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Heat Exchangers for Thermoelectric Devices

David Astrain and Álvaro Martínez
Public University of Navarre
Spain

1. Introduction

Heat exchangers play an important role in the performance of thermal machines, namely, electric power generators, engines and refrigerators. Regarding thermoelectrics, this influence is even higher, owing to the difficulty of transferring heat from the small surface area of a typical thermoelectric module to a bigger one. Particularly, in the hot face of an average 40 mm x 40 mm Peltier module, the heat flux readily yields 40600 W/m². The thermoelectric effects, namely, Joule, Seebeck, Peltier and Thomson, describe the interaction between thermal and electric fields, and are well known since the XIX century (Rowe, 2006).

German physicist Thomas J. Seebeck discovered in 1821 that an electric circuit composed of two dissimilar conductors *A* and *B* connected electrically in series and exposed to a thermal gradient induces an electric current -or an electromotive force (E_{AB}) if the circuit is opened- which depends on the materials and the temperature difference between junctions (ΔT). This phenomenon is called **Seebeck effect**, characterized by the *Seebeck coefficient* α.

$$\alpha_{AB} = \frac{\Delta E_{AB}}{\Delta T} = \alpha_A - \alpha_B \tag{1}$$

Likewise, in 1834, French physicist Jean Peltier discovered that if an electrical current (I) is applied across the electric circuit composed of two dissimilar conductors, the inverse effect takes place, that is, heating occurs at one junction whereas cooling occurs at the other. This phenomenon is called **Peltier effect**, described by the *Peltier coefficient* π.

$$\dot{Q}_P = \pm I\pi_{AB} = \pm I\,T\left(\alpha_B - \alpha_A\right) \tag{2}$$

In 1851, William Thomson stated the *Thomson effect*, which indicates that a homogeneous material exposed to thermal and electrical gradients absorbs or generates heat. Moreover, he described the relation between Seebeck and Peltier effects, given by *Thomson coefficient* τ.

$$\tau_A - \tau_B = -T\frac{\partial \alpha_A}{\partial T} + T\frac{\partial \alpha_B}{\partial T} = T\frac{\partial}{\partial T}(\alpha_B - \alpha_A) \tag{3}$$

The possibility of using thermoelectric devices to produce electric power was raised by John W. Strutt in 1885. Subsequently, between 1909 and 1911, Edmund Altenkirch proved that thermoelectric materials must feature high Seebeck coefficient (α), high electrical conductivity (σ) and low thermal conductivity (λ), in order for the material to retain heat in the junctions and minimize losses due to Joule effect. These three parameters were combined to form the Figure of merit ($Z = \alpha^2\sigma/\lambda$), key parameter in the characterization of thermoelectric materials. By then, further developments had been rejected because of the low efficiencies attained, and it was not until the application of semiconductor materials to thermoelectric devices by Abram F. Ioffe in 1957, that thermoelectric technology contemplated its major breakthrough. Since that moment, scientific efforts focused on increasing the Figure of merit via new thermoelectric materials.

Although the thermoelectric effects were discovered almost two centuries ago, the application of thermoelectric technology to either heating or cooling (Peltier effect), and electric power generation (Seebeck effect) was not relevant until the fifties of the last century, when this technology was successfully used for military and aerospace purposes. The application to other fields was then rejected because of the high price of thermoelectric materials, but now has become a reality. In this regard, some in-depth reviews on the state of the art of thermoelectric technology can be found in the literature (Goldsmid, 1964, 1986, 1995; Riffat & Xiaoli, 2003). Nowadays, the successful development of thermoelectrics for civil purposes depends mainly on two aspects: thermoelectric materials development and heat exchangers thermal design. Whereas the first one intends to increase the Figure of merit and efficiency of the devices via new thermoelectric materials, the second one focuses on enhancing the heat transfer via improving the heat exchangers.

Thermoelectric technology presents significant advantages with respect to common devices used for refrigeration or electric power generation, since thermoelectric devices have no moving parts (no compressor, turbine, etc. must be installed), which makes them virtually noiseless and increases their lifespan to a great extent. Furthermore, thermoelectric devices are easily and accurately controlled. All these advantages, along with the fact that the prices of Peltier modules are constantly decreasing, boosted the development of highly interesting thermoelectric applications, competing nowadays in the civil market with good prospects for the future (Bell, 2008; Chang et al., 2009; Chein & Huang, 2004; Gordon et al., 2002; Hongxia & Lingai, 2007; Khattab & El Shenawy, 2006; Martínez et al., 2010; Min & Rowe, 1999, 2006; Omer et al., 2001; Riffat et al., 2006; Vian et al., 2002; Vian & Astrain, 2009a, 2009b; Yang & Stabler, 2009; Yodovard et al., 2001). Regarding the last comment, it is common knowledge that efficiency of thermoelectric devices represents the key point to bear in mind, in order for these prospects to become reality.

