Characteristics of Cooling Processes through TEC Technology of Processors

Amado ȘTEFAN, Daniel CONSTANTIN, Cristian MOLDER and Lucian GRIGORE

***Abstract*—This paper describes how a processor cooling system based on the Peltier effect allows cooling in a relatively closed environment. The research activity was carried out for the realization of a prototype of a cooling panel with Peltier elements of the Autonomous Modular Thermo Vibro Insulating System. The cooling module with Peltier elements has been designed and built for a SMARTER system "Autonomous modular thermo-vibro-insulating system for critical equipment and products". The TEC cooling / heating elements are arranged on the housing of the box that houses a communications server. A cooling system with Peltier elements has been chosen as the assembly is protected from both thermal and electromagnetic points of view. In other words, we have a closed system. The obtained results demonstrated the viability of the designed solution.**

***Index Terms*—Peltier element, processor, radiator, thermal insulation, Seebeck coefficient.**

I. Introduction

Highlighting the heat transfer principles specific to a cooler for computer processors can be done with Peltier elements [1]. Peltier elements are preferred due to their small size, compactness and especially because they allow a very good temperature control, in conditions of very good reliability. Basically, the system is functional until the processor is replaced.

The choice of Peltier elements is made taking into account the performance curves, which present information about: $\Delta T_{\max}$, $I_{\max}$, $V_{\max}$ and $Q_{\max}$. The optimization of the operating parameters requires a fairly simple mathematical device, which allows the performance of simulations in the sense of a global heat transfer. Next, a methodology will be presented, which allows the accurate measurement of thermoelectric characteristics.

TEC (Thermoelectric Cooling) technology is an active thermal management technique based on the Peltier effect [2,5]. This phenomenon involves heating or cooling two thermoelectric materials (Bismuth and Telluride) by passing current through the junction between the two materials. During operation, direct current flows through the TEC module causing heat to be transferred from one element to another. This creates a cold and a warm portion. If the direction of the current is reversed, the cold and hot sides are reversed [3]. The cooling power can be adjusted by changing the intensity of the operating current.

A typical cooler consists of two ceramic plates with materials (bismuth, tellurium) between the ceramic plates, organized as a semiconductor p/n (Fig. 1 - http://www.huimao.com/about/show.php?lang=en&id=4). The elements of semiconductor material are electrically connected in series and in parallel from a thermal point of view [4].

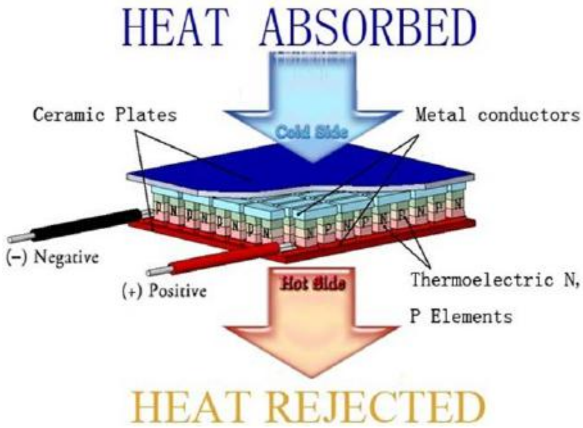

Figure 1. Example of a typical cooler based on TEC technology

TECs have the following advantages for temperature regulation: high precision and stability, fast response time, a wide temperature range and a simple structural design without moving components. They are also small and light, noise-free and environmentally friendly. However, compared to other temperature control systems (radiators, compressors), for applications requiring high thermal power consumption, TECs have the following disadvantages: low efficiency, low thermal power, high cost of both TECS and controllers and the fact that complex solutions are required for high efficiency [6].

