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User-friendly and intuitive graphical approach to the design of thermoelectric cooling systems

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Abstract

This study proposes a user-friendly graphical method for calculating the steady-state operational point of a thermoelectric cooler (TEC)-based active cooling system, including the heatsink role. The method is simple and intuitive and provides comprehensive information about the cooling system such as its feasibility, required heatsink, the TEC current, temperatures of the cold and hot sides, and coefficient of performance (COP). The method could help designers to examine and choose a thermoelectric module from catalogues to meet a specific cooling problem. To start using the method, designers need only the experimental TEC data provided by practically all manufacturers of such devices. The experimental results of this study verify the high accuracy of the proposed model and graphical approach.

Keywords: Thermoelectricity; Process; Design; Calculation; Performance; COP

Approche conviviale et intuitive à la conception des systèmes de refroidissement thermoélectriques

Mots clés : Thermoélectricité ; Procédé ; Conception ; Calcul ; Performance ; COP

1. Introduction

The demand for small-size active cooling equipment has increased in recent years, since the traditional passive cooling systems (heatsink and fan) are not powerful enough to cope with the task of cooling a variety of modern electronic devices. One potential alternative solution is active cooling [1,2]. In various applications, thermoelectric active cooling systems can help maintain electronic devices at a desired temperature condition better than passive coolers. Thermoelectric coolers (TEC) are especially useful when the temperature of a device needs to be precisely controlled. The difference between passive and active cooling is depicted in Fig. 1. The passive cooling system (Fig. 1a) includes a heatsink, possibly with a fan, with thermal

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Nomenclature

a, b	segments of the y-axis of the plot giving information on COP (K)
COP	coefficient of performance, COP = cooling capability/electric power
I	electrical current (A)
I_{max}	data sheet parameter. The current that provides a temperature difference of ΔT_{max} under a specific T_h and heat flux $q_c = 0$ (A)
N	number of thermoelectric couples in the TEC
q_c	amount of heat dissipated by thermal load = amount of heat, pumped out by the TEC (W)
q_{cr}	required q_c in a specific application (W)
q_h	heat dissipated by heatsink (W)
Q_{max}	amount of heat that can be pumped by the TEC for $I = I_{max}$ and $T_h = T_c$ (W)
Q_{opt}	maximum possible amount of heat that can be pumped by the TEC for $T_h = T_c$, $Q_{opt} > Q_{max}$ (W)
R	electrical resistance of the couple (Ω)
R_m	electrical resistance of the TEC (Ω)
T_{amb}	temperature of the ambient air (K)
T_c	temperature of the cooling surface = temperature of the cold side of the TEC (K)
T_{ca}	$T_c - T_{amb}$ (K)
T_{car}	required T_{ca} in specific application (K)
TEC	thermoelectric cooler (chiller)
T_h	temperature of the hot side of the TEC (K)
T_{ha}	$T_h - T_{amb}$ (K)
U_{max}	data sheet parameter. The voltage drop across the TECs' terminals, corresponding to current I_{max} and the temperature difference ΔT_{max} (V)
V	voltage (V)
x, y	labels of the coordinate axes, argument and function correspondingly
α	Seebeck coefficient ($V K^{-1}$)
α_m	energy conversion coefficient of the TEC ($V K^{-1}$)
$\Delta T_{km}(I)$	apparent temperature source of the TEC with heatsink as a function of current (K or °C)
$\Delta T_{hkm}(I)$	apparent temperature source of the TEC with heatsink as a function of current for hot side (K or °C)
ΔT_{max}	data sheet parameter. The largest temperature differential that can be obtained between the hot and cold ceramic plates of a TEC for the given level of T_h and $q_c = 0$ (K or °C)
Θ	thermal resistance of the couple (K/W)
Θ_k	thermal resistance of the heatsink (K/W)
Θ_m	thermal resistance of the TEC (K/W)
$\Theta_{km}(I)$	apparent thermal resistance of the TEC with heatsink as a function of current (K/W)
$\Theta_{kmh}(I)$	apparent thermal resistance of the TEC with a heatsink as a function of current, for a hot side (K/W)

