Universal Thermoelectric Design Curves

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UNIVERSAL THERMOELECTRIC DESIGN CURVES

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Abstract

A method has recently been introduced which enables present or potential users of thermoelectric heat pumps to specify or analyze any single-stage cooling application. This method was derived through computer analysis of temperature dependent thermoelectric theory applied to a generalized thermoelectric heat pump. Design parameters for the cooling mode normalized to their respective "maximum cooling" values were found to be relatively invariant as a function of base temperature. This introduced a set of universal design curves applicable over a base temperature range of -125°C to +125°C.

This method has now been expanded to include the performance of a heat pump in the reverse, or heating mode of operation. The same design parameters are used together with the same normalization constants derived from the maximum cooling condition. Although inclusion of the heating mode quadrant to the universal design curves introduces some complications, it nonetheless affords a more complete understanding and characterization of a thermoelectric heat pump.

Device Parameters

The parameters describing a thermoelectric heat pump and its performance are referred to as "device" parameters as given below:

N = number of thermoelectric couples
λ = length/area of thermoelectric pellet
I = current
V = voltage
Q = heat absorbed by heat pump top side
T_B = heat pump base temperature
T_T = heat pump top temperature

Design Parameters

Analysis of the fundamental equations governing thermoelectric effects has revealed the fact that certain combinations of various "device" parameters are invariant with geometry. In fact, in the final analysis with a given set of thermoelectric N and P-type materials, these design parameters are functions only of the temperatures T_B and T_T:

$I\lambda$: current capacity
V/N: voltage capacity
$Q\lambda/N$: heat pumping capacity
ΔT: temperature differential, $T_B - T_T$

The cooling performance of a thermoelectric heat pump operating from a constant heat sink temperature is essentially parabolic. That is, ΔT increases rapidly at low currents but Joule heating eventually dominates at high currents resulting in the existence of a maximum ΔT: ΔT_m. $I_m\lambda$ and V_m/N are the respective design parameters at this condition. If heat is applied to the top of the heat pump, the ΔT will decay linearly with applied heat. The intercept or point where $\Delta T = 0$ is $Q_m\lambda/N$. As stated before, design parameters are functions only of the boundary temperatures but these maximum design parameters reduce to functions only of T_B as shown in Figure 1.

Normalization

The interdependence of the design parameters over the continum from zero to their maximum values can be conveniently defined by utilization of a normalization process. That is, each design parameter is normalized by the respective maximum value defined above. The results are illustrated in Figure 2. The locus of points for the optimum or maximum C.O.P. = Q/IV condition is plotted defining the set of design parameters for each ΔT which results in minimum input power for a given heat load.

The I vs. V characteristics are shown in Figure 3. Voltage is not only dependent on current but also upon ΔT. That is, voltage varies linearly along any given constant current line of Figure 2. It is largest at the respective maximum ΔT intercept due to Seebeck voltage and decays to the Ohmic or zero ΔT value. These boundary values are shown together with their mathematical average in Figure 3. The convergence at high current is due to temperature dependence of thermoelectric material parameters. For the purposes of simplicity in design and analysis, the average voltage is usually used introducing typically less than 5% error.

Cooler Design

Design of a cooler begins with the specification of T_B and T_T followed by the determination of the maximum parameters from Figure 1. The optimum set of design parameters is then determined from these values applied to Figure 2. The quantity N/λ is subsequently determined from the optimum $Q\lambda/N$ and the specified heat load, Q, to be pumped by the device. Finally, the closest standard module to the determined N/λ is chosen from Table 1. With geometry thus specified, a performance chart for any T_B is formed by converting the maximum design parameters to maximum "device" parameters and applying these to Figures 2 and 3.

The combination of Figure 1 with Figures 2 and 3 provides all the data to optimize, characterize, or analyze literally any single stage Marlow Industries thermoelectric heat pump for use in any conceivable cooling application within a heat sink temperature range of -125°C to +125°C.