II. TEC Calculation Methodology

The method takes into account: Seebeck effect (tem electromotive voltage), electrical resistance and thermal conductivity, all depending on $\Delta T_{\max}$, $I_{\max}$, $V_{\max}$ and $Q_{\max}$, provided by the manufacturer [7]. The analytical determination of the physical properties, such as: s, ρ and k, is made if the number of junctions and the ratio G between the surface of the cross section and the length of each thermoelectric element are known [8].

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The performances of thermoelectric materials (Fig. 2) are assessed by a dimensionless factor Z (1) [1]:

$$Z = \frac{\alpha^2}{\rho k} [-] \quad (1)$$

$$Q_c = 2N\left[sIT - \frac{1}{2} I^2 \frac{\rho}{G} - kG\Delta T \right][W] \quad (2)$$

$$V = 2N\left[I\frac{\rho}{G} + s\Delta T \right][V] \quad (3)$$

$$Q_p = VI\,[W] \quad (4)$$

$$Z = \frac{s}{\rho k} [-] \quad (5)$$

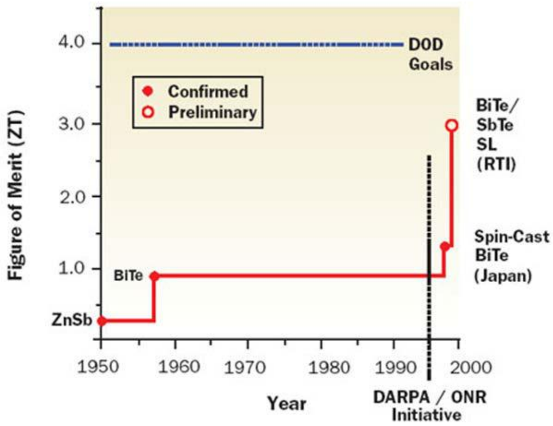

Figure 2. Variation of Z material characteristic over time in an enclosure

Based on (1)–(5), the physical characteristics of the TEC can be defined as a device [9,10]:

$$S_M = 2sN \left[V/K \right] \quad (6)$$

$$R_M = \frac{2\rho N}{G} [\Omega] \quad (7)$$

$$K_M = 2kNG \left[W/K \right] \quad (8)$$

Substituting (6)–(8) into (1)–(5) is obtained:

$$Q_c = S_M T_c I - \frac{1}{2} I^2 \frac{\rho}{G} - K_M \Delta T\,[W] \quad (9)$$

$$V = IR_M + S_M \Delta T\,[V] \quad (10)$$

$$Z = \frac{S_M^2}{R_M K_M} [-] \quad (11)$$

The parameters s, ρ and k are the fundamental physical properties of TEC materials and S_M, R_M and K_M are the physical characteristics of TEC as a device. Z is directly related to the ability of the TEC to be similar to a heat pump and is a criterion for evaluating the quality of the TEC. All these parameters are required for calculations and simulations [12]. These terms are not found in the manufacturers' catalogs, so they must be obtained individually on an experimental basis.

Analyzing (9), we can say how $\Delta T\,[K]$ varies:

$$\Delta T = \frac{1}{K_M}\left(S_M T_c I - \frac{1}{2} I^2 R_M \right)[K] \quad (12)$$

$$\frac{d\Delta T}{dI} = \frac{1}{K_M}\left(S_M T_c - IR_M \right)[K] \quad (13)$$

Considering that (13) is equal to 0 and solving the equation according to the term $I\,[A]$, with a maximization of the temperature variation, we obtain:

$$I = \frac{S_M}{R_M} T_c\,[A] \quad (14)$$

(14) is required to determine the maximum value of the temperature difference $\Delta T_{\max}\,[K]$, where $I_{\max}\,[A]$ is the maximum current, and the maximum voltage is denoted by $V_{\max}\,[V]$:

$$\Delta T_{\max} = \frac{1}{2} Z T_c^2\,[K] \quad (15)$$

$$V_{\max} = I_{\max} R_M + S_M \Delta T_{\max}\,[V] \quad (16)$$

$$I_{\max} = \frac{S_M}{R_M}\left(T_h - \Delta T_{\max} \right)[A] \quad (17)$$

$$\Delta T_{\max} = \frac{1}{2} Z \left(T_h - \Delta T_{\max} \right)^2 [K] \quad (18)$$

$$Q_{\max} = S_M T_c I_{\max} - \frac{1}{2} I_{\max}^2 R_M\,[W] \quad (19)$$

Two methods have been developed for a validation of the TEC calculation methodology.

