Thermoelectric Cooling With Constrained Heat Removal

V. Semenyuk[1,2], R. Dekhtyaruk[1]

[1]*THERMION Company, Odessa, Ukraine, E-mail: semeniouk@thermion.tenet.odessa.ua*
[2]*Odessa State Academy of Refrigeration, Odessa, Ukraine*

Abstract

Considered is the problem of application of thermoelectric coolers (TECs) for thermal management of electronic and electro-optic devices under the conditions of constrained system size and power. The limit combinations of the initial constraints whose presence makes the maintaining of the given temperature conditions impossible are determined. It is shown that under less severe constraints, the use of a TEC allows to considerably reduce the cooled object temperature as compared with the option of passive cooling. The results of development of thermoelectric system for cooling CPU with thermal output of up to 67 W, the system sizes being limited to 60x60x60 mm, are presented.

Introduction

Thermoelectric coolers find wide application for thermal management of electronic elements and systems with high density of heat dissipation. Such are semiconductor lasers, power amplifiers and processors of modern personal computers. When cooling such objects, one meets a row of problems, resulting from the system size and power constraints. In particular, the most widespread problem is constrained heat rejection from TEC hot junctions. It would be not practical to use a cumbersome heat sink in the device, destined for cooling of a miniature object. This is why, in the applications under discussion the heat sink dimensions are limited, its thermal resistance is relatively high and this may lead to considerable overheat of a TEC hot side over ambient temperature. Another conjugated problem is in the fact that the development of modern microelectronics exhibits a tendency to increase heat flux density what procreates additional difficulties for the creation of prospective electronic and electro-optic devices and systems.

It should be kept in mind that TEC is an energy consumer itself. Its use leads inevitably to the increase in the overall heat load at the heat exchanger, hampering the heat removal process. As a result, the expected effect may not be assured – in stead of additional cooling, the rise of the cooled object temperature may take place. In particular, it may occur when the choice of the TEC configuration does not meet the requirements of minimum power consumption. Under such conditions, the substantiated choice of a TEC configuration and its operating mode becomes of primary importance.

The influence of the heat exchange conditions on the TEC performance has been considered by many authors [1-3]. The problem of a TEC application under the conditions of restrained heat removal from its hot junctions was discussed in [4, 5]. In [4], the use of a TEC is interpreted as a method of heat removal intensification equivalent to the increase of heat exchanger efficiency. It was demonstrated that the use of a TEC is sensible for small temperature differences, when the coefficient of performance (COP) is within 2 to 3.

The following question retains to be the most important: what could be the upper limit value of thermal resistance at the TEC hot side at which the maintaining of specified cold side temperature is still available. Solution of this problem will allow to determine the physical feasibility of the system under consideration and to formulate reasonable technical requirements. Another important approach is to define the minimum available temperature of the cooled object compatible with the specified limits to the system size and parameters.

This paper gives the solution of these problems. The generalized approach to thermoelectric cooling under the conditions of restrained heat removal is given and the ultimate combinations of the initial restrictions, defining the limit confines for the system feasibility are determined. The results of development of a TE system for cooling CPU with the thermal output up to 67 W, the system dimensions being limited to 60x60x60 mm, are presented.

1. Statement of the problem

There is an object of specified dimensions with dissipated power Q_c and a heat exchanger with thermal resistance R_h. The ambient temperature is constant and equals T_a. The maximum operating temperature is limited to $T_{c\max}$. In the absence of a TEC (passive cooling option), the heat exchanger maintains the temperature of the cooled object T_{c0} at the level of $T_{c0} = T_a + Q_cR_h$. The case with $T_{c0}>T_{c\max}$ is considered, when the passive cooling does not provides safe temperature of the cooled object and there is a need for a TEC.

The problem is to select a TEC which could provide the required temperature $T_c \le T_{c\max}$ with minimum power consumption.

2. Initial equations

The interconnection of the TEC cold side and hot side temperatures T_c and T_h with the corresponding heat flows Q_c and Q_h at the TEC external surfaces can be given by the following equations [1]:

$$Q_c = (\alpha i T_c - \frac{1}{2} i^2 \rho l - \frac{\lambda}{l}(T_h - T_c))F = const \qquad (1)$$

$$Q_h = (\alpha i T_h + \frac{1}{2} i^2 \rho l - \frac{\lambda}{l}(T_h - T_c))F \qquad (2)$$

$$T_h = T_a + Q_h R_h \qquad (3)$$

where α, ρ, λ - are the averaged Seebeck coefficient, electric resistivity, and the thermal conductivity of semiconducting materials corresponding; i - is the current density; F - is the total surface of the TEC cold/hot junctions; l - is the thermoelement height.