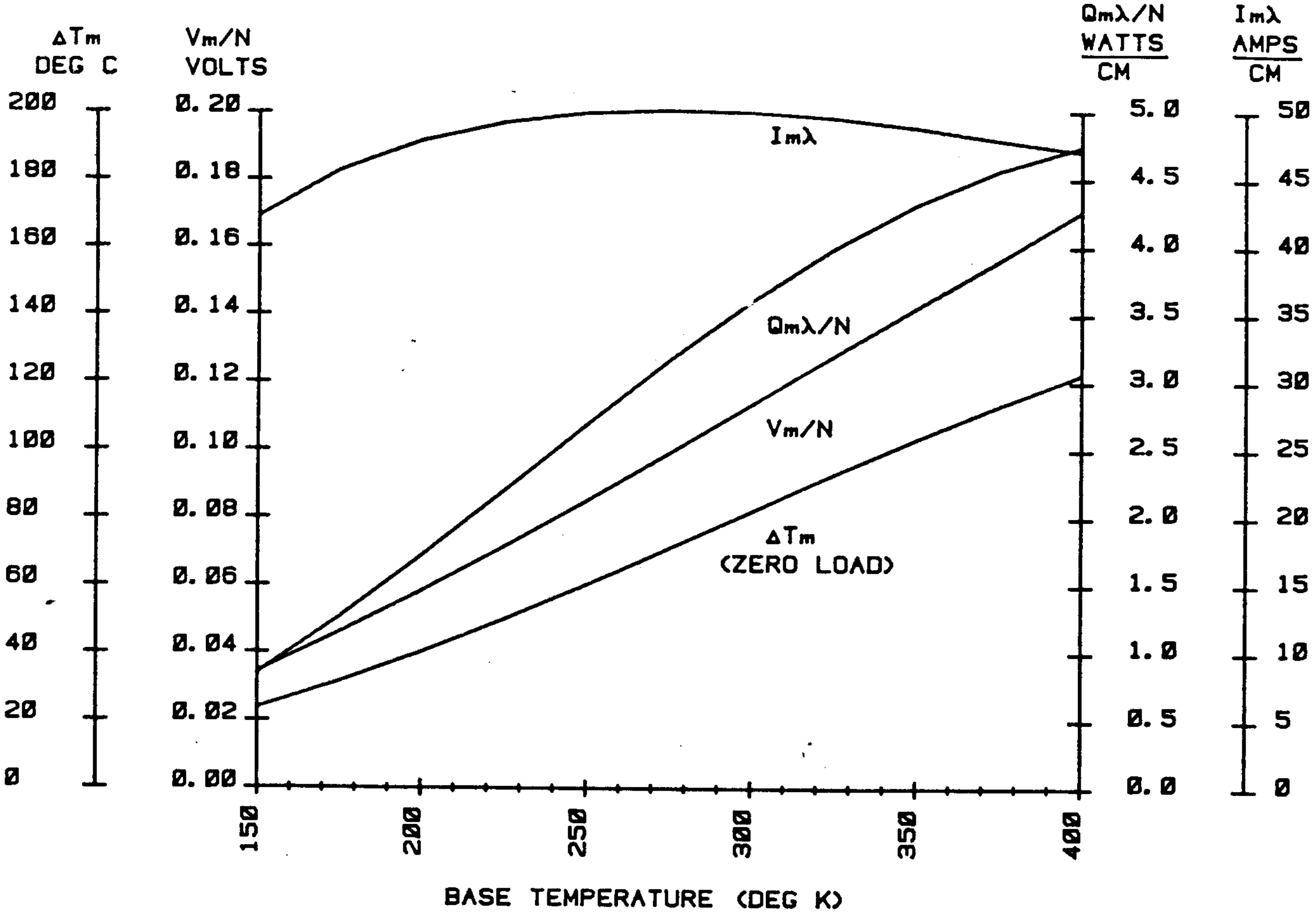

Fig. 1 Maximum design parameters vs. base temperature

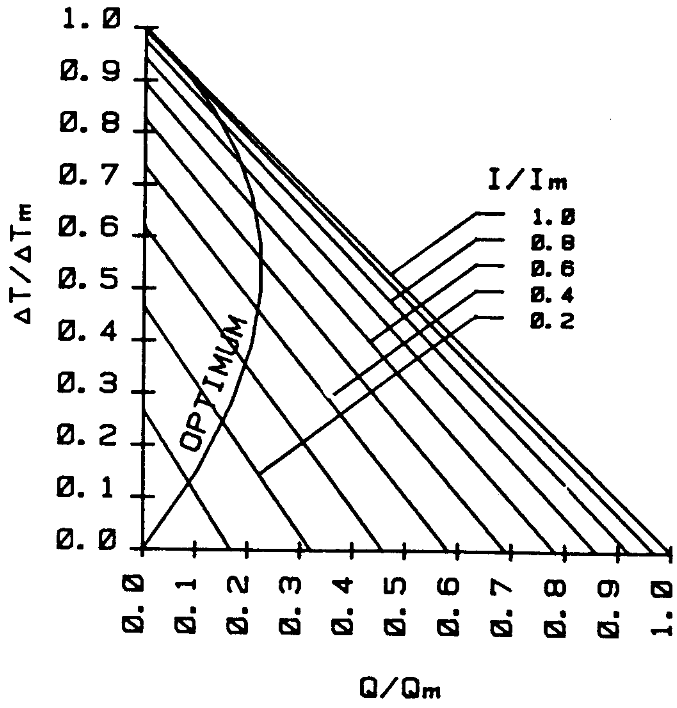

Fig. 2 Cooling mode performance chart

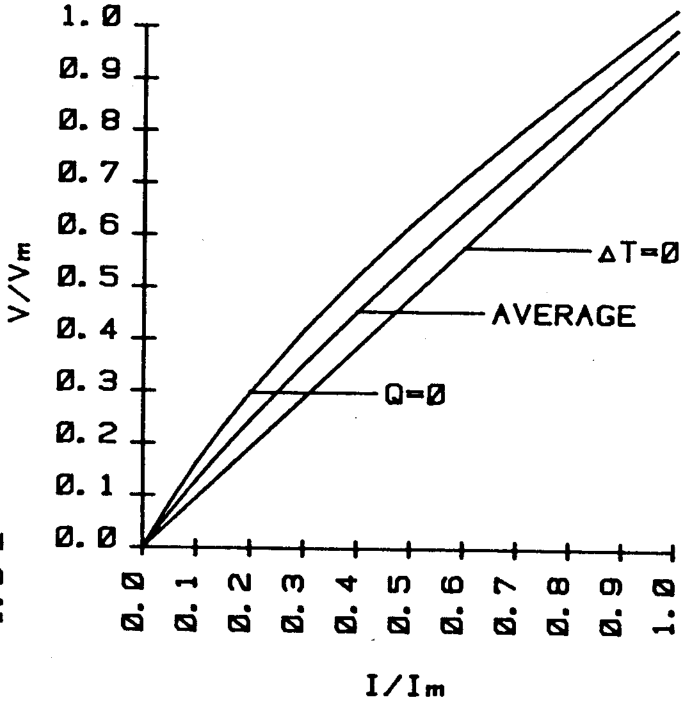

Fig. 3 Cooling mode voltage vs. current

TABLE 1 - STANDARD HEAT PUMPS

Model No.	N	λ (cm^{-1})	N/λ (cm)
MI 1063	71	7.27	9.766
MI 1142	31	3.27	9.480
MI 1120	31	4.14	7.488
MI 1092	31	5.18	5.985
SP 1198	39	7.27	5.365
SP 1226	71	13.94	5.093
MI 1062	35	7.27	4.814
MI 1050	35	9.21	3.800
MI 1023	71	25.20	2.817
MI 1061	17	7.27	2.338
MI 1140	7	3.27	2.141
MI 1013	71	49.21	1.443
MI 1090	7	5.18	1.351
MI 1022	31	25.20	1.230
SP 1022	10	9.21	1.086
SP 1078	54	50.39	1.072
MI 1060	7	7.27	0.963
SP 1161	39	49.21	0.793
MI 1021	17	25.20	0.675
MI 1012	31	49.21	0.630
SP 1237	7	13.94	0.502
MI 1025	11	25.20	0.437
SP 1085	10	27.00	0.370
MI 1011	17	49.21	0.345
MI 1020	7	25.20	0.278
SP 1288	11	49.21	0.224
MI 1010	7	49.21	0.142
MI 1024	2	25.20	0.079
MI 1014	2	49.21	0.041

