THERMOELECTRIC COOLERS AS POWER GENERATORS

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ABSTRACT

There are many applications where thermoelectric (TE) coolers can be used effectively as power generators. The literature available on this subject is scarce and very limited in scope. This paper describes the configuration, capability, limitations and performance of TE coolers to be used as power generators. Also presented are performance curves enabling the user to design the optimum TE module for any given power generation application.

INTRODUCTION

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

However, there are many lower 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. Thermoelectric modules normally designed for cooling are excellent for these applications because they are manufactured from materials of highest thermoelectric efficiency at these nominal temperatures. As such, they represent the highest efficiency devices possible for use as thermoelectric power generators for low level 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 attached to a heat sink of one kind or another 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. The resultant is that the top surface becomes cold. The top surface can also supply heat by simply reversing DC polarity.

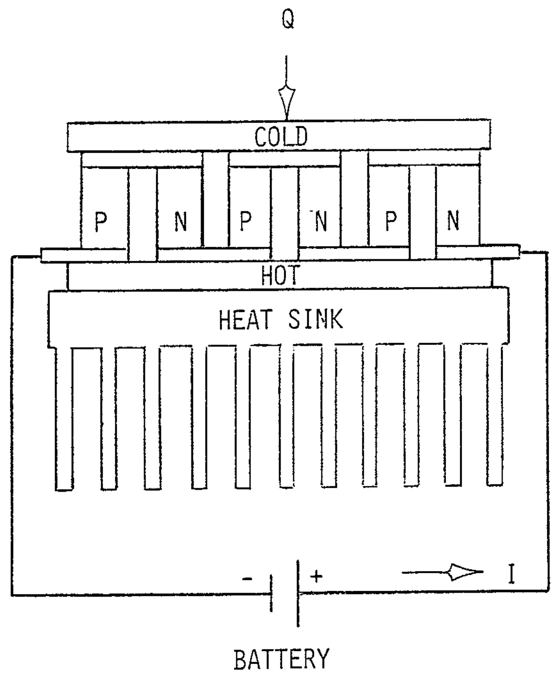

Figure 1. TE Module in the Cooling Mode

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 module as illustrated in Figure 2. Note that the polarity of the power delivered is opposite the assigned 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.

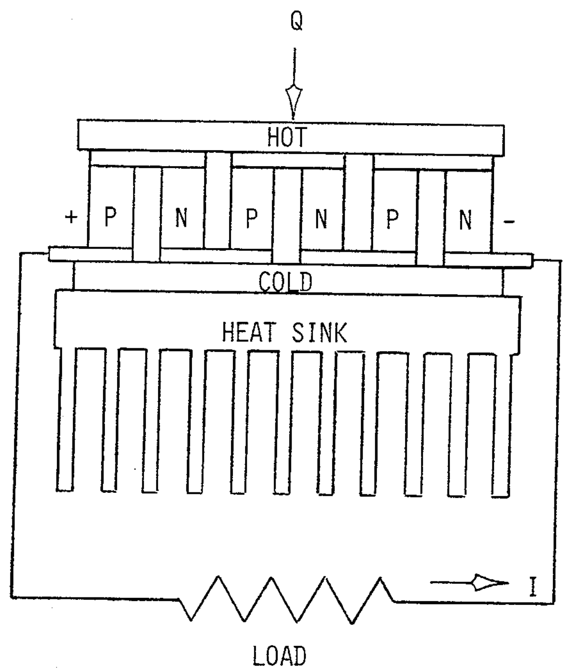

Figure 2. TE Module in the Power Generation Mode

COOLERS VS. 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 180°K to 400°K. 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 level energy sources with maximum temperatures of 500°K.

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. Most standard TE coolers 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 short term exposure to temperatures over 200°C.

In either 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 manufacturers of TE coolers employ no barrier material at all. Although application of a barrier material is generally standard on the "High temperature" TE coolers 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. This is an area of intense research and development at Marlow Industries and results of those basic studies will be presented in future seminars.

PERFORMANCE

Through analysis of fundamental equations, we have discovered that generalized equations were obtainable by combining certain device parameters. We have derived two key "lumped parameter" variables: Current (I) X pellet length (L) ÷ pellet area (A) = IL/A; and voltage (V) ÷ number of N & P pellet couples (N) = V/N. This substitution yields generalized equations which are functions of boundary temperatures and TE material properties. The data presented herein deals exclusively with standard Marlow Industries TE materials whose properties are also dependent on temperature. Consequently, the resulting fundamental equations reduce to functions with only boundary temperatures as independent variables. The maximum power generation efficiency (E) was determined for a single stage module by optimizing IL/A and V/N and, as a consequence, these optimum values plus E were also dependent only on boundary temperatures.

