DEVELOPMENT OF LOW TEMPERATURE AIR COOLED THERMOELECTRIC COLD PLATE

Gurevich Alex[1]

1- TES Thermoelectric Solutions Ltd, Yavne, Israel
Contact author: agurevich@tes.co.il

1. Introduction.

Environmental testing of electronic products is an important part of manufacturing process especially for the components meeting military standards. According to the Military Standard electronic components should perform regularly in the ambient temperature range of -55 C to 125 C. Many manufacturers especially in the field of high performance high power amplifiers need to make complex test using multiple equipment for the small manufacturing batches.
Existing environmental chambers providing required conditions are bulky and not convenient for small batches evaluations. Thermoelectric technology that allows to make compact cooling system seems as an optimal solution. But the existing thermoelectric chamber and cold plates reach the minimum temperature of about -40 C which is not sufficient for the mentioned application. The most efficient way to improve performance of TE system is complex optimization of all the system parameters (1)

To reach the specified temperature differential ambient to cold plate of 80 C the three stage cooling scheme was chosen.
During development process each stage was optimized

2. Optimization scheme.

The following optimization factors for each cooling stage were chosen: geometrical factor of the TE module, thermoelectric material performance at working temperature, number of the modules used in the stage, heat sinks and heat spreader characteristics, working voltage of each module.
Optimization parameters: temperature differential, cooling power, COP were calculated for each stage.
The optimization goal is to minimize energy consumption at required cooling power output for each cooling stage.
The cooling power of the TE module is calculated from the following equation:

$$Q_c = \frac{\Delta t_{\max}(I) - R_H * V(I) * I - \Delta t}{R_C + R_H + R_{cnt} + (1/(2 * N * k * G))} \quad (1)$$

Where:
$\Delta t_{\max}$ – the maximum temperature differential at specified working current I,
R_H, R_C - thermal resistances of the heat dissipating parts located on the hot and cold plates of the TE module,
R_{cont} - total contact resistance between the TE module plates and heat dissipating parts,
$V(I)$ - voltage drop on the TE module at specified working current I,
Δt - temperature differential between exterior media on the both sides of the thermoelectric system including the mentioned module,
N – number of couples in the TE module,
k – thermal conductivity of the TE material,
G – geometrical factor of the TE module.

The maximum temperature differential of the module at current I is equal to:

$$\Delta t(I) = \frac{\alpha * I * T_C - I^2 * \rho/(2 * G)}{k * G} \quad (2)$$

Where:

α - the Seebek coefficient,

T_C - temperature on the TE module's cold plate,
ρ - electrical resistivity of the TE material.
The voltage drop on the TE module is calculated as follows:

$$V(I) = \frac{k * G}{\alpha} * ((1 + 2 * Z * T_H)^{0.5} - 1) \quad (3)$$

Where:
Z-Figure of Merit of the TE material,
T_H - temperature of the TE module's hot plate.

Suppose that on the stage "m" the number of TE modules is n_m so the total cooling power of this stage is:

$$Q_{Cm} = n_m * Q_C \quad (4)$$

The power consumption for this stage is calculated as follows:

$$Q_{Pm} = 2 * N * (I * \rho / G + \alpha * (T_H - T_C)) * n_m \quad (5)$$

To simplify calculations procedure we have introduce a new parameter – relative current:

$$i = I / I_{\max} \quad (6)$$

Where:
$I_{\max}$ - the maximum current of the TE module.
The system of equations (1) – (6) has been used to optimize design of the cold plate according to the following general scheme:

- For each stage the power consumption Q_{Pm} is minimizing at constant cooling power Q_{Cm} by variation of the following variables: n_m, i and G.

The optimization procedure is starting from the coldest (third) stage. The required cooling power is calculated as a sum of thermal loses from the cold plate to environment and heat load of components to be tested:

$$Q_T = Q_L + Q_H$$

Where:
Q_T - total heat load on the TE modules,
Q_L - thermal loses,
Q_H - heat dissipation of the components to be tested.

For the second stage the required cooling power is equal to:

$$Q_{C2} = Q_{C3} + Q_{P3}$$

Where:
Q_{P3} - the optimized power input for the third stage.

The similar equation is for the first stage:

$$Q_{C1} = Q_{C2} + Q_{P2}$$

3. System design

A goal of the present work is to design low temperature thermoelectric cold plate according to the following specification:

Minimum cold mode temperature: - 60 C
Maximum hot mode temperature: 130 C
Ambient air temperature: 20 C
Hot side cooling medium: forced air
Cold plate dimensions: 200x250 mm
Maximum power dissipation of the component : 10 Watts
Maximum overall dimensions: 550 x 400 x 350 mm

As it was mentioned earlier we have started optimization from the coldest third stage. The required cooling power consists of two parts: heat loses from the plate at temperature of -60C to environmental air with temperature of 20C and heat dissipation of the component during the test.
The heat loses can be estimated as follows:

$$Q_L = \Delta t / (R_{p-a} + R_{ins})$$

Where:
Δt - temperature differential cold plate to environment
R_{p-a} - thermal resistance plate to surrounding air

R_{ins} - thermal resistance of insulating material covering the cold plate.