Heating Mode

If negative current is applied to a heat pump, the thermoelectric effect reverses and heat is evolved at the top side. In addition to Joule heating, Peltier heat is "pumped" to the top side making a thermoelectric cooler more efficient than a resistive heater for most applications. The following discussion pertains to this heating mode and resulting data can be used to define and design heat pumps for this condition.

In reference to Figures 2 and 3, the heating mode performance would be graphically represented by the third quadrant or all negative combinations of ΔT, Q, I and V.

For example, the thermal and voltage design parameters normalized to the values shown in Figure 1 are plotted in Figures 4 and 5, respectively, for a set of T_B values from 150 to 300°K.

Figure 6 was formed by simply reading, plotting and connecting the $T_B = 300°K$ intercepts shown in Figure 4 for selected values of normalized current. Notice that the first quadrant is identical to the data in Figure 2. A similar design curve can be generated for any base temperature implicitly defined in Figure 4. Practically no changes in the first quadrant will occur and only slight changes will occur in the heating mode zero Q intercepts. Conversion of these graphs to "device" performance charts is accomplished exactly as for the cooling mode described earlier.

Although the "average" voltage curve can be used in the cooling mode with only slight error, the heating mode requires a more precise determination procedure. This is evident in Figure 5 at large negative currents where the two voltage intercepts diverge. This divergence is due to the fact that the Seebeck voltage increases with ΔT and the material property temperature variance tends to add to this effect rather than compensate as in the cooling mode. The voltage, V, for any given I and ΔT can be found by linearly scaling between the two voltage curves:

$$V = V_1 + (V_2 - V_1)\Delta T/\Delta T_2 \qquad (1)$$

where: V_1 = voltage at I for $\Delta T = 0$ (Fig. 5)
V_2 = voltage at I for $Q = 0$ (Fig. 5)
ΔT_2 = ΔT at I for $Q = 0$ (Fig. 4)

Notice that this method also can be applied to the cooling mode for more precise voltage calculations.

Conclusions

The introduction of design parameters plus normalizing them to their maximum cooling values has led to the derivation of universal design curves. These few simple graphs have been used effectively in the optimization and characterization of thermoelectric heat pumps for the cooling mode. Analysis of the heating mode has produced more comprehensive curves. These now enable the user to design for or determine performance of any Marlow Industries single-stage heat pump in the heating as well as cooling mode of operation.