The resulting data is presented in Figures 3, 4, and 5 as generalized performance curves. These curves provide a simple graphical method to design or analyze TE power generators given only the hot side temperature (Th) and cold side temperature (Tc). Notice that the optimum variable set E, IL/A, and V/N is determinable by reading from the Figures given only Th and Tc. Device geometry: L, A, and N are determinable from the output current and voltage. The amount of incident heat (Q) required at the hot side of the module is determinable from the formula for efficiency:

$$E = IV/Q \qquad (1)$$

Electrical power is derived from heat flow, not just heat. Therefore, no thermoelectric generation system is complete without some means of heat sinking or dissipating heat. 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 sink above ambient temperature (Ta) per watt of power dissipated. This power is essentially the incident heat (Q) at the hot side less the power converted to electricity (IV).

$$Tc = HSR\ (Q-IV) + Ta \qquad (2)$$

EXAMPLES

Two examples will be presented to provide an understanding of the use of the performance curves for two typical types of problems encountered.

Example 1: Thermoelectric power generators are to be used to supply power to electronics in a remote section of a processing plant. The following conditions are given:

Known	Unknown
a) Th = 410°K	f) N
b) Tc = 330°K	g) L/A
c) V = 1.5 volts	h) Q
d) I = 590 milliamps	i) HSR
e) Ta = 300°K	

STEP	FUNCTION	RESULT
1	Read E from Fig. 3	E = 3.2%
2	Read IL/A from Fig. 4	IL/A= 5 Amps/cm
3	Read V/N from Fig. 5	V/N = 0.021 volts
4	Calculate N = V ÷ V/N	N = 71.4 couples
5	Calculate L/A=IL/A ÷ I	L/A = 8.47 /cm
6	Select Module	MI 1063 (N=71;L/A=8.46 /cm)
7	Calculate Q = E ÷ IV	Q = 27.7 watts
8	Calculate HSR (Eq. 2)	HSR = 1.1°C/W

After the optimum N and L/A are determined, a TE module with these exact values may not be available. Two options exist to the designer at this point: 1) fabricate a custom module built to the optimum design or; 2) select a standard module, with the next largest N and the next lowest L/A. Note, however, that although that standard module will have ultimate capacity to deliver the needed I and V, this off-optimum design will be lower efficiency than the optimum module design.

Example 2: A solar collector delivers a known quantity of heat to a TE power generator. A natural convection heat sink is to be used for the cold side of the TE generator and exchanges heat with the ambient. The following conditions and requirements are shown below. Note that in this example both Tc and Th are not given.

Known	Unknown
a) Q = 55 watts	f) Tc
b) HSR = 0.75°C/W	g) Th
c) Ta = 310°K	h) N
d) I = 1.25 amps	i) L/A
e) V = 1.60 volts	

STEP	FUNCTION	RESULT
1	Calculate E (Eq. 1)	E = 3.6%
2	Calculate Tc (Eq. 2)	Tc = 350°K
3	Read Th from Fig. 3	Th = 450°K
4	Read IL/A from Fig. 4	IL/A= 5.6 Amps/cm
5	Read V/N from Fig. 5	V/N = .026 volts
6	Calculate N=V ÷ V/N	N = 61.5 couples
7	Calculate L/A=IL/A ÷ I	L/A = 4.48 /cm
8	Select Module	MI 1120 (N=31;L/A=4.14 /cm)

The MI 1120 TE module has the nearest pellet L/A and two of these devices will be connected electrically in series to obtain the correct number of couples (N = 62).

CONCLUSIONS

Thermoelectric coolers can be used as power generators using low level 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 500°K since they are fabricated from the highest performance material available. The data presented herein is very sensitive to TE material parameters and is based on standard Marlow Industries' materials. Subject to that constraint, the resulting design curves enables the designer to define the ultimate capability of thermoelectrics for use as a low-level power generator and to define in detail the actual device required.