Method 1

As the parameters S_M, R_M and K_M are unknown, TEC providers provide four working parameters, as follows:

$$Z = \frac{2\Delta T_{\max}}{\left(T_h - \Delta T_{\max} \right)^2} [-] \quad (20)$$

$$S_M = \frac{V_{\max}}{T_h} \left[V/K \right] \quad (21)$$

$$K_M = \frac{\left(T_h - \Delta T_{\max} \right) V_{\max} I_{\max}}{2 T_h \Delta T_{\max}} \left[W/K \right] \quad (22)$$

$$R_M = \frac{\left(T_h - \Delta T_{\max} \right) V_{\max}}{T_h I_{\max}} [\Omega] \quad (23)$$

Method 2

Compared to the first method, it provides only 3 parameters [13]:

$$S_M = 2\frac{Q_{\max}}{I_{\max}} \cdot \frac{1}{\left(T_h + \Delta T_{\max} \right)} \left[V/K \right] \quad (24)$$

$$K_M = \frac{\left(T_h - \Delta T_{\max} \right)}{\left(T_h + \Delta T_{\max} \right)} \cdot \frac{Q_{\max}}{\Delta T_{\max}} \left[W/K \right] \quad (25)$$

$$R_M = \frac{S_M^2}{Z K_M} [\Omega] \quad (26)$$

$$COP = \frac{Q_c}{Q_p} [-] \quad (27)$$

$$R_{heatsink} = \frac{\left(T_h - \Delta T_{\max} \right)}{\left(Q_c + Q_p \right)} [-] \quad (28)$$

Ideally, there should be a correspondence between (16)–(19), and the results obtained by the two calculation methods. However, we do not always have such correspondence [14]. Errors are exemplified in Table I.

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TABLE I. ERRORS APPEARING IN THE APPLICATION OF THE TWO CALCULATION METHODS

Item	Input the Performance Specifications
T_h	$300\,[K]$
ΔT_{max}	$69.65\,[K]$
I_{max}	$3.08\,[A]$
V_{max}	$11.71\,[V]$
Item	**Calculate the Physical Characteristics**
Z	$0.002625\left[\frac{1}{K}\right]$
S_M	$0.03903\left[\frac{V}{K}\right]$
R_M	$2.9193\,[\Omega]$
K_M	$0.1988\left[\frac{W}{K}\right]$
Item	**Input the Operating Conditions**
I	$1.181\,[A]$
T_h	$323\,[K]$
T_c	$293\,[K]$
T_a	$298\,[K]$
Item	**Calculate the Operating Parameters**
Q_c	$5.507\,[W]$
V	$4.619\,[V]$
Q_p	$5.455\,[W]$
COP	$1.010\,[-]$
$R_{heatsink}$	$2.281\left[\frac{K}{W}\right]$
Item	**Input *N* & *G***
N	$96\,[-]$
G	$0.072\,[cm]$
Item	**Calculate the Basic Physical Properties**
ρ	$0.001095\,[\Omega \cdot cm]$
s	$0.0002\left[\frac{V}{K}\right]$
k	$0.0144\left[\frac{W}{cm \cdot K}\right]$

III. VIRTUAL MODEL

Thermoelectric cooling systems, based on Peltier devices, with TEC modules can be considered as solid-state heat pumps. Due to its small size and mass and especially the reaction speed, it is very suitable to be used as a built-in cooling / heating system for equipment that is limited in terms of space.