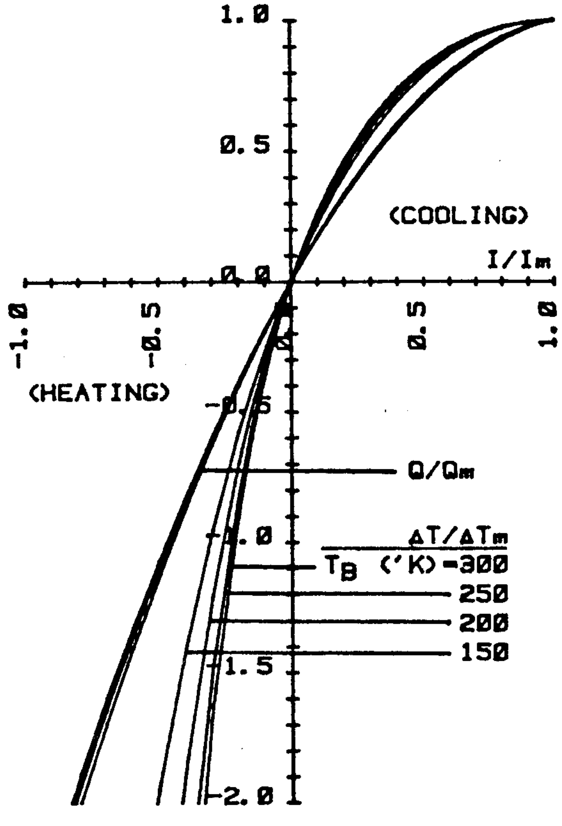

Fig. 4 Thermal characteristics vs. current

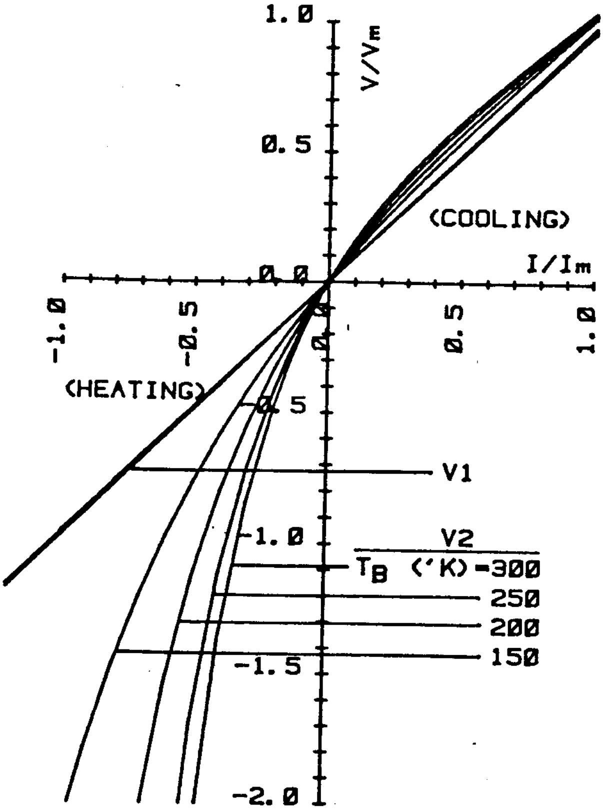

Fig. 5 Voltage vs. current

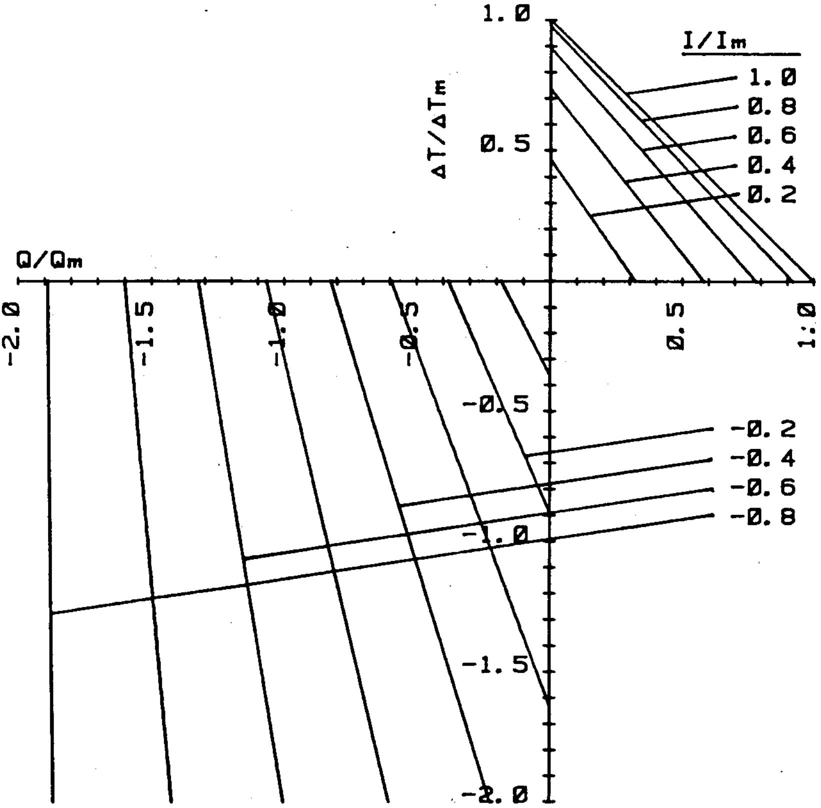

Fig. 6 Design curve for 300°K base temperature