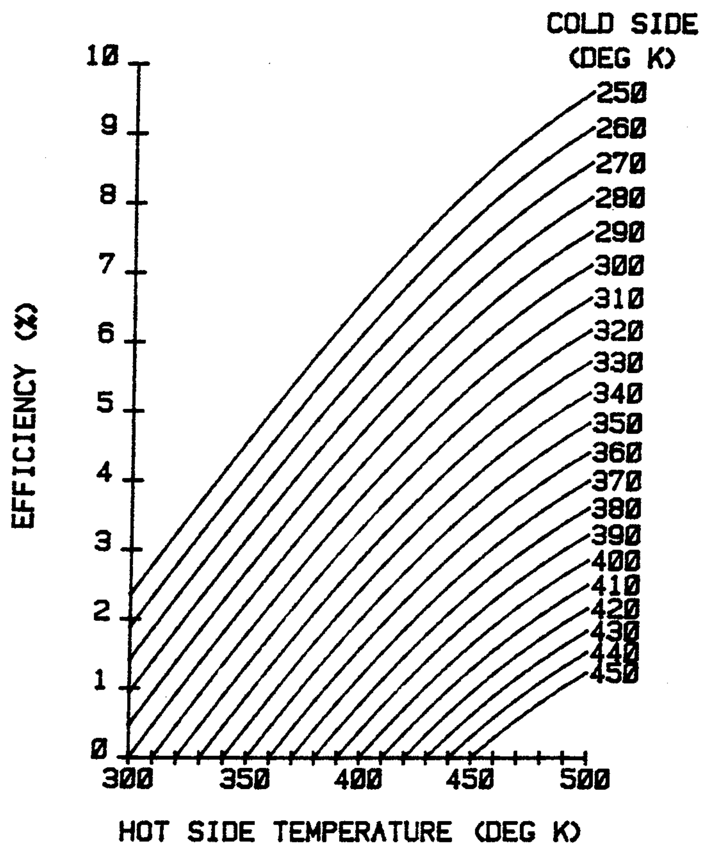

Figure 3. Maximum efficiency of a thermoelectric module as a function of junction temperatures.

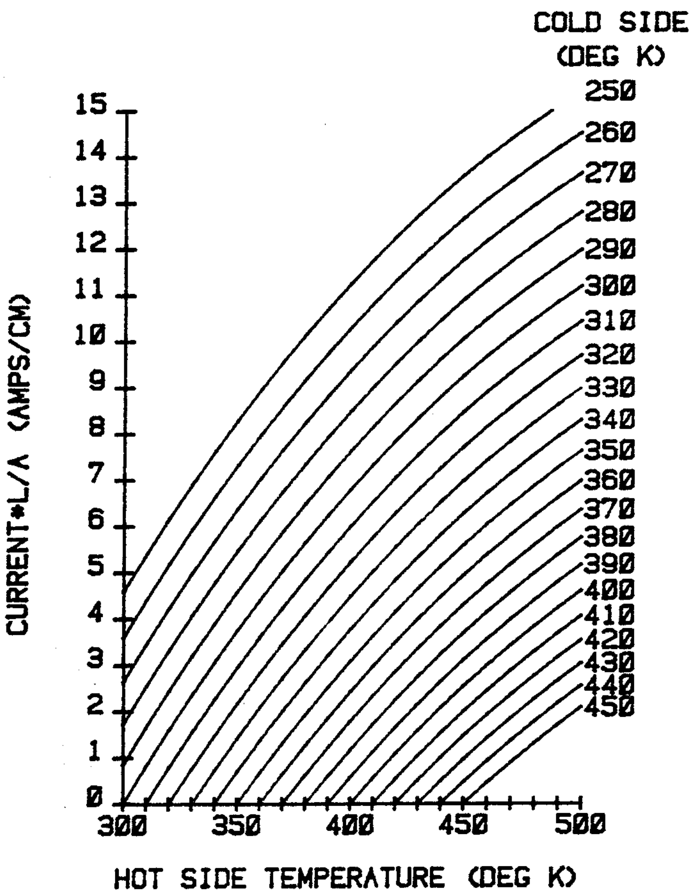

Figure 4. Current X thermoelectric pellet length per unit area at maximum efficiency as a function of junction temperatures.

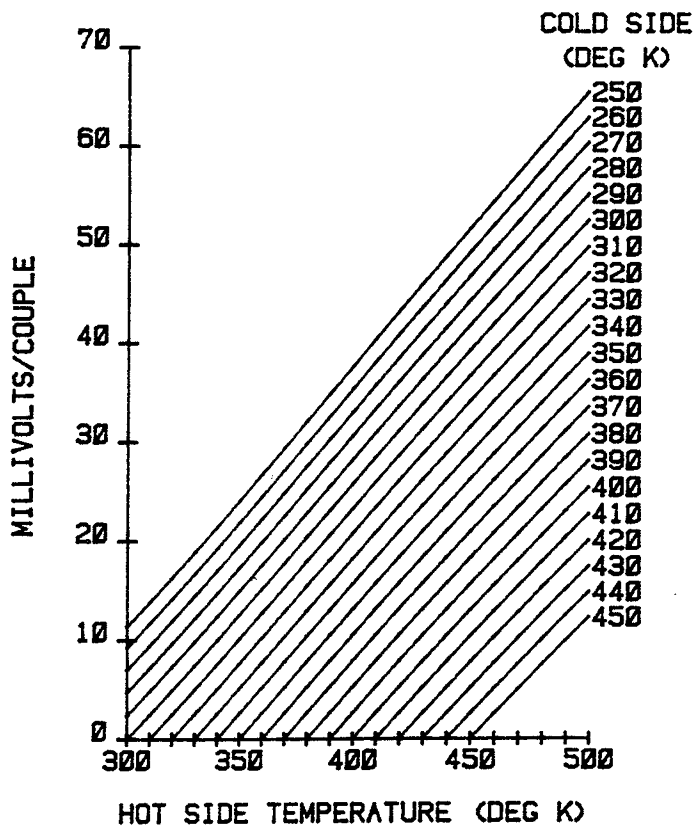

Figure 5. Voltage per couple of a thermoelectric module at maximum efficiency as a function of junction temperatures.