Effect Of Heat Sink Design On Thermoelectric Cooling Performance

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INTRODUCTION

Module manufacturers typically specify module performance parameters at a constant hot side temperature. This means using an "infinite" heat sink combined with perfect thermal interfaces between the module and heat sink. This, of course, is impossible. In the application of these modules in real world cooling systems the modules hot side temperature, T_h, is neither known or constant. For any given heat sink resistance (HSR) which is non-zero, T_h will vary both with the input power to the thermoelectric module (TEM) and with the net heat pumped from the cold side. System designers trying to use these typical module performance curves are then faced with a problem. Net heat pumping, and the power required to pump this heat, are dictated by T_h. However, T_h is not known until the input power to the TEM is known. The system designer is forced to estimate T_h and the possibility of errors is introduced.

A set of correction factors have been developed to address these problems. These correction factors allow the user to derate the TEM's maximum cooling parameters (I_{max}, V_{max}, DT_{max}, and Q_{max}) as a function of its heat sink resistance. This permits accurate design for maximum or optimum cooling as long as the heat sink resistance is known.

This process also allows the system designer to troubleshoot their design if cooling performance is less than expected. The second portion of this paper examines some of the parameters that affect system performance: HSR, a module's internal resistance and heat loads.

GENERAL THERMOELECTRIC EQUATIONS FOR SOFT HEAT SINKS

Heat sink resistance may be included in the basic heat balance and voltage equations for a TEM as shown in Equations 1 & 2.

where:
α = Material Seebeck Coefficient
ρ = Material Resistivity
κ = Material Thermal Conductivity
S = Device Seebeck Coefficient = $N\alpha$
R = Device Resistance = $N\dfrac{\rho L}{A}$
K = Device Thermal Conductance = $N\dfrac{\kappa A}{L}$
I = Device Current
V = Device Voltage
T_a = Ambient Temperature
T_c = Cold Side Temperature
H = Heat Sink Resistance
N = Number of TE Pellets/Device
L = Pellet Length
A = Pellet Footprint Area

$$Q_c = SIT_c - I^2R/2 - K(T_a + (IV + Q_c)H - T_c) \tag{1}$$

$$V = S(T_a + (IV + Q_c)H - T_c) + IR \tag{2}$$

These equations simply replace T_h with Ta+(IV+Qc)H. They can be further generalized to be independent of geometry by dividing them by the geometrical factors as shown in equations 3 & 4.

Calling $i = I\dfrac{L}{A}$, $q_c = \dfrac{Q_cL}{AN}$, $h = \dfrac{HNA}{L}$, and $\nu = \dfrac{V}{N}$

$$q_c = \alpha i T_c - i^2\rho/2 - \kappa(T_a + (i\nu + q_c)h - T_c) \tag{3}$$

$$\nu = \alpha(T_a + (i\nu + q_c)h - T_c)i\rho \tag{4}$$

These equations are now called geometry independent because the values of i, q_c, h, and ν are constant regardless of the geometry of the device or the number of pellets it contains.

COMPUTER MODELED EFFECTS OF HSR ON PERFORMANCE PARAMETERS

Equations 1 through 4 present the reader with an understanding of how HSR may be added and geometry removed from the general heat balance and voltage expressions. However, their analytical use, when combined with the temperature dependent properties of thermoelectric materials, becomes tedious. For this reason TE Technology, Inc.'s proprietary modeling software was used to examine the effects of HSR on maximum device parameters. The data for Figures 1 and 2 was achieved by modeling specific TEM's and then generalizing the results for all geometries. This operation was performed on several different TEM's of vastly different geometrics and yielded identical generalized results for all cases. For each case, the heat sink resistance was stepped until the product of HSR*Q_{max} approached 600°C. At each different HSR the new maximum device parameters were calculated. These new maximum device parameters (Q_{maxh}, V_{maxh}, I_{maxh}, and DT_{maxh}) were divided by their corresponding constant hot side maximum parameters(Q_{max}, V_{max}, I_{max}, and DT_{max}). It should be noted that DT_{maxh} is now specified as the maximum temperature difference between T_c and T_a, and not the maximum temperature difference between the hot and cold surfaces of the TEM.