A proper analysis of thermoelectric applications requires detailed studies on heat transfer between the thermoelectric modules, the heat source and the heat sink. In this sense, wrong selection of either the dissipation method (natural or forced convection, thermosyphons, etc.) or the refrigerant (air, water, eutectic fluids, etc.) leads to poor heat transfer and finally to low efficiencies. Although published improvements on heat transfer processes for other fields of knowledge are very common in scientific literature, thermoelectric developers have not been able to use all this information and apply it to the thermoelectric field, though this fact is being corrected nowadays. Thus, several studies have come out recently which address the application of different dissipation techniques to thermoelectric modules (Astrain et al., 2003, 2005, 2010; Knight et al., 1991; Omer et al., 2001; Ritzer & Lau, 1994, 2000; Rowe et al., 1995, Stockholm & Stockholm, 1992; Vian & Astrain, 2008, 2009a).

This chapter shows in the first place the influence of heat exchangers on the performance of both thermoelectric generation and thermoelectric refrigeration devices. Then, there are presented different types of heat exchangers specifically designed for dissipating high heat fluxes from the cold and the hot side of thermoelectric devices. After that, the chapter studies the improvement in the efficiency of thermoelectric devices achieved with these heat exchangers. Finally, the concept of thermoelectric self-refrigeration is introduced; this application uses thermoelectric technology for the refrigeration and temperature control of a device, without electricity consumption.

2. Influence of heat exchangers on thermoelectric devices

A thermoelectric pair can be used to generate electric power, since Seebeck effect indicates that if the junctions of two thermoelectric legs type "p" and "n" are exposed to different temperatures, an electric current is induced. On the other hand, if an external electric source supplies power to the thermoelectric pair, Peltier effect states that one junction absorbs heat whereas the other one generates heat, so that the thermoelectric pair performs like a thermal machine that receives electric work, removes heat from a cold reservoir and emits heat to a hot reservoir. There are in the market different types of Peltier modules, composed of several thermoelectric pairs connected electrically in series and thermally in parallel. Figure 1 shows an average thermoelectric module working as refrigerator. In order to improve the heat transfer both in the hot and the cold side, a heat exchanger must be installed at either side of the Peltier module to increase the heat transfer area.

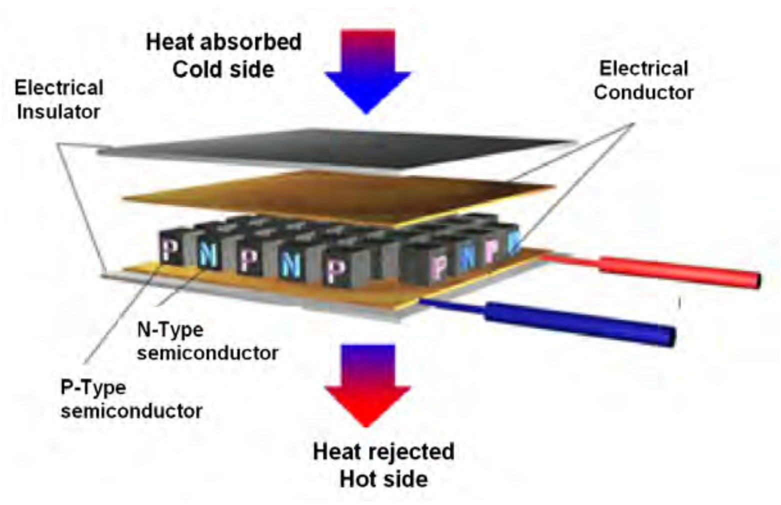

Fig. 1. Sketch of a Peltier module working as refrigerator.

The Peltier module is a small device that emits –or absorbs- large amounts of heat, so that the heat density or heat flux is significantly high. The face of a Peltier module is so small that increasing the heat transfer surface area of the heat exchanger (finned dissipator and cold plate in Figure 2) is virtually useless, since the effectiveness of the heat exchanger decreases as more heat transfer surface area is added. This makes difficult to attain proper heat transfer. Therefore, efficiencies of thermoelectric modules and thermoelectric devices in general, designed for either generation or refrigeration purposes, depend to a great extent on the thermal resistances of the heat exchangers installed at either side of the modules.