The coefficient of performance (COP) of a TEC can be expressed as:

$$\varepsilon = \frac{Q_c}{Q_h - Q_c}. \tag{4}$$

Let us consider the condition of the $\varepsilon(i)$ maximum for the case, when the hot junctions temperature depends on the current density *i.* Taking into consideration the relations (1) – (3) one finds that ε is a composite function of the form $\varepsilon = \varepsilon(i, T_h(i))$, so the equality

$$\frac{d\varepsilon}{di} = \frac{\partial\varepsilon}{\partial i} + \frac{\partial\varepsilon}{\partial T_h}\frac{dT_h}{di} = 0 \tag{5}$$

have to hold true in the point of the maximum.

When using consequently the relations (4) and (3), one finds that with Q_c=const, the condition $\varepsilon(i) = \max$ gives minimum to both Q_h and T_h values, i.e. equality (6) become true

$$\frac{dT_h}{di} = 0 \tag{6}$$

and so the condition (5) reduces to the following form:

$$\frac{d\varepsilon}{di} = \frac{\partial\varepsilon}{\partial i} = 0. \tag{7}$$

The result obtained means that for the considered TEC model with thermal resistance at the hot junctions the same extreme conditions are valid as those for the idealized case with the constant T_h value, and consequently, the well-known extreme relations are still applicable [6, 7]:

$$i_\varepsilon = \frac{\alpha(T_h - T_c)}{\rho l(M-1)} \tag{8}$$

$$\varepsilon_{\max} = \frac{T_c}{T_h - T_c}\frac{M - T_h/T_c}{M+1} \tag{9}$$

where

$$M = \sqrt{1 + z\frac{T_h + T_c}{2}}, \qquad z = \frac{\alpha^2}{\rho\lambda} \tag{10}$$

The difference consists in the fact that for the case under consideration the temperature T_h is unknown and needs to be determined. The corresponding solution can be obtained by equating the right parts of the equations (4) and (9). With consideration (3), one finds a simple relation for determination of T_h value:

$$T_h^2 - (MT_c + T_a - M\theta)T_h + T_c(MT_a - \theta) = 0 \tag{11}$$

where $\theta = Q_c R_h$ - is the complex, which defines the overheating of cooled object over ambient in the absence of a TEC.

The approximate value of T_h can be obtained directly from the equation (11), assuming M=const. For instance, one may use the expression $M = \sqrt{1 + zT_c}$ instead of formula (10). The value of T_h obtained from (11) is used then in (10) to obtain more specific M value. The successive approximation is repeated until the next T_h value coincides with the previous one within the preset accuracy.

3. Permissible R_h Upper Limit

It can be shown that the equation (11) contains all the necessary information concerning the permissible upper limit of thermal resistance at a TEC hot side, compatible with the condition of attainability of the specified cold side temperature T_c. Indeed, the solution of the equation (11) exists in only case, when its discriminant is nonnegative. With this condition, one obtains the following inequality:

$$\theta \le \left(\frac{\sqrt{T_c(M^2 - 1)} - \sqrt{MT_a - T_c}}{M}\right)^2 \tag{12}$$

which determines the physical feasibility of the system with specified T_a and T_c temperatures. The condition (12) being not fulfilled (the thermal resistance of heat exchanger and/or the Q_c value are relatively high), the stationary state of the cooled object with the given temperature T_c cannot be achieved. The equality in the expression (12) determines the looked for maximum vale of the complex $\theta = \theta_{\max} = (Q_c R_h)_{\max}$.

It should be noted that the Q_c and R_h values enter into the parameter Θ not as they are, but in a form of product, hence the reduction of heat emission of the cooled object and the heat exchanger thermal resistance decrease are the alternative ways of achieving the specified thermal conditions.

Figure 1 shows the dependence of $\Theta_{\max}$ on T_a at different T_c values. To plot the dependences, the equality in the relation (12) was used. It should be noted that the M value in (12) is a function of the temperature T_h, which is unknown at the beginning of calculations. It can be determined by successive iterations analogous to those described above. For the beginning the value T_h=T_c can be used. Then the values of M and $\Theta_{\max}$ can be obtained from (10) and (12) to be applied for more exact T_h value definition.

The dependences at the Figure (1) allow to find the limits of the Θ value for different temperature combinations and to separate the feasible options from unrealizable ones. For instance, at T_a=310 K, the temperature of the cooled object can be maintained at T_c=320 K in only case when Θ does not exceed 25 K.