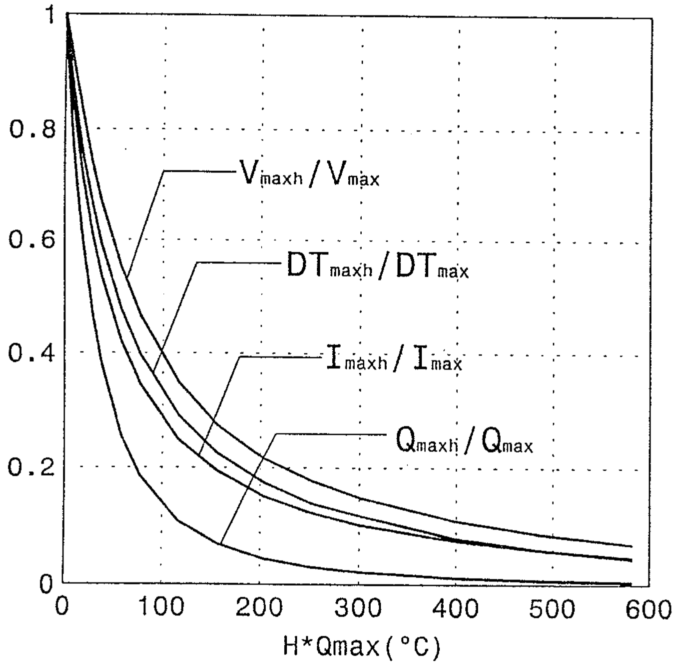

FIGURE 1. Correction factors for derating module performance specifications.

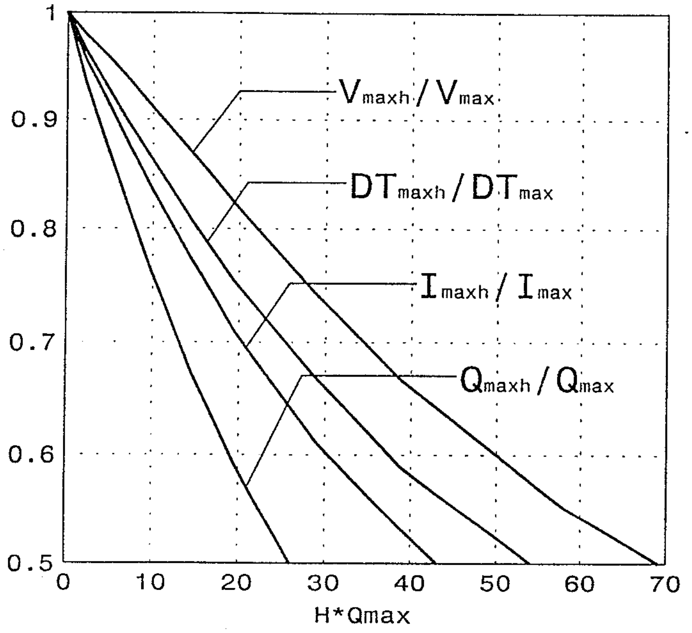

FIGURE 2. Correction factors in a module's typical operating region.

Figures 3 through 6 examine the effects of HSR, internal resistance, heat loss conductance, and constant heat loads on I_{max}. These cases were modeled with a 127 couple, 8 Ampere module similar to a Melcor CP1.4-127-045. Current was increased, in each case, until net cooling from the TEM decreased. Figure 3 shows the effect of increasing the HSR of the cooling system from 0 to 0.5°C/Watt. Figure 4 shows the effect of increasing ρ by up to 50% and thereby increasing module resistance by 50%. This simulates a redoping of the thermoelectric material. Figures 5 and 6 show the effects of constant and proportional heat loads on cooling performance.

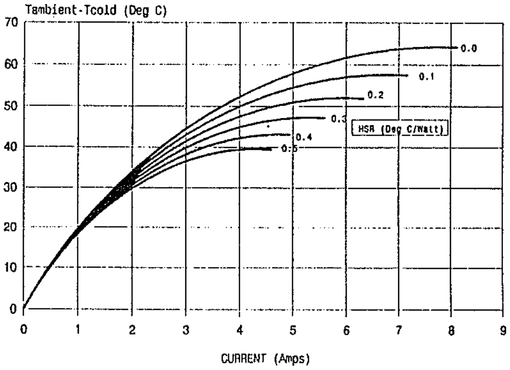

FIGURE 3. The effect of heat sink resistance on cooling performance for a 127 couple, 8 Amp module.

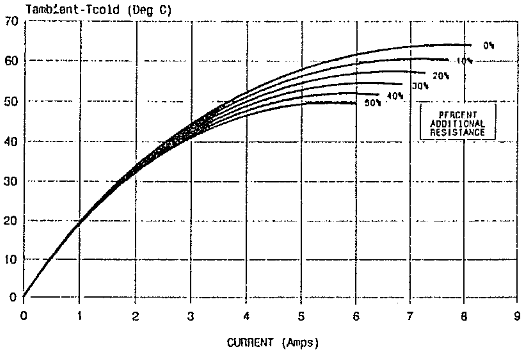

FIGURE 4. The effect of additional internal resistance on the cooling performance of a 127 couple, 8 Amp module.

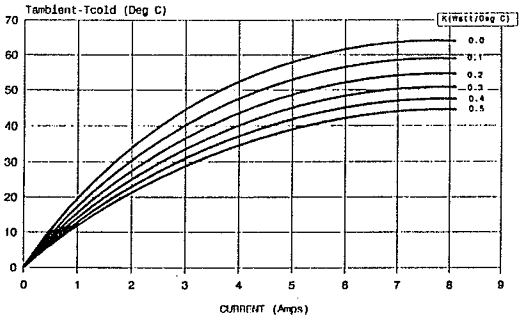

FIGURE 5. The effect of a heat loss conductance on the cooling performance of a 127 couple, 8 Amp module.