In order to create the virtual model for determining the cooling capacity of the radiator-fan system, a system used for cooling a server located in a thermally and electromagnetically insulated enclosure from the outside environment, the following were required [15,16]:

- analysis of thermodynamic installations;
- analysis of low-potential heat transport systems;
- identification of analytical models for the calculation of temperatures and temperature gradients;
- creating a calculation model that allows the choice of the technical solution for a cooler / heater, so that the system meets the requirements for use in extreme environments;
- electrical installation design;
- design of the thermodynamic installation (Fig. 3);
- realization of the automation system;
- making software for system control.

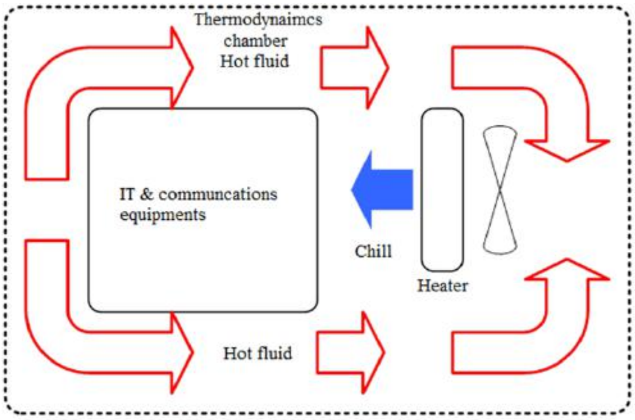

Figure 3. Schematic of the cooling / heating principle in a closed enclosure for a server

The processor for which the use of a Peltier element was chosen in order to cool it is part of a closed server in a thermodynamically and electromagnetically protected enclosure [11]. A high-performance cooler / heater has been provided at the thermodynamic enclosure, so that the server can be used as IT and communications equipment in extreme conditions, independently, in various geographical locations whose environmental conditions can be characterized extreme thermodynamics variations. For this purpose, at the level of the enclosure, a cooling / heating system with liquid fluid was chosen, considering that it can be recirculated through the radiator located in the enclosure (transport box). The hot air coming from the work equipment is pushed to circulate through the radiator ensuring the thermal transfer of the heat from the air inside the transport box to the coolant.

The liquid cooling system (Fig. 4) has the following main advantages:

- easy connection with flexible hoses;
- the possibility of using a running water source to replace the thermodynamic cooling system of the working agent.

The following is the main diagram of the test stand of the air conditioning system for a server.

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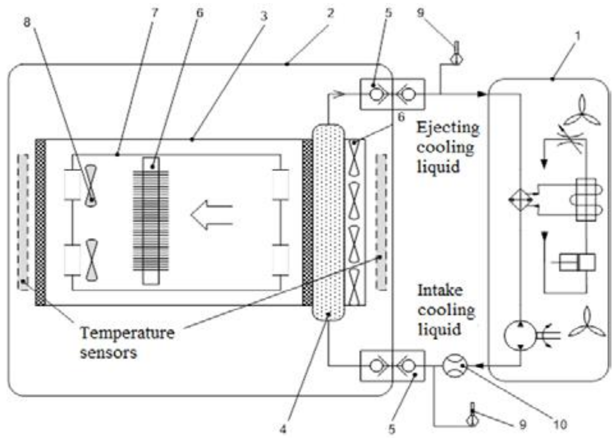

Figure 4. Schematic of the cooling / heating installation in a closed enclosure for a server: 1. Liquid cooling installation; 2. Transport box; 3. RACK TEMPEST; 4. Heat exchanger; 5. Quick couplings connecting liquid cooling system; 6. Heating elements; 7. Model of IT equipment; 8. Mock-up fans of IT equipment; 9. Liquid temperature sensors; 10. Sensor for measuring liquid flow