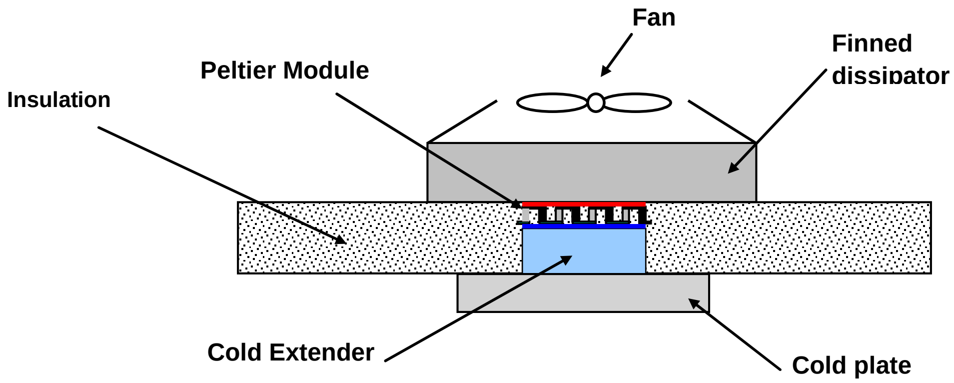

Fig. 2. Thermoelectric device.

Several computational models have been developed (Stockholm & Stockholm, 1992; Astrain et al., 2005, 2010; Crane & Bell, 2006; Crane et al., 2009) to study the whole thermoelectric system, including the heat exchangers. These models serve as study and design tools for both thermoelectric refrigeration and generation devices.

2.1 Development and validation of a computational model for thermoelectric systems

The computational model described in this section is an example that serves to assess the influence of the thermal resistances of the heat exchangers on the performance of thermoelectric devices. This model (Astrain et al., 2010) solves the non-linear system composed of thermoelectric and heat transfer equations, using the implicit finite-differences method. When used to simulate thermoelectric generation devices, the model requires the following inputs: geometric data, material properties, number and type of thermoelectric modules, thermal resistances of the heat exchangers, ambient temperature and energy introduced into the system. Then, the model outputs are: efficiency, voltage, electric current, electric power generated, temperatures and heat fluxes, all of them time-dependent. On the other hand, when the model simulates thermoelectric refrigeration devices, the inputs must be: geometric data, material properties, number and type of thermoelectric modules, thermal resistances of the heat exchangers, ambient temperature and voltage supplied to the modules. Then, the model provides temperatures and heat fluxes, coefficient of performance (COP), electric current and electric power consumed, again all of them time-dependent.

The model solves the one-dimensional thermal conduction equation in transitory state, being ρ density, c_p specific heat under constant pressure, t time, and $\dot{q}$ heat flux generated.

$$\rho c_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}\right) + \dot{q} \tag{4}$$

Firstly, the system must be discretized, that is, reduced into a set of representative nodes, as can be seen in Figure 3 for a thermoelectric generation system. Then, after using the first and second derivatives in finite differences (Özisik, 1994), the one-dimensional thermal conduction equation in transitory state is transformed into the finite differences form, applied to a node "i".

$$\frac{C_i}{\delta\tau}\left(T_i' - T_i\right) = \frac{T_{i-1}' - T_i'}{R_{i-1,i}} + \frac{T_{i+1}' - T_i'}{R_{i,i+1}} + \dot{Q}_i \tag{5}$$

The thermal resistance between nodes "i" and "i+1", as well as the thermal capacity of node "i" are expressed by the following equations, being $L_{i,i+1}$, A_i and V_i respectively the distance, cross section and volume between two connected nodes. Thermal resistances and capacities of commercial thermoelectric modules can be found in the scientific literature (Astrain et al., 2005, 2010; Min & Rowe, 2006). Thermal contact resistances between the components of the thermoelectric system can be found in the literature (Ritzer & Lau, 1994). The thermal resistances of the heat exchangers are parameters of study; therefore they are model inputs.

$$R_{i,i+1} = \frac{L_{i,i+1}}{k_i A_i} \tag{6}$$

$$C_i = V_i \rho_i cp \tag{7}$$

The generated (or absorbed) heat flux in node "i" is represented by the last member on the right of the equation (5), and its value is given by the Peltier, Joule and Thomson effects.

Regarding thermoelectric generation, one can obtain the voltage and the electric power generated by a thermoelectric module with the following expressions, where m stands for the ratio of the electrical load resistance to the electrical resistance of the module, and N represents the number of thermoelectric pairs of the module.

$$\Delta V = \left(\frac{m}{1+m}\right) 2N\left(\left(\alpha_h T_h - \alpha_c T_c\right) - \tau\left(T_h - T_c\right)\right) \tag{8}$$

$$P = \Delta V I \tag{9}$$

Regarding thermoelectric refrigeration, the thermal resistance of the insulating chamber of a thermoelectric refrigerator is provided by the following expressions, where S and e represents the surface area and thickness of the chamber, whereas U stands for the global heat transfer coefficient. The convection coefficients inside and outside the chamber (h_{in}, h_{out})

are calculated with equation (12), which is an experimental expression of the convection coefficient in a plane plate that considers laminar flow and dismisses viscosity dissipation (Parmelee & Huebscher, 1947).