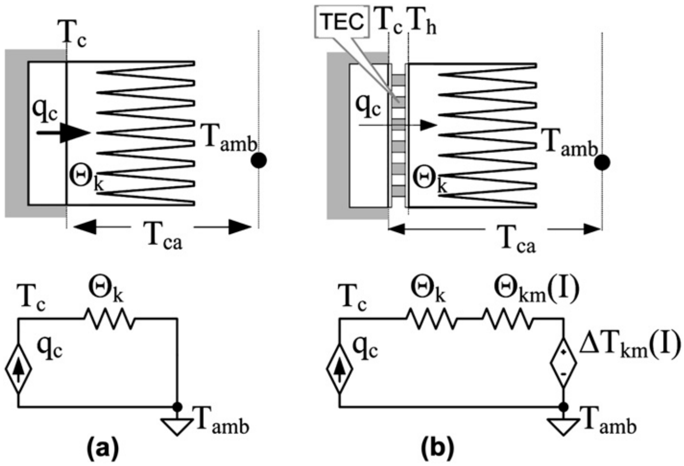

Fig. 1. Schematic representation of a passive (a) and an active (b) cooling systems, shown under similar system terms. T_c is the temperature of the surface of interest, q_c is the heat dissipated by the thermal load, T_{amb} is the ambient temperature, T_{ca} is the temperature difference between the surface and the ambient, $\Theta_{km}(I)$ is the apparent thermal resistance, and $\Delta T_{km}(I)$ is the apparent temperature source.

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resistance Θ_k (K/W). The active cooling system (Fig. 1b) uses an energy conversion process to absorb the thermal energy from the surface needed to be cooled and to pump this energy out. Active cooling can be realized by applying a thermoelectric (Peltier) cooler (TEC) and a heatsink of thermal resistance Θ_k.

The main problem of designing thermoelectric active cooling systems is the fact that the system depends on a large number of parameters. The parameters involved are thermal resistance of the heatsink, temperature of the ambient air, the many parameters of the TEC, and the electrical current through it.

The objective of this work has been to simplify the treatment of TEC-based cooling systems by applying a unified model. The paper proposes a universal graphical method for the design of TEC-based active cooling systems.

2. The unified TEC model

The behavior of a thermoelectric couple is determined by three fundamental parameters: Θ is the thermal resistance of the couple in the direction of the heat flow, R is the electrical resistance of the couple, and α is the Seebeck coefficient. Commercial TECs include N couples. Assuming that all couples are identical, and that the heat flow is unidirectional, the lumped parameters of the TEC α_m, Θ_m, and R_m will be:

$$\alpha_m = \alpha N \tag{1}$$

$$R_m = RN \tag{2}$$

$$\Theta_m = \Theta / N \tag{3}$$

Practically all TEC manufacturers ([3–5] and others) use the following parameters to specify their products: ΔT_{max} is the largest temperature difference (K) that can be obtained between the hot and cold ceramic plates of a TEC for the given level of hot-side temperature T_h, I_{max} is the input current (A) which will produce the maximum possible temperature drop ΔT_{max} across a TEC, and U_{max} is the DC voltage (V) that will deliver the maximum possible temperature drop ΔT_{max} at the supplied I_{max}.

As shown earlier [6,7], the following expressions can be used to calculate the fundamental TEC parameters from the set of data given by manufacturers (T_h, ΔT_{max}, U_{max}, I_{max}):

$$\alpha_m = \frac{U_{max}}{T_h} \tag{4}$$

$$R_m = \frac{U_{max}}{I_{max}} \frac{(T_h - \Delta T_{max})}{T_h} \tag{5}$$

$$\Theta_m = \frac{\Delta T_{max}}{I_{max} U_{max}} \frac{2T_h}{(T_h - \Delta T_{max})} \tag{6}$$

Following the first law of thermodynamics, one can express the energy equilibrium at each side of the thermoelectric module, defined as the cold (c) and hot (h) junctions. Note that all parameters taken, in first order approximation, are time invariable and temperature independent, and that the contribution of the Thomson effect is neglected, as suggested in Refs. [1,2].