The mathematical model that allows the determination of heat transfer capacity is based on the characteristic relationships of a cooling system with fins [17]

$$\frac{T(x)-T_{\infty}}{T_b-T_{\infty}}=\frac{\cosh\left[\sqrt{\frac{h\cdot p}{k\cdot A_c}}\cdot\left(L_c-x\right)\right]}{\cosh\sqrt{\frac{h\cdot p}{k\cdot A_c}}\cdot L_c}\left[-\right] \quad (29)$$

$$\dot{Q}_{convection}=\sqrt{h\cdot p\cdot k\cdot A_c}\cdot\left(T_b-T_{\infty}\right)\cdot$$
$$\cdot\,\mathrm{tgh}\left(\sqrt{\frac{h\cdot p}{k\cdot A_c}}\cdot L_c\right)\left[W/_{cm^2}\right] \quad (30)$$

The TEC-based temperature control system is made up of five key components: the temperature sensor, the conditioned sensor circuit, the error-detection and amplification circuit, the compensation and H-bridge output network, all in series to control a thermoelectric cooling device (Fig. 5).

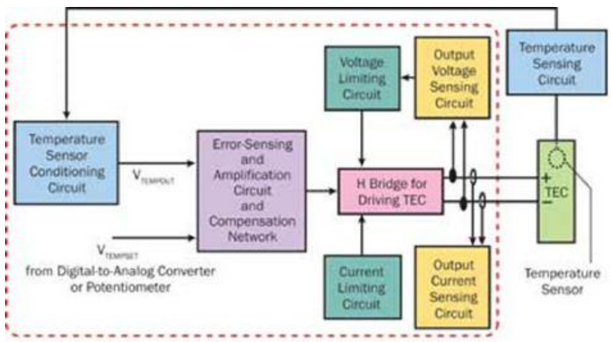

Figure 5. Schematic of the temperature control system based on TEC

The error of detection and amplification of the measurements in the circuit is given by the voltage difference between $V_{TEMPOUT}$ and $V_{TEMPSET}$, which is an analog voltage representing the set temperature, and the one that amplifies the output difference of the H-bridge. Having the thermal mass and the thermal resistance of the Peltier elements, the cold plate and the thermal charging at any delay caused between the moment of application of the direct current and the time of the appearance of the thermal load will lead to the change of its temperature. That is why a compensation network is needed to balance the detection error and the amplification circuit. Otherwise, the closed-loop control loop would not be stable.

The H-bridge circuit introduces a direct current into the TEC, with the magnitude and direction precisely controlled by the output voltage of the error amplifier.

IV. System Subject to Test Procedures

The following is the designed and built system that is equipped with thermal and electromagnetic protection elements of a server intended to be used in extreme environmental conditions (Fig. 6).

Usually, an object must be cooled to a certain temperature. If the object to be cooled is in contact with the cold surface of the thermoelectric module, the desired temperature of the object can be considered the temperature of the cold part of the Peltier element after a certain time.

Peltier elements are able to create a temperature difference of 72 *K*, if there is no thermal load.

If it is desired to obtain a larger temperature difference, it is necessary to insert the TEC controller, which is supplied with an external power source. The largest temperature difference is obtained when the Peltier elements are arranged in a cascade.

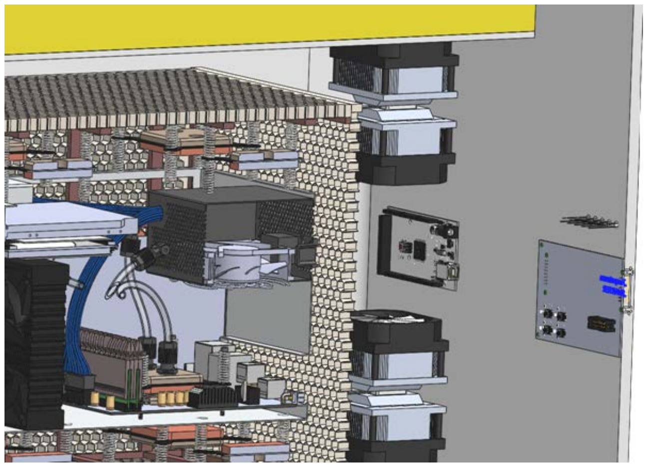

Figure 6. The system as a whole in which the thermal and electromagnetic protection elements for a server can be observed