Numerical values for these parameters have been calculated as follows:
$\Delta t = 80$ C
R_{p-a} = 4 C/W
R_{ins} = 4.5 C/W
So the heat loses are equal to 8.4 Watts and the required cooling power of the TE modules located on the third stage is 18.4 Watts.
According to application requirements the cold plate is made of aluminum with dimensions of 250 x 200 x 10 mm. Assuming that a load is distributed evenly over the surface of the cold plate the spreading thermal resistance R_{C3} can be estimated based on thermal spreading calculations made using the finite elements software COSMOSM as follows:

R_{C3} = 0.03 C/W

This value was achieved based on assumption that tested component are attached directly to the cold plate with good thermal contact.
The hot side thermal resistance of the third side is calculated by the similar way, only the heat spreading plate on this side is made of copper and the thickness is 3 mm:

R_{H3} = 0.05 C/W

Temperatures of the TE modules cold and hot plate were chosen as follows:

T_H = -33 C, T_C = -60 C

Due to the fact that this stage is operating at low temperature of -33 C on the hot side we have used special TE material for these modules. Performances of the material were optimized for about average temperature of -40C.

Optimization was performed using Multicriteria Optimization Software IOSO MN .
Optimization analysis was made for the three variables: relative current i, geometrical factor of the module G and number of modules in the stage n_3.
Two constrains were used:

$$I_{\max} = \frac{k*G}{\alpha} * ((1 + 2 * Z * T_H)^{0.5} - 1) \quad (7)$$

And Q_{C3} = 18.4 Watts , where Q_{C3} is calculated according to the equation (1).
The objective of optimization was power consumption Q_{P3} calculated according to the equation (5).
Results of optimization for the third stage are as follows: i = 0.45, G = 0.12, n_3 = 4.
The optimized power consumption of 47 Watts was found. Temperature differential reached on the stage was 23 C.
For the second stage temperatures are defined as follows: T_{C3} = -32 C, T_{H3} = -5 C. So the average temperature of this stage is -23.5 C and the regular TE material can be used for this stage. The required cooling power:

$$Q_{C2} = Q_{C3} + Q_{P3} = 18.4 + 47 = 65.4W$$

Thermal resistances were calculated using the heat spreading formulas (3) for the copper spreading plates with thickness of 3 mm on the both sides of the modules:

R_{C2} = 0.09 C/W and R_{H2} = 0.07 C/W

Optimization for the three variables i, G and n_2 was performed at constrains (7), Q_{C2} = 65.4 Watts and Δt_2 = 27 C.
The objective (power consumption Q_{P2}) calculate according to the equation (5).
The optimal variables for the stage two were found as follows: i = 0.51, G = 0.12, n_2 = 12.
The optimized power consumption for the second stage is Q_{P2} = 281 Watts.
Using the data receive from optimization of the second stage we have defined cooling power required for the modules located on the first stage:

$$Q_{C1} = Q_{C2} + Q_{P2} = 65.4\text{W} + 281\text{W} = 346.4\text{ W}$$

Thermal resistance on the cold side is calculated using heat spreading formulas for the copper plate with thickness of 3 mm:

R_{C1} = 0.05 C/W

For the hot side heat dissipation forced air convection was specified. The bonded fins heat sinks were used with two axial fans. The following parameters of the heat sinks were used for calculations:
Length: 180 mm, width: 73.5 mm, base plate thickness: 8 mm, fins height: 62 mm, fins thickness: 1.2 mm, fins space: 2.4 mm. Each heat sink was designed for two TE modules. Assuming that average air flow rate through the fins is 5 m/s thermal resistance of 0.2 C/W per each module was received. The calculations were performed using finite elements software Cosmos M.
Temperatures of the TE modules plates for the first stage were as follows: T_{C1} = -5 C, $T_{H1} = 35C$. So the average temperature of TE material is 15 C and the regular TE material can be used.

Optimization of the three variables i, G and n_1 was performed at the constrains (7) and Q_{C1}= 346.4 Watts and Δt = 40 C. The objective of optimization was power consumption of the first stage Q_{P1}.
The optimal variable for the first stage were found as follows: i = 0.75, G = 0.17, n_1 = 24.
The optimized power consumption for the first stage is: Q_{P1} = 1730 Watts.

4. Testing of real system.
Based on the optimized design the real cold plate was designed and fabricated.
The system has overall dimensions of 530 x 370 x 310 mm. The cold plate has dimensions of 250 x 200 mm and made of aluminum Al6063. The cold cavity on top of the cold plate was insulated using polyethylene foam with thickness 50 mm. The heat spreading plates were made of copper. The heat sinks located on the first stage were made boding fins to the base plate using heat conductive epoxy. Air flow on the first stage was supplied by two axial 230 VAC fans with the maximum air flow of 200 CFM.
Evaluations made on the units showed that the cold plate reaches required temperature range of -60 C at cooling mode and 130 C at heating mode. The maximum ambient air temperature during the test was 20 C.
Based on successive evaluation a batch of Cold Plate was manufactured and supplied to the customers.

References:

1. Crane D. T. Modeling High-Power Density Thermoelectric Assemblies Which Use Thermal Isolation. Proceedings 22nd International Conference on Thermoelectrics, Herault, France, August 2003.