For the absorbing (cold) side one can write:

$$q_c = \alpha_m T_c I - \frac{\Delta T}{\Theta_m} - \frac{I^2 R_m}{2} \tag{7}$$

and for the emitting (hot) side:

$$q_h = \alpha_m T_h I - \frac{\Delta T}{\Theta_m} + \frac{I^2 R_m}{2} \tag{8}$$

where q_c is the heat absorbed at the cold side of the TEC, q_h is the heat dissipated at the hot side, T_c and T_h are the temperatures of cold and hot sides, respectively, in K, and $\Delta T = T_h - T_c$.

The electrical section of the module is described as an electrical resistance R_m in series with an emf-source:

$$V = \alpha_m \Delta T + I R_m \tag{9}$$

Finally, the temperature of the hot side of the TEC can be expressed as a function of the heat transferred from that side to the passive heat removal (heatsink).

$$T_h = T_{amb} + q_h \Theta_k \tag{10}$$

Applying the set of equations (Eqs. (7)–(10)), one can eliminate the variables q_h, T_h, and V and get an expression for T_c, the temperature of the absorbing side of the TEC. The solution can then be used to develop an equivalent circuit type model of the TEC system (Fig. 1b) for which the temperature difference between the cooled side (T_c) and the ambient (T_{amb}), T_{ca}, is expressed as:

$$T_{ca} = (T_c - T_{amb}) = q_c(\Theta_k + \Theta_{km}(I)) + \Delta T_{km}(I) \tag{11}$$

where

$$\Theta_{km}(I) = \frac{(1 - I\alpha_m\Theta_k)^2 \Theta_m}{1 + I\alpha_m\Theta_m(1 - I\alpha_m\Theta_k)} \tag{12}$$

is the apparent thermal resistance of the TEC (Fig. 1b), and

$$\Delta T_{km}(I) = \frac{I^2 R_m \Theta_k + \left(\frac{I^2 R_m}{2} + I\alpha_m T_{amb}\right)\Theta_m(1 - I\alpha_m\Theta_k)}{1 + I\alpha_m\Theta_m(1 - I\alpha_m\Theta_k)} \tag{13}$$

is the apparent temperature source (Fig. 1b). This representation provides an intuitive understanding of the cooling process of a TEC. It shows that the TEC introduces a temperature difference $\Delta T_{km}(I)$ and an apparent thermal resistance $\Theta_{km}(I)$ both of which are dependent on the TEC parameters and the current I that drives it. In the event of negative values of $\Delta T_{km}(I)$, TEC operates as a cooling device.

Although the above expressions seem complex, they include only the fundamental parameters of the TEC that can be calculated from the manufacturers' data by Eqs. (4)–(6). All expressions can, of course, be easily evaluated by using commonly available software.

3. Graphical method

Since a direct application of the analytical solution of Eq. (11) for the design of TEC-based systems could be rather involved, we propose here a simple and intuitive graphical approach. It is based on a parametric representation of current dependent values of Eq. (11) denoted here as the $S(I)$ curve. The x and y values of the $S(I)$ (current dependent) curve are defined as:

$$S(I) = \begin{cases} x = \Theta_k + \Theta_{km}(I) \\ y = \Delta T_{km}(I) \end{cases} \quad (14)$$

It should be noted that in this presentation, the x-axis variable is thermal resistance, whereas the y-axis variable is temperature. A typical $S(I)$ plot is shown in Fig. 2. Notice that each point of the $S(I)$ curve corresponds to a specific TEC current. The graphical solution for a given active cooling system is facilitated by drawing on the same plot a line, denoted as the d line that represents the objective thermal problem on hand, defined as:

$$y = T_{car} - q_{cr}x \quad (15)$$

where y- and x-axis are as above. The slope of this line q_{cr} corresponds to the power needed to be dissipated by the cooled unit, whereas T_{car} is the required surface temperature of the cold side of the TEC (assumed to be equal to the surface of the heat source), referred to the ambient temperature. The intersection(s) between the $S(I)$ curve and the d line (if existing) satisfies both equations and is thus the solution of the given TEC cooling system (Eq. (11)).