An important criterion for determining the performance of Peltier elements is the COP performance coefficient, respectively the ratio between the heat absorbed by the cold part of the Peltier element over the input power. A high COP requires a minimum input power, so that the minimum total heat dissipated by the radiator is minimal. The graph in Fig. 7 illustrates the influence of consumed currents and the size of the COP.

In this case a Peltier element with a $Q_{\max}$ between 20 and 40 *W* must be chosen. If the $Q_{\max}$ approaches the optimum (where $Q_{\max}$ is chosen) a high COP is achieved, in other words a maximum efficiency is obtained. An element with $Q_{\max}$ close to the maximum $Q_{\max}$ will produce lower costs, but with a reduced cooling capacity. The Peltier element will be used close to its limits.

The $I/I_{\max}$ ratio is found in the diagram in the following figure, at the intersection of $\Delta T/\Delta T_{\max}$ and the value $Q_C/Q_{\max}$, vertically. The value corresponding to the intersection of the vertical line with the lower axis is retained. In the optimal case $I/I_{\max}=0.5$.

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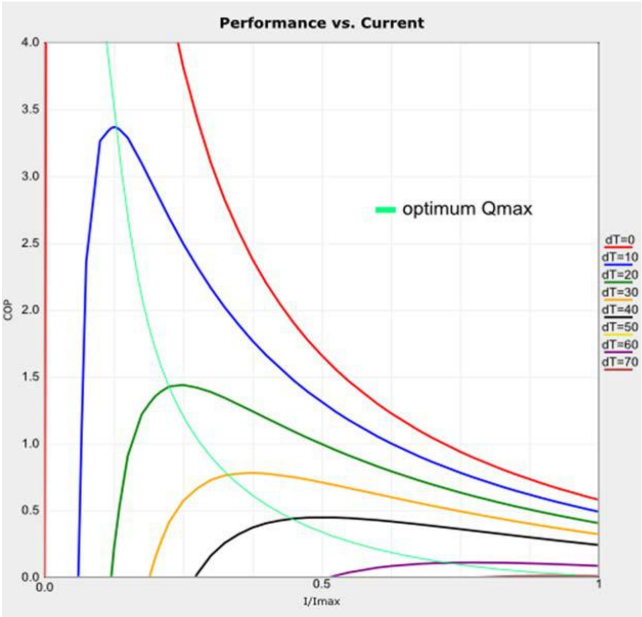

Figure 7. Optimal graph of the correspondence between heat and current supplied for a given temperature difference ΔT

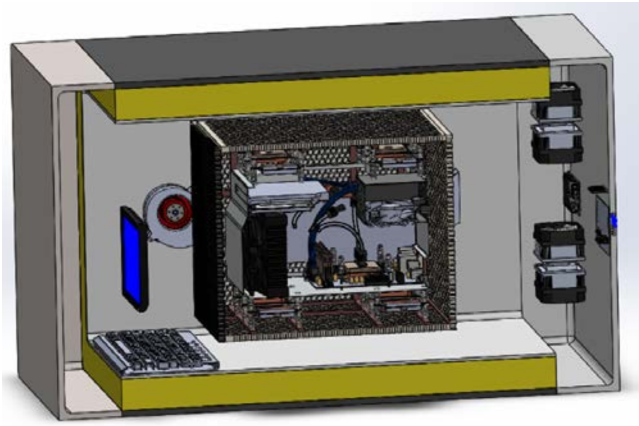
Figure 8. Detail regarding the SMARTER enclosure

In order to be able to control the temperature of the object, a temperature probe positioned directly on the object of study is required, stating that the point of contact must be as close as possible to the critical point on that object, whether or not that temperature is taken into account in the calculation.