$$R_{ins} = \frac{1}{US} \tag{10}$$

$$U = \frac{1}{1/h_{in} + e/k + 1/h_{out}} \tag{11}$$

$$\begin{gathered} \mathrm{Nu_L} = 0.664 \cdot \mathrm{Pr}^{1/3} \cdot \mathrm{Re_L}^{1/2} \\ 0.6 \le \mathrm{Pr} \le 50, \mathrm{Re} < \mathrm{Re}_{x,c} \approx 5 \cdot 10^5 \end{gathered} \tag{12}$$

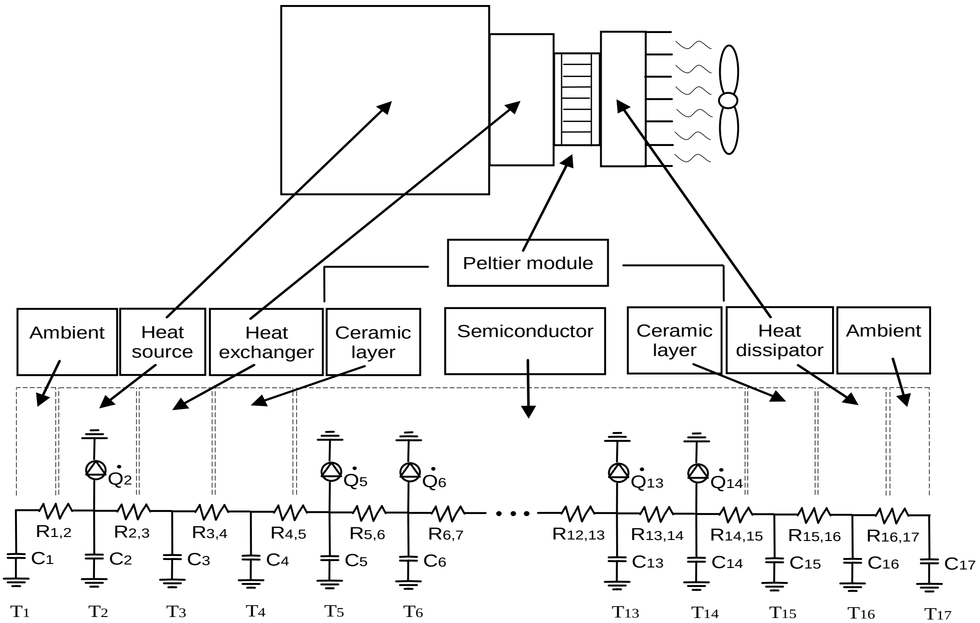

Fig. 3. Sketch and discretization of a thermoelectric generator.

The experimental validation proved that this computational model predicts the experimental values of the output parameters with errors always lower than 10%. Therefore, this model is an appropriate tool to study and present the significant influence that the heat exchangers have on the performance of both thermoelectric refrigerators and generators.

2.2 Influence of heat exchangers on the performance of thermoelectric refrigerators

Different values of thermal resistances of the heat exchangers at either side of the thermoelectric module are introduced in the computational model in order to study their influence on the performance of a thermoelectric refrigerator. Moreover, resulting model simulations were complemented with experimental tests conducted with a prototype thermoelectric refrigerator supplied with 12 V, and different configurations of heat exchangers. A controllable fan was installed over the heat exchanger outside the refrigerator (consisting of a finned dissipator), which allows the control of the air flowing through the fins of this heat exchanger and, therefore, its thermal resistance. Inside the refrigerator, the studied configurations of heat exchanger were: flat plate (no fins) without fan, finned dissipator without fan, finned dissipator with a fan supplied with 3 V (0.5 W).

Table 1 shows experimental and simulated temperatures inside the refrigerator (T_{int}) and at either side of the Peltier module (T_{hp} and T_{cp}), as well as the temperature difference between the inside and the ambient (T_{amb}-T_{int}). The model predicts temperatures accurately, and the maximum error in temperature differences reaches 1.2 K. What is more, the study highlights the significant influence of the thermal resistances of the heat exchangers on the performance of thermoelectric refrigerators; particularly, the temperature difference between the inside of the refrigerator and the ambient increases by more than 40% when configuration 4 is used instead of configuration 2.

Configuration	Test characteristics	Temperature (K)	Model	Prototype
1	Outside: Finned dissipator, fan supplied with 12 V. Inside: Flat plate, no fan.	T_{int}	278.9	277.7
		T_{hp}	311.2	308.4
		T_{cp}	263.3	261.6
		(T_{amb}-T_{int})	*17.8*	*19*
2	Outside: Finned dissipator, fan supplied with 4 V. Inside: Flat plate, no fan.	T_{int}	280.6	279.8
		T_{hp}	316.2	312.1
		T_{cp}	265.2	264
		(T_{amb}-T_{int})	*16.1*	*16.9*
3	Outside: Finned dissipator, fan supplied with 12 V. Inside: Finned dissipator, no fan.	T_{int}	278.5	277.3
		T_{hp}	312.6	309.4
		T_{cp}	265.3	264.2
		(T_{amb}-T_{int})	*18.1*	*19.3*
4	Outside: Finned dissipator, fan supplied with 12 V. Inside: Finned dissipator, fan supplied with 3 V.	T_{int}	273.7	272.7
		T_{hp}	311.4	308.8
		T_{cp}	266.6	266
		(T_{amb}-T_{int})	*22.9*	*23.9*

Table 1. Experimental and simulated results for 12 V of supplied voltage to the Peltier module, ambient temperature 296.6 K and 60% of relative humidity.