By way of illustration, consider an active heat removal case that applies a TB-127-1,4-1,2 [3] module and a heatsink with $\Theta_k = 1$ K/W, $T_{amb} = 300$ K. The data supplied by manufacturer for the TEC are $\Delta T_{max} = 70$ K, $I_{max} = 7.6$ A, and $V_{max} = 15.9$ V, under the condition that the temperature of the hot side $T_h = 300$ K. The module has dimensions of 40 mm by 40 mm, and is enclosed between two ceramic plates. It is assumed that the power dissipated by the surface to be cooled is 10 W and that the required surface temperature is $T_{amb} - 10$ K = 290 K.

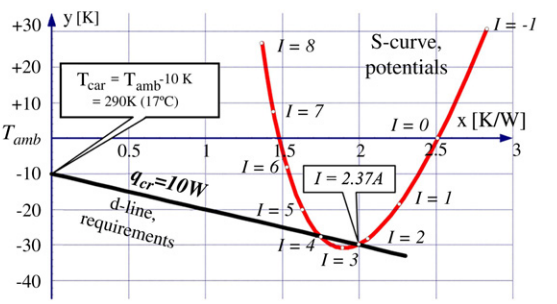

Fig. 2. Geometrical solution for the system: TEC (TB-127-1,4-1,2 [3]) with heatsink ($\Theta_k = 1$ K/W). $T_{amb} = 300$ K and a specific thermal problem: $T_{car} = -10$ K (10 K below the T_{amb}), $q_{cr} = 10$ W. The thermal requirement is met when the d line intersects the S-curve (at $I = 2.37$ A and $I = 4$ A).

Applying the transformation equations (4)–(6), we can first calculate the fundamental parameters of the TEC. They are found to be $\Theta_m = 1.51$ K/W, $\alpha_m = 53$ mV K^{-1}, $R_m = 1.6\ \Omega$. Then, by using Eqs. (12) and (13), one can plot the $S(I)$ curve, see Table 1. The d line is constructed according to the thermal data, as shown in Fig. 2. The intersections between the $S(I)$ curve and the d line are the solutions of the problem. The currents of the $S(I)$ curve at the intersection points are the currents needed to drive the TEC in order to obtain the desired cooling effect. Between the two solutions that are normally obtained, one would obviously choose the lower current. The coordinates of the intersection points between the S and d curves correspond to the apparent thermal resistance and temperature source of the equivalent circuit (Fig. 1b). In this example, the apparent thermal resistance (for $I = 2.37$ A) is found to be $\Theta_{km} = 2$ K/W and the value of the temperature source $\Delta T_{km} = -30$ K. It should be noted that since the $S(I)$ curve includes the information of the heatsink used, a different $S(I)$ curve needs to be drawn for each thermal resistance of the alternative heatsinks as shown in Fig. 3.

4. Proposed active cooling design procedure

The proposed graphical design procedure will be illustrated by way of an example in which a commercial TEC (TB-127-1,4-1,2 [3]) is considered. It is assumed that the surface of the unit to be cooled dissipates $q_{cr} = 40$ W and that it needs to be maintained at a temperature of less than 50 °C at an ambient temperature of $T_{amb} = 300$ K (27 °C). That is, $T_{car} \approx 20$ K. Fig. 3 shows a family $S(I)$ curves, each corresponding to a specific value of Θ_k. The solid d line, starts at point (0, 20) and drops downward with angle coefficient of 40 W. As evident from the graphical representation of the problem (Fig. 3), there are no real solutions for $\Theta_k \geq 0.8$ K/W. For the case of $\Theta_k = 0.6$ K/W, the d line crosses at two points: $I \approx 2$ A, and $I \approx 4$ A. Operation at the lower current is obviously more desirable.