In addition to high accuracy, measuring the temperature of the object also requires a wide range of temperatures. From this point of view, Pt100 type sensors are preferred. To be able to measure temperatures well below 0°*C*, Pt100 and / or Pt1000 thermocouples are required. These very low temperatures cannot be measured with NTC probes, as their resistance increases with decreasing temperature.

The resistance value of the sensor must be less than the reference resistance of the TEC controller.

V. Conclusion

The mathematical model takes into account the thermomechanical elements, electronics, programmable automata, etc., whose equations describe as accurately as possible the physics of the system as a whole, but also of the subsystems. The mathematical model followed the simulation in real time, so that it could overlap with the values obtained experimentally. The subsystems were operated discreetly, over time, with finite differences, so that the DAC output signals could be combined with the simulated ones.

It is estimated that the analytical model regardless of the PID or HIL simulation mode leads to values significantly close to the measured values. The introduction of correction algorithms, by the method of finite differences and successive iterations, simultaneously with the simplification of the constructive solution, from a physical point of view, allowed the validation of the analytical model used.

Appendix A

Explain the notations used [18-20]

Item	UM	Explain
I	$[A]$	TEC operating current
V	$[V]$	TEC operating voltage
$I_{\max}$	$[A]$	The operating current that determines the maximum difference $\Delta T_{\max}$
Q_c	$[W]$	The amount of heat that can be absorbed on the cold side of the TEC
Q_p	$[W]$	The amount of heat entering the TEC by the cold surface
$Q_{\max}$	$[W]$	The maximum amount of heat that can be absorbed by the cold face of the TEC, for $I = I_{\max}$ and $\Delta T = 0$.
T_{hot}	$[°K]$	Warm face temperature when TEC is running
T_{cold}	$[°K]$	Cold face temperature when TEC is running
ΔT	$[°K]$	The difference between the hot and cold temperatures of the two sides of the TEC: $\Delta T = T_h - T_c$
$\Delta T_{\max}$	$[°K]$	The maximum difference between the hot and cold temperatures of the two sides of the TEC: $\Delta T = T_h - T_c$, when: $I = I_{\max}$ and $Q_c = 0$
$U_{\max}$	$[V]$	Working voltage when: $I = I_{\max}$
ε	[%]	TEC mode cooling efficiency
α	$[V/°K]$	The thermoelectric transfer coefficient of the material due to the Seebeck phenomenon
σ	$[1/cm \cdot \Omega]$	The electric transfer coefficient depending on the thermoelectric characteristic of the material
k	$[W/cm \cdot °K]$	Thermoelectric conductivity coefficient of the material
N	$[-]$	Number of thermoelectric elements ($p-n$ junctions)
$I_{\varepsilon\max}$	$[A]$	The value of the current applied to the hot face when the cold face absorbs heat, for a TEC module and a specified temperature to obtain maximum efficiency
COP	$[-]$	TEC coefficient of performance
s	$[V/°K]$	Seebeck coefficient
ρ	$[\Omega \cdot cm]$	Resistivity
k	$[W/cm \cdot °K]$	Conductivity
Z	$[-]$	Dimensional factor that specifies the characteristics of a thermoelectric material
G	$[cm]$	The ratio between the surface and the length of the thermoelectric element
N	$[-]$	Number of pairs of thermoelectric elements
S_M	$[V/°K]$	The electromotive voltage of the Seebeck device
R_M	$[\Omega]$	Electrical resistance of the Seebeck device
K_M	$[W/°K]$	Thermal conductivity of the Seebeck device
T_a	$[K]$	Ambient temperature
$R_{heatsink}$	$[K/W]$	Thermal resistance of the radiator

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