2.3 Influence of heat exchangers on the performance of thermoelectric generators

A methodology similar to that used for thermoelectric refrigerators was applied to study the influence of the thermal resistances of the heat exchangers at either side of the thermoelectric modules on the electric power generated by a thermoelectric generator. Figure 4 shows the electric power as a function of both thermal resistances, where one can observe the significant increase in the electric power that occurs when decreasing the thermal resistances of both heat exchangers. As an example, if both thermal resistances improved from 0.5 to 0.4 K/W, the electric power generated would increase by 20 %. On average, a decrease by 10 % in both thermal resistances entails an increase in the electric power by around 8 %. This serves to illustrate the importance of the design of heat exchangers in thermoelectric generation applications.

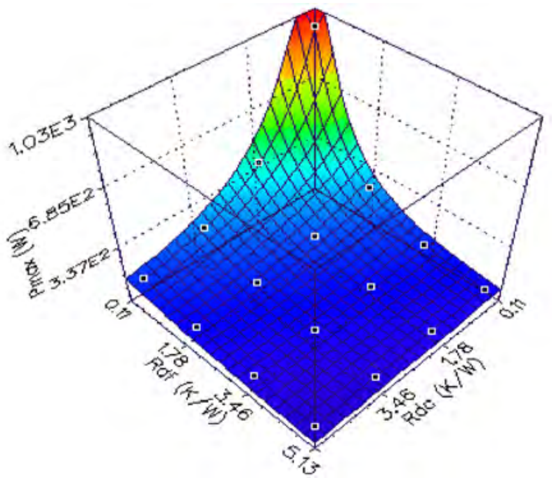

Fig. 4. Electric power generated (P_{max}) versus thermal resistance of the hot side heat exchanger (R_{dc}) and thermal resistance of the cold side heat exchanger (R_{df}).

3. Heat exchangers analysis

Once we have demonstrated the enormous importance that thermal resistances of heat exchangers have on the performance of thermoelectric devices, it is of high interest to show the most significant designs of heat exchangers applied to thermoelectrics.

3.1 Finned dissipator

This type of heat exchanger represents the most used heat dissipation system in thermoelectric refrigeration, essentially because of its low manufacturing cost. However, this is not the best option whatsoever. Major problems of this design relate to constriction thermal resistances (Lee et al., 1995), which are inherent to the small surface areas of Peltier modules. This fact entails that a significant surface area of the dissipator is useless, as can be seen at the top of Figure 5.

Some works (Astrain & Vian, 2005) have already addressed the optimization of a finned dissipator for the hot end of a Peltier module. The optimization parameters were: position of the module, position and type of fan, thickness of the dissipator base, and height of the fins. The most outstanding conclusions were:

- When the fan is placed at one end of the dissipator so that the air crosses the dissipator from one side to the other, the optimal position of the module is not the exact centre but a bit closer to the fan. Moreover, this fact gains significance as the air flow increases.
- If an axial fan is installed over the dissipator, the thermal resistance decreases by 5.5 % with respect to the previous case.
- Increasing the base thickness of the dissipator leads to a decrease in the thermal resistance without affecting the pressure losses. Specifically, if this parameter increases from 8 mm to 16 mm, the thermal resistance decreases by 13.2 %. However, this fact also leads to heavier and more expensive dissipators.

- Increasing the height of the fins is also beneficial from both a thermal and hydrodynamic point of view. Specifically, if this parameter rises from 40 mm to 60 mm in a dissipator with an axial fan over it, the thermal resistance reduces by 10.4 %.