Table 1
Building the parametric curve $S(I)$ for TB-127-1,4-1,2, T_{amb}

I (A)	X from Eq. (14) (K/W)	Y from Eq. (14) (K)
−1	2.829918	30.77659
0	2.511161	0
1	2.25968	−18.5922
2	2.056482	−28.1765
3	1.889145	−30.7909
4	1.74921	−27.7789
5	1.630722	−20.036
6	1.529381	−8.15179
7	1.442007	7.505923
8	1.366212	26.74094
9	1.300181	49.50119

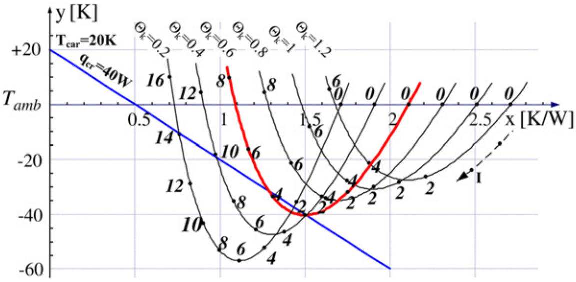

Fig. 3. The S-curve for TB-127-1,4-1,2 with different heatsinks (Θ_k from 0.2 to 2 K/W) for $T_{amb} = 300$ K. Solid line specifies the requirements imposed on active cooling system ($T_{car} = 20$ K, $q_{cr} = 40$ W).

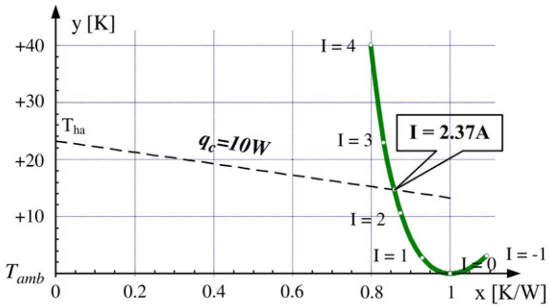

Fig. 4. Geometrical solution for the temperature of the hot side of the TEC ($T_h = T_{ha} + T_{amb}$). The value of the current is obtained from the solution for the cold side (Fig. 2).

5. The temperature of hot side and the coefficient of performance (COP)

An important issue is the temperature of the hot side of the TEC, especially since semiconductor TECs are limited to low temperature operation (normally lower than 125 °C). Thus, one needs to make sure that the hot side is not overheating. Applying the set of equations (Eqs. (7)–(10)), one can eliminate the variables q_c, T_c, and V and get an expression for the temperature of the TEC's hot-end above the ambient, given by

$$T_{ha} = T_h - T_{amb} = q_c \Theta_{kmh}(I) + T_{kmh}(I) \tag{16}$$

where

$$\Theta_{kmh}(I) = \frac{\Theta_k}{1 + I\alpha_m \Theta_m (1 - I\alpha_m \Theta_k)} \tag{17}$$

$$T_{kmh}(I) = \frac{I^2 R_m}{2} \frac{I\alpha_m \Theta_m + 2\left(1 + \frac{\alpha_m^2 \Theta_m}{R_m} T_{amb}\right)}{1 + I\alpha_m \Theta_m (1 - I\alpha_m \Theta_k)} \Theta_k \tag{18}$$

Applying Eq. (16), one can obtain the temperature of the hot side of the TEC using the same method as for the temperature of its cold side. The curve S_h is described parametrically as:

$$S_h(I) = \begin{cases} x = \Theta_{kmh}(I) \\ y = T_{kmh}(I) \end{cases} \tag{19}$$

The d_h line is constructed by starting it from a point on the $S(I)$ curve corresponding to the current of operation (I), that was found in Fig. 2, and continuing the line with angular coefficient of q_c (see the dotted line in Fig. 4). In the illustrated case, the d_h line intersects the Y-axis at about 23 K which implies that, at steady state, the hot side of the TEC will be 23 K + T_{amb} = 50 °C.