4. Minimum Attainable Temperature

Let us consider now another practical case, when the preset parameters are Q_c and R_h, i.e. the value of complex Θ=$Q_c R_h$ is determined and cannot be varied. The question arises: what is the minimum temperature that can be achieved using TEC and how low will it be as compared to the passive cooling? Considering the discriminant in (11) as a function of T_c, one comes to the following condition:

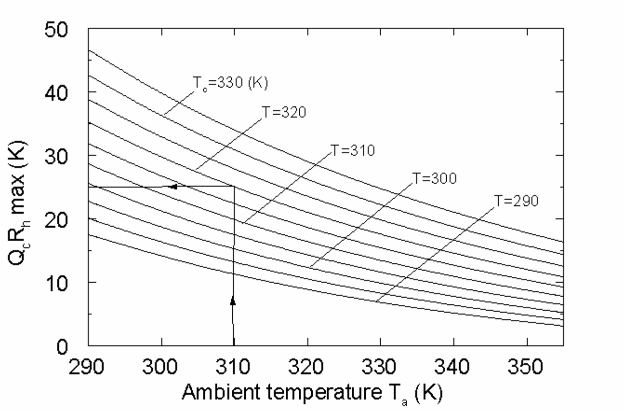

Fig. 1 The dependence of the complex Q_cR_h upper limit on the ambient temperature at different temperatures of the cooled object.

$$T_c \geq \left(\frac{\sqrt{\theta(M^2-1)} + \sqrt{MT_a - \theta}}{M} \right)^2, \quad (13)$$

where the equality in (13) corresponds to the lowest achievable temperature of the cooled object $T_{c\min}$.

The relation (13) was used to calculate $T_{c\min}$ for different T_a and Θ values, the M value being specified by successive iterations, as it was done earlier when calculating $\Theta_{\max}$. The results of calculations are presented in the form of dependences of the additional (as compared to the passive cooling) temperature lowering $\Delta T_c = T_{c0} - T_{c\min}$ at different Θ and T_a (Fig. 2).

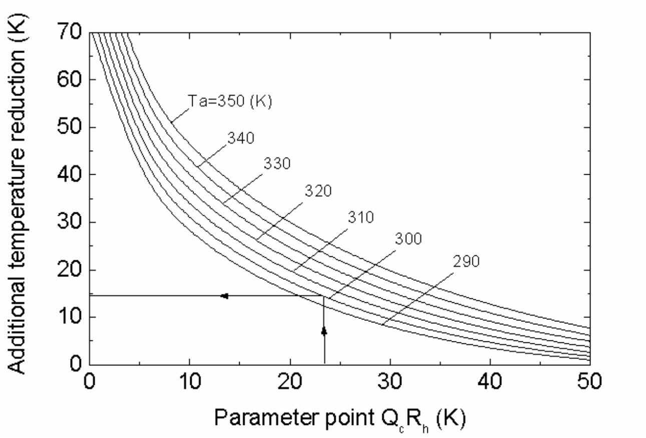

Fig.2 Dependence of additional (as compared to passive cooling) temperature reduction on parameter Q_cR_h at different ambient temperatures.

It is seen that the advantage is increasing with improvement of heat removal and with increase of ambient temperature. For instance, at Θ=23.5 K and Ta=300 K, the use of a TEC provides an additional temperature decrease by 15 K while at Θ=15 K, the additional effect of 25 K becomes available.

5. Optimum TEC Configuration

Let us consider again the general case, when the temperatures T_a, T_c, and the complex Θ are preset, and it is proved using the method described in the Section 3 that the parameter Θ does not exceed its maximum permissible level ($\Theta < \Theta_{\max}$), i.e. the system with the given parameters is physically feasible. Let us also assume that the TEC hot side temperature T_h is defined already. The further task reduces to finding such a TEC configuration that will provide minimum power consumption for the specified temperature conditions. The problem can be solved using the relations (1) and (8). For this purpose we reduce (1) to the following form:

$$\frac{F}{l} = \frac{Q_c}{\alpha j T_c - \frac{1}{2} j^2 \rho l - \lambda (T_h - T_c)} \quad (14)$$

where $j=il$.

At given T_c and T_h, the relation (8) defines uniquely the $j_\varepsilon = i_\varepsilon l$ value which corresponds to the COP maximum, so the ratio F/l can be also calculated. It should be noted that the theory does not impose restrictions separately on F or l values. This provides definite freedom when choosing these parameters on the condition that the F/l ratio is kept constant. The corresponding choice can be based on the geometrical compatibility of the TEC and the cooled object. For instance, the surface area of the TEC may be chosen equal or approximately equal to the cooled object surface area, what predefines the height of the thermoelectric leg. The matter of dicing of the total TEC area onto separate TE pellets is not connected with the process of a TEC optimisation and can be considered at the last stage of the design, basing on the power supply requirements. If the feeding current I is fixed, the junction area s and thermoelectric branches number n can be defined by the equalities $s=I/i_\varepsilon$ and $n=F/s$. The voltage U being preset, the TEC electric power $P=Q_c/\varepsilon_{\max}$ and electrical current $I=P/U$ need to be determined first and then the task is reduced to the previous one.