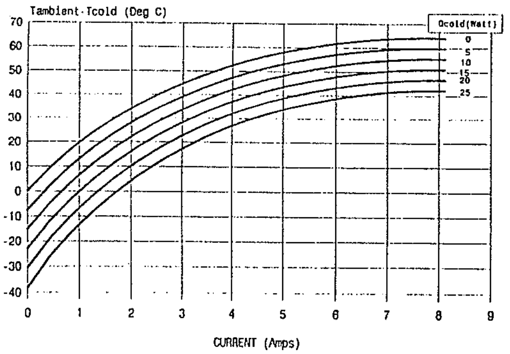

FIGURE 6. The effect of a constant heat load on the cooling performance of a 127 couple, 8 Amp module.

RESULTS

Figures 1 and 2 show that, for any given TEM, maximum cooling parameters must be degraded as the product of HSR*Q_{max} increases. Figure 3 reinforces Figures 1 and 2 by showing a specific case where I_{max} is decreased by an increasing HSR. DT_{max} is achieved at successively lower and lower current as HSR is increased from 0.0 to 0.5°C/Watt.

Internal resistance also affects I_{max}. Figure 4 shows that I_{max} is reduced from 8 Amps to about 5.5 Amps when the TE material resistivity is increased by 50%.

Additional heat loads, both constant and proportional, do not affect I_{max}. An increase in the module or system loss conductance, shown in Figure 5, will decrease DT_{max} with respect to ambient, but I_{max} still occurs at the same point (about 8 Amps). Constant heat loads also affect the maximum DT with respect to ambient, but do not affect I_{max}. Heat load is increased from 0 to 25 Watts in Figure 6, but I_{max} remains constant at 8 Amps in each case.

DISCUSSION

The data presented provides the user with several design and troubleshooting options. For any given HSR and module combination, the user can determine V_{maxh}, I_{maxh}, Q_{maxh}, and DT_{maxh}. Figures 1 and 2 show that, for any given TEM, maximum cooling parameters must be degraded as the product of HSR*Q_{max} increases. As an example, let us examine the use of a Melcor CP1.4-127-06 with a 0.4°C/Watt HSR. We find from Melcor's data sheets that V_{max}=15.4 Volts, I_{max}=6.0 Amps, Q_{max}=51.4 Watts and DT_{max}=67°C. The product of Q_{max} and HSR is 0.4 x 51.4 = 20. From Figure 2 we find that the derating factors are about 0.82 for V_{maxh}/V_{max}, 0.70 for I_{maxh}/I_{max}, 0.58 for Q_{maxh}/Q_{max} and 0.75 for DT_{maxh}/DT_{max}. Thus, for the cooling system, V_{maxh} = 0.82 x 15.4 = 13 V, I_{maxh} = 0.70 x 6 = 4.2 Amps, Q_{maxh} = 51.4 x 0.58 = 30 Watts, and DT_{maxh} = 0.75 x 67=50°C (with respect to ambient). This data can be used to determine if needed cooling specifications can be satisfied or if a specific voltage or current will exceed the system's limits for maximum cooling.

The data presented in Figures 3 through 6 allow the user to analyze a system if performance goals are not met. These diagnostic test can be done without dismantling or disassembling the TE system. By stepping current until the point of maximum cooling is reached, the designer can compare this value with calculated or previously measured values of I_{max}. If I_{max} has shifted, then the designer knows either the module's material has been redoped or there has been a change in heat sink resistance. If the module's material has been redoped, a simple check with an AC resistance meter may expose this problem. Changes in HSR may come from simple to detect problems such as a dirty heat sink or malfunctioning fan which restricts heat transfer.

Miscalculated heat loads do not effect I_{max}. Therefore, if I_{max} has not shifted and cooling is not up to specification, an underestimated proportional or constant heat load may be the culprit. Extra proportional heat loads can come in the form of plate-to-plate losses between heat and cold sinks, or in a poorly insulated system. A cold side fan which draws more power than expected may represent an additional constant heat load.

CONCLUSION

The presented derating curves allow the TE system designer to find new maximum device parameters for any TEM and heat sink combination. TEM device parameters must all be derated if the module is to be attached to a heat sink whose temperature varies with its heat rejection (i.e. HSR>0). A method for diagnosing malfunctioning systems was also presented. By finding I_{max} of the system and comparing it to the calculated or previously measured I_{max}, several failure modes can be identified. If a shift in I_{max} has occurred, HSR or internal resistance of the module has shifted. If no shift in I_{max} is evident, an additional constant or proportional heat load is present.

REFERENCES

Buist, R.J., "Universal Thermoelectric Design Curves," in *Proceedings of the 15th Intersociety Energy Conversion Engineering Conference*, Seattle, Washington, USA, August 18-22, 1980.