It should be noticed that the apparent temperature source has zero value when the current is zero, thus the S_h curve's minimum point corresponds to $I = 0$, and that this minimum value touches the X-axis, at $Y = T_{amb}$, the reference temperature. This is, of course, expected since at $I = 0$, the TEC is in conductive heat transfer operation mode. The value of X-axis that the minimum point of the S_h touches corresponds to the thermal resistance of the heatsink (Θ_k).

The coefficient of performance (COP) represents the balance between injected energy and the pumped energy. Applying the definition of the COP given in Ref. [2]:

$$\mathrm{COP} = \frac{q_c}{q_h - q_c} \tag{20}$$

and multiplying the nominator and the denominator of Eq. (20) by Θ_k we find:

$$\mathrm{COP} = \frac{q_c \Theta_h}{T_{ha} - q_c \Theta_h} = \frac{a}{T_{ha} - a} = \frac{a}{b} \tag{21}$$

where $a = q_c \Theta_k$ and $b = T_{ha} - a$.

The ratio a/b can be obtained graphically as demonstrated in Fig. 5 for the illustrated example. Since "a" is the heatsink surface temperature above ambient temperature when electrical power is off, it can be estimated by drawing a d_h line of slope of q_c from the S_h minimum (which corresponds to $Y = T_{amb}$ and $\Theta_{kmh} = \Theta_k$). The intersection of this line with the Y-axis is the solution of $a = q_c \Theta_k$ (Fig. 5). Since $b = T_{ha} - a$, it can be evaluated as the difference between the TEC hot-side temperature T_{ha} found earlier and "a," as shown in Fig. 5.

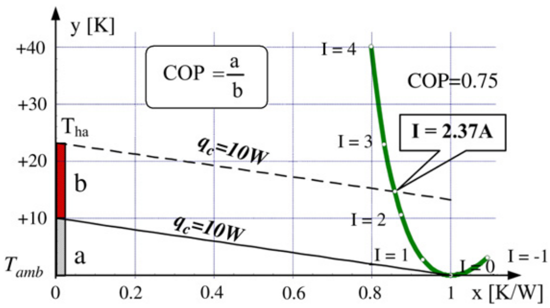

Fig. 5. Geometrical solution for the COP: the ratio of lengths of "a" and "b."

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6. Experimental

The graphical analysis was verified by two different methods: (a) laboratory experiments that were carried out on a specific TEC, and (b) calculations according to the proposed approach and comparison to experimental data given by manufacturers for different TECs.

The experimental setup (Fig. 6) included a TEC, a heat source, a heatsink with fan and aluminum plate with an embedded thermocouple for temperature measurements. A series of measurements of the steady-state difference of temperatures of T_1 (which is close to T_c) and T_{amb} under different heat dissipation conditions, and for different TEC currents, were carried out. The results of the measurements are shown in Table 2. Fig. 7 depicts the $S(I)$ curve that corresponds to the data of the experimental TEC (TB-127-1,4-1,2) and the $\Theta_k = 0.67$ K/W of the heatsink and fan, at $T_{amb} = 294.8$ K. The slope of the d lines corresponds to the heat generated by the heat source. Each line starts at an $S(I)$ point that corresponds to each of the experimental TEC currents. The point of intersection between the d line and the "y"-axis is the estimated value of T_{ca} – the temperature of the cold side above the ambient temperature. The values of these model estimates are summarized in Table 2. Good agreement was found between the measured temperature differences and the ones estimated by the proposed graphical method (Table 2).

Applying the experimental data given by manufacturers, we have used the unified model to recalculate the value of Q_{max} also given in the commercial data sheets. Q_{max} is defined as the amount of heat (W) that can be pumped by the TEC for $I = I_{max}$ and ΔT equal to zero. To evaluate this case by proposed method, one needs to construct the $S(I)$ curve using Eq. (14) and substituting $T_{amb} = T_h = 300$ K (standard temperature of the experiment) and $\Theta_k = 0$. This substitution means that the temperature of the hot side of the TEC is constant and equal to the temperature of the cold side (Fig. 8). Now, the straight line from the origin to the point on the S-curve that corresponds to I_{max} has a slope of Q_{max}. The tangential line from the origin to the S-curve (Fig. 8) has an angle of Q_{opt} – the maximum possible amount of heat for the experimental condition, which is also quoted by some manufacturers.