6. Experiment

The results obtained were used for developing TEC destined for cooling Athlon 64 3200+ CPU with thermal output up to 67 W at ambient temperature of 303 K. The surface area of the CPU body is 60x60 mm. On the condition of compactness, the system dimensions were limited to 60x60x60 mm, including TEC, heat exchanger and fan. The following question was under consideration: what additional cooling can be obtained using TEC as compared with passive heat rejection in view of specified dimensional constraints.

The cooler implemented according to our optimization procedure comprises 9 TE modules with the top and bottom dimensions 15x15 mm, each containing 96 TE pellets with the height of 0.5 mm and the cross-section of 1x1 mm.

The heat exchange system comprises heat exchanger in the form of finned copper plate and the fan FD1260255D from USUNG Company. The parameters of the heat exchanger are indicated in Table 1. The thermal load of the processor is simulated by the film heater on a ceramic plate 60x48 mm.

Table 1. Heat Exchanger Parameters

Dimensions (mm)	Numerical value
Base	60x60
Fin height	25
Fin thickness	0.18
Fin pitch	1.5

According to the calculations and measurements, the thermal resistance of the heat exchange system was 0.35 K/W, what provided the maintaining of the CPU temperature at the level of 326.5 K without TEC.

Fig.3 The general view of the cooling system

The general view of the assembly with the heat removal system is shown in Figure 3. The prototype was tested in the chamber maintained at 303 K with thermal load of 67 W. The measured were the TEC and the heater electrical parameters and the temperature of the system elements including heater and heat sink base as well as the temperatures of air at inlet and outlet of the heat exchanger.

Figure 4 shows the dependence of the heater temperature on the TEC current. It is seen that the minimum temperature of the heater 316 K is achieved at 3.35 A, what corresponds to the theoretical prediction. Thus, the use of the TEC resulted in achieving of additional temperature lowering of the cooled object by 10 K as compared to the passive cooling.

7. Prospects for Further Improvement

According to this study, the optimal TEC configuration is characterized by relatively large dimensions in comparison with the CPU hot spot. Thus the problem of the TEC and the CPU dimensional matching is still of current importance. To solve the problem, extremely short-legged TECs have to be created. The latest achievements in this field made it possible to multiply increase TEC cooling power density. Coolers with TE pellets as short as 200 and 130 microns are developed [8]. The use of these TECs with mini-contact pads which concentrate TEC cooling power made it possible to implement on-chip hot spot cooling [9] as a novel and effective means in IC technology.

Conclusion

The problem of the ultimate thermal resistance at a TEC hot side, when the TEC fails to proceed with maintaining given cooling temperature, is considered. Solution of this problem makes it possible to predetermine physical feasibility of the cooling system and to formulate the reasonable technical requirements. Such requirements being fulfilled, the use of a TEC allows to achieve considerably lower temperature in comparison with passive cooling.

To achieve the highest system efficiency, the optimum correlation of all the system parameters have to be done, including those for cooled object, a TEC, heat exchanger and a fan.

Obtained theoretical results are confirmed experimentally when developing a cooling system for CPU with the heat output of 67 W, the system dimensions being limited to 60x60x60 mm.

Further researches have to be carried out aimed to the reduction of the cooler area to the dimensions of CPU hot spot.

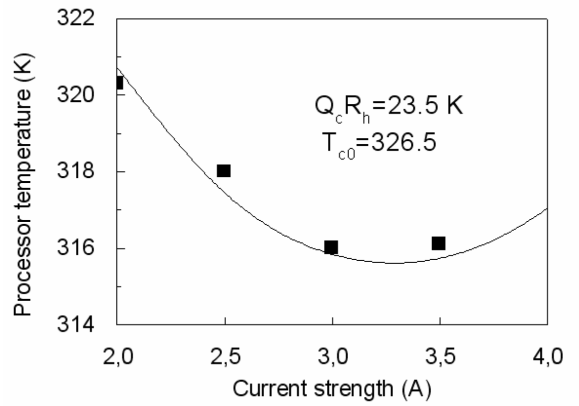

Fig.4 Dependence of CPU temperature on the TEC current.

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