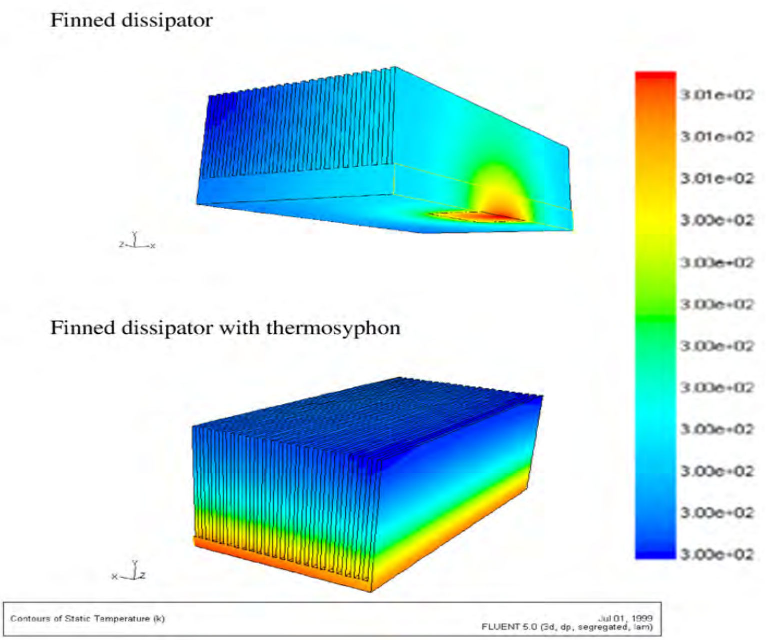

Fig. 5. Temperature distribution in a finned dissipator, with and without thermosyphon.

Finally, this work presents a prototype thermoelectric refrigerator that served to experimentally prove that the COP improves by 10 % if the thermal resistance of the heat exchanger installed at the hot side of the Peltier modules decreases by 13 %.

In conclusion, this work makes evident the important role that holds the thermal resistance of the heat exchangers in the efficiency of a thermoelectric refrigeration device. Likewise, it also indicates that the thermal resistance of a finned dissipator is too high despite the optimization process. This fact indicates that it is absolutely necessary to design new types of heat exchangers in order to reduce even more the thermal resistance and increase the efficiency of thermoelectric devices. In this line of work, there have been developed the phase-change thermosyphons, described in the following section.

3.2 Thermosyphon for the hot end of a Peltier module

A thermosyphon is a hermetically sealed container in the shape of a straight prism, enclosing a fluid. The Peltier module is attached to the bottom of the rear surface, so that the heat flux produced by the module is transmitted to the fluid, which begins to boil. Vapour produced in the process rises up to the top of the thermosyphon by natural convection. Likewise, the cold reservoir (usually the ambient) is connected to the front surface of the thermosyphon, where several fins are installed. Thus, when the vapour touches this cold surface, it cools down, then condensates and finally gravity makes it go down to the bottom of the thermosyphon. As a result, the fluid forms a cycle completely closed and self-sufficient. Figure 6 describes the process.

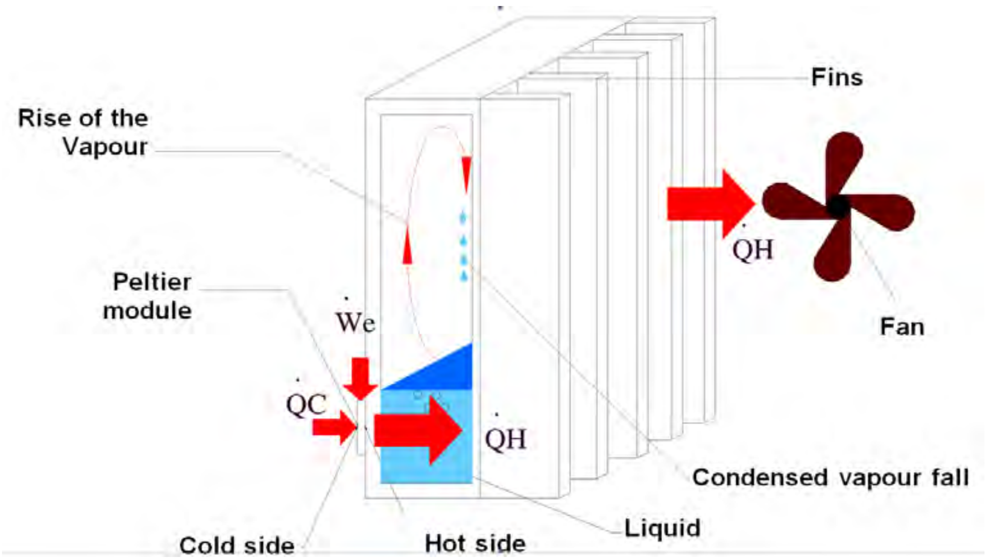

Fig. 6. Phase-change thermosyphon for the hot end of a Peltier module.

The heat flux emitted by the module (Q_c) is uniformly distributed along the base area of the finned dissipator, as can be seen at the bottom of Figure 5, thus increasing significantly the efficiency of the system. Likewise, the heat flux produced by the condensation process (Q_h) is transferred to the ambient. A fan enhances the heat transfer.