Fig. 9 shows the distribution of the error in the recalculated values of Q_{max} for 54 commercial TEC devices as compared to the independent data given by the manufacturers. In about 90% of the cases, the error in the recalculated Q_{max} by the proposed model, relative to the values given in the data sheets, was found to be less than 5%.

Table 2
Results of the experimental measurements by reference to results estimated using proposed graphical method

Measured values			Estimated T_{ca} from Fig. 7
q_c (W)	I (A)	T_{ca} (K)	
24.75	1	30	30
25.2	2.9	7	7
24.5	4	1	0.9
25.2	5	2	2

7. Discussion and conclusions

In some applications, thermoelectric active cooling systems can help maintain electronic devices at desired temperature conditions better than passive coolers. Active cooling is especially useful when the temperature of a device needs to be precisely controlled. This study proposes a user-friendly

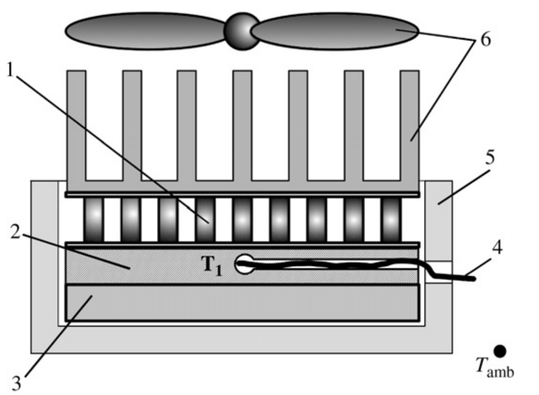

Fig. 6. Experimental setup: (1) TEC, (2) massive aluminum plate, (3) heat source (q_c, W), (4) thermocouple, measuring temperature T_1 (K), (5) thermal insulation, (6) heatsink and a fan with thermal resistance $\Theta_k = 0.67$ K/W. The temperature of the ambient air during the experiment was $T_{amb} = 294.8$ K.

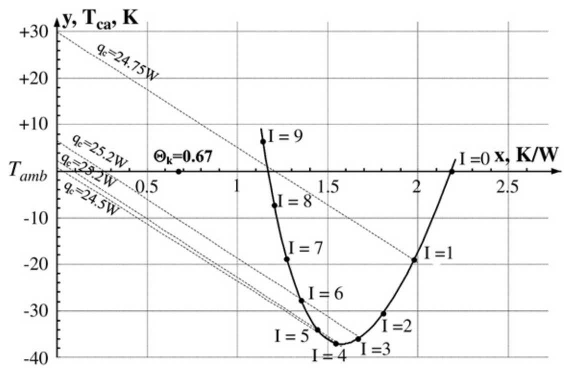

Fig. 7. The $S(I)$ curve of the experimental system of TEC and heatsink, showing the points that correspond to specific TEC drive currents, and graphical representations of the experimental conditions (d lines). The slope of each d line corresponds to the power of thermal load (q_c, in W) of each experiment. The intersections of the d lines with the vertical axis (y) are the estimates of the temperature of the TEC cold side above the ambient temperature in K, for each experimental I.

