax = 0.18
3	Read I/Imax from Fig. 5	I/Imax = 0.16
4	Calculate Vmax from c & 2	Vmax =8.33 volts
5	Calculate Imax from d & 3	Imax = 3.75 amps
6	Calculate Qhot = I*V / E	Qhot = 30.0 watts
7	Calculate HSR (Eq. 2)	HSR = 1.7°C/W

Two options exist to the designer at this point: 1) fabricate a custom module built to the optimum design or; 2) select a standard (HT) module, with the next largest Vmax and Imax.

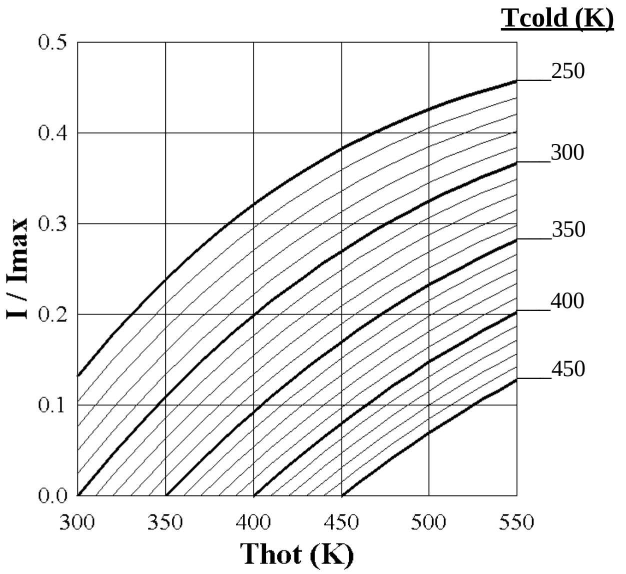

Figure 5. I/Imax of a thermoelectric module as a function of junction temperatures.

Note, however, that although that standard module will have ultimate capacity to deliver the needed I and V, this off-optimum design will have lower efficiency than the optimum module design depending on the degree of adjustment made. The TE module with approximately these specifications is a standard amongst most TE cooling module manufacturer's specifications as a 71 couple, 4.0 amp module.

Example 2: A solar collector is used to charge a 12 volt battery. It delivers a known flow of heat to a TE power generator with a known HSR. The following conditions and requirements are shown below. Note that in this example both Tcold and Thot are not given.

KNOWN
a) Qhot = 188 watts
b) HSR = 0.14°C/W
c) Ta = 295K
d) V = 15 volts
e) I = 0.5 amps

UNKNOWN
f) Tcold
g) Thot
h) Vmax
i) Imax
j) TE Module

STEP	FUNCTION	RESULT
1	Calculate E (Eq. 1)	E = 4.0%
2	Calculate Tcold (Eq. 2)	Tcold = 320K
3	Read Thot from Fig. 3	Thot = 430K
4	Read V/Vmax from Fig. 4	V/Vmax = 0.21
5	Read I/Imax from Fig. 5	I/Imax = 0.20
6	Calculate Vmax from d & 4	Vmax= 71.4 volts
7	Calculate Imax from e & 5	Imax= 2.5 amps

There are many standard TE modules to choose from with an Imax of 2.5 amps. However, none of them have a value of Vmax near the specified 71.4 volts. However, the set of 3 each 127 couple modules (Vmax=15.4V) plus 3 each 71 couple modules (Imax=8.6V), all wired electrically in series,. would have a Vmax of 72 V, but still with and Imax of 2.5 amps. Clearly, this set meets the requirement.

Conclusions

Thermoelectric coolers can be used as power generators using low intensity energy sources if consideration is made for effects of exposure to high temperatures. Moreover, they provide the highest conversion efficiency thermoelectrics can provide, at temperatures below 550K, since they are fabricated from the highest performance material available for that temperature range.

The data presented herein are based on standard TE materials which produce 68K ΔTmax at a 300K hot side temperature in a vacuum environment. TE modules with a higher ΔTmax would, of course, produce a proportionally higher power generation performance. Therefore, subject to the precautions and limitations described herein, the design curves presented in this paper enable the designer to define the ultimate capacity of thermoelectrics for use as a low-intensity power generator and to define in detail the actual device required.

References:

[1] P.G. Lau, R.J. Buist. "Calculation of Thermoelectric Power Generation Performance Using Finite Element Analysis", Proceedings of the XVI International Conference on Thermoelectrics, August 26-29, 1997 Dresden, Germany.