Figure 7 presents experimental values of thermal resistances of a prototype thermosyphon (called TSF) attached to a commercial 40 mm x 40 mm Peltier module, for different ambient temperatures, along with the thermal resistance of a similar-in-weight commercial dissipator (Astrain et al., 2003). It can be seen that the thermal resistance of this TSF decreases as the ambient temperature increases, owing to the fact that the boiling and condensation coefficients improve with temperature. This thermosyphon attains a thermal resistance ranging from 0.125 ºC/W for 20 ºC of ambient temperature to 0.079 ºC/W for ambient temperature 35 ºC. This leads to an improvement in the dissipation by 23.8 % at 20 ºC, and 51.4 % at 35 ºC of ambient temperature, with respect to the values obtained with a similar commercial dissipator. This heat exchanger was installed in a prototype thermoelectric refrigerator and the COP increased by 21.3 % for ambient temperature 19 ºC, and 36.5 % for ambient temperature 30 ºC.

As indicated before, the major advantage of thermoelectric technology with respect to vapour compression refrigeration lies on the reduction in the number of moving parts, since no compressor needs to be installed. However, the thermosyphon TSF does need a fan. Further designs present optimized thermosyphons that require no fans at all, thus removing all the moving parts, such as the Bosch-Siemens patented thermosyphon called TSV (Astrain

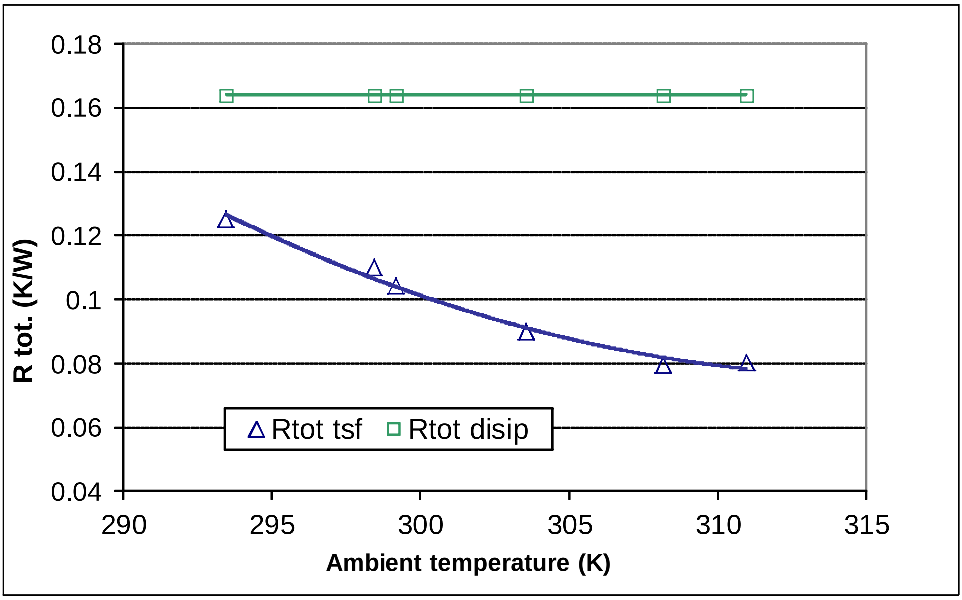

Fig. 7. Thermal resistance of a real thermosyphon and a similar finned dissipator versus ambient temperature.

et al., 2006a). Figure 10 shows a sketch of a thermoelectric device that incorporates a cylindrical TSV for the hot side of the Peltier module. Its basic concept is similar to that behind the TSF, so that a deposit for the liquid and a condensation zone must be included in the design. The latter represents the major difference with respect to the TSF, since it must be cylindrical now, thus increasing the heat transfer surface area, which makes TSV work properly with natural convection. Experimental values of TSV's thermal resistances are showed in Figure 8, where they are compared with those obtained with a TSF for both natural and forced convection.

3.3 Thermosyphon and capillarity lift for the cold end of a Peltier module

At the cold side of a Peltier module, the problem remains similar to that at the hot side, though in this case the heat flux is not emitted but absorbed by the module, and the objective is to improve the heat transfer between the thermoelectric module and the refrigeration chamber of a thermoelectric refrigerator.

Like in the previous case, the most used heat exchanger is a finned dissipator due to its low cost. However, new designs combining thermosyphon and capillarity lift technologies have been proposed, such as the Bosch-Siemens patented thermosyphon TMP (Astrain et al., 2006b), which improves significantly the thermal resistance of this heat exchanger. The TMP is installed in the refrigerator so that one face is attached to the cold end of the module, and the opposite face is inside the refrigeration chamber. This thermosyphon increases the heat transfer surface area from the small surface of the Peltier module to the significantly bigger surface area of a finned dissipator, taking advantage of the high heat transfer inherent to