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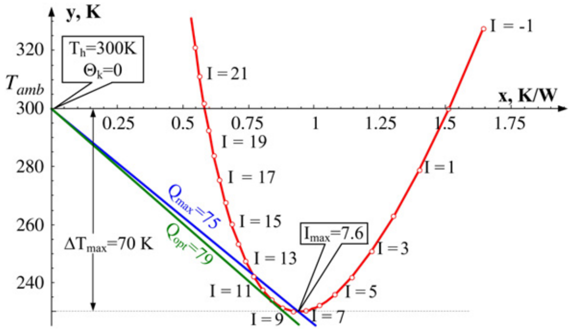

Fig. 8. Verification of the graphical method against experimental data given by manufacturers. The *S*-curve shown is for TB-127-1,4-1,2 with $T_{amb} = T_h = 300$ K, i.e. $\Theta_k = 0$. The parameter Q_{max} is the slope of the straight line from $T_{amb} = 300$ on the *Y*-axis, to the point of $I = I_{max}$ on the *S*-curve (the minimum of *S*-curve). The slope of the tangential line from the origin is Q_{opt}.

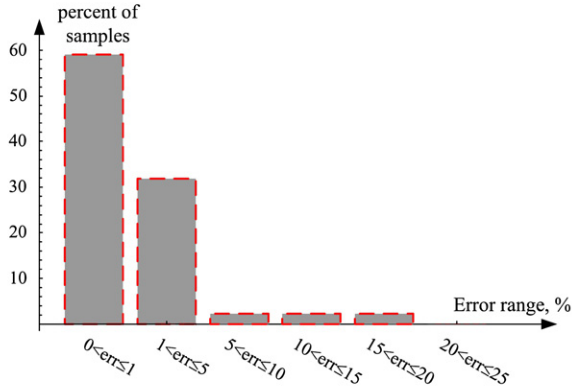

Fig. 9. Comparison of the recalculated Q_{max} by the proposed model with the data given by TEC manufacturers for 54 commercial TEC units.

graphical method for calculating the steady-state operational point of a TEC-based active cooling system. The method is simple and intuitive, and provides comprehensive information about the cooling system such as its feasibility, required heatsink, the TEC current, temperatures of the cold and hot sides, and coefficient of performance (COP). The method could help designers to examine and choose a thermoelectric module from catalogues to meet a specific cooling problem. To start using the method, designers need only the experimental TEC data provided by practically all manufacturers of such devices.

The proposed method is 'graphical' in the sense that it provides a clear graphical representation and hence an intuitive understanding of the cooling process by a TEC. It is based on a very basic equivalent circuit of a generic cooling system (Fig. 1b) that includes a thermal source, an apparent thermal resistance and a temperature source. The strength of the graphical approach is that it can help the designers to examine and compare different TEC and heatsink combinations in a very user-friendly way. In fact, once having defined a given cooling problem by a '*d*' line and drawing a family of '*S*' curves for a range of heatsinks, one can immediately identify the best design options. After a design is selected, accurate calculation of the operating conditions of the system can be carried out by applying the equations developed in this work. For example, the exact value of the required TEC drive current for a given case can be obtained by solving numerically Eqs. (11) and (15) for current *I*. Indeed, practically all the numerical results quoted in this paper were obtained by numerical solutions of the corresponding equations.

The proposed 'graphical' approach was verified against experimental results collected during this study and independent data given by manufacturers. The excellent agreement that was observed attests to the high accuracy of the proposed model and graphical approach. This good agreement also justifies the approximations that were done in the development of the proposed model (e.g. neglecting the Thompson effect and variations of the parameters values with temperature).

References

[1] A.F. Ioffe, Semiconductors Thermoelements and Thermoelectric Cooling, Infosearch Limited, London, 1957.

[2] S.L. Soo, Direct Energy Conversion, Prentice-Hall, London, 1968.

[3] Kryotherm Co., products, online Available from: http://www.kryotherm.ru.

[4] Beijing Huimao Cooling Equipment Co., products online Available from: http://www.huimao.com.

[5] Marlow Industries, products, online Available from: http://www.marlow.com.

[6] S. Lineykin, S. Ben-Yaakov, Modeling and analysis of thermoelectric modules, in: Applied Power Electronics Conference APEC'05, Austin, Texas, USA, 2005, pp. 2019–2023.

[7] S. Lineykin, S. Ben-Yaakov, Analysis of thermoelectric coolers by a SPICE-compatible equivalent circuit model, Power Electronics Letters 3 (2) (2005) 63–66.

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