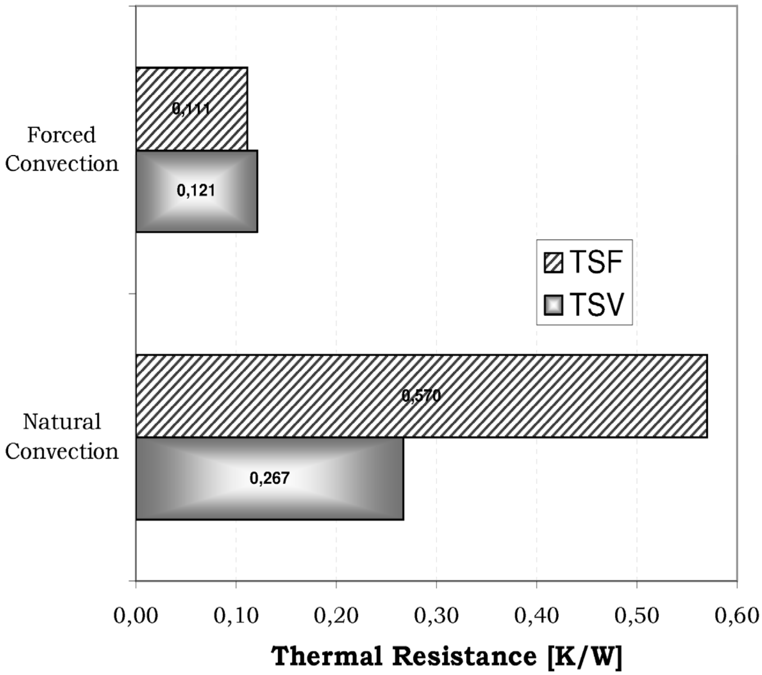

Fig. 8. Thermal resistances of TSF and TSV for natural and forced convection.

phase-change processes, capillarity lift through porous materials and gravity pulling down condensed liquids.

As can be seen in Figure 9, the TMP basically consists of a watertight compartment and a porous layer attached to one of its inner faces. When heat is absorbed from the refrigerated chamber, the liquid evaporates and transfers this heat to the cold end of the Peltier module. The porous layer makes the fluid at the bottom of the TMP ascend by capillarity, surmounting gravity, thus making use of all the surface area of the TMP for the evaporation process. Vapour formed ascends by natural convection, condenses near the cold face of the Peltier module and goes down as liquid pulled by gravity, thus forming a completely closed and self-sufficient cycle.

Subsequently, this TMP was incorporated into a prototype of thermoelectric refrigerator, which served to assess the improvement attained with respect to a similar thermoelectric refrigerator including a finned dissipator for the cold side of the Peltier modules (Vian & Astrain, 2009b). The TMP had a thermal resistance of 0.323 K/W when a small fan with 0.75 W of electric power consumption was installed in the refrigeration compartment. In the same conditions, a finned dissipator similar in size to the TMP provided a significantly higher thermal resistance of 0.513 K/W. Likewise, it was experimentally proved that the COP of the thermoelectric refrigerator endowed with a TMP increases by 32 % with respect to the COP of this refrigerator but including a finned dissipator at the cold side of the Peltier module.

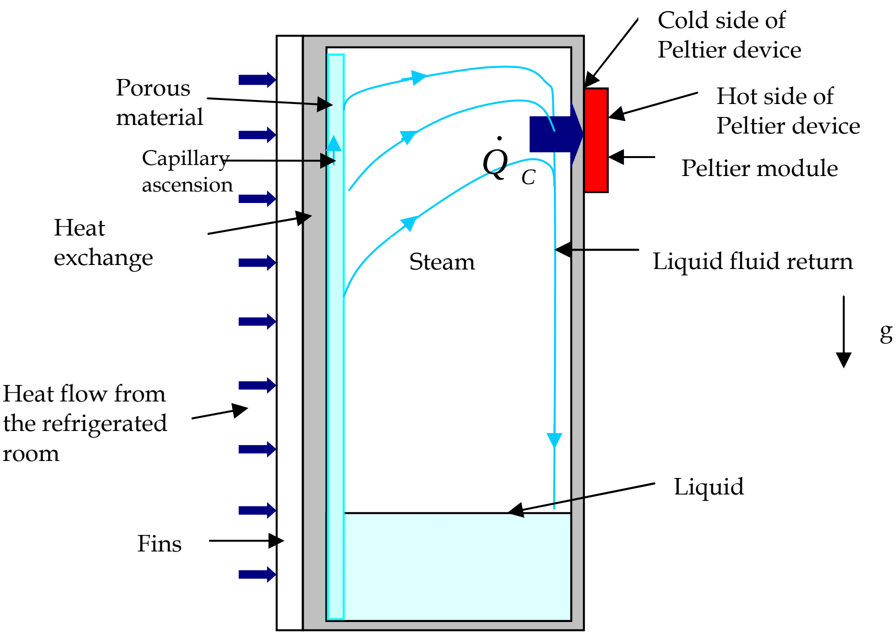

Fig. 9. Performance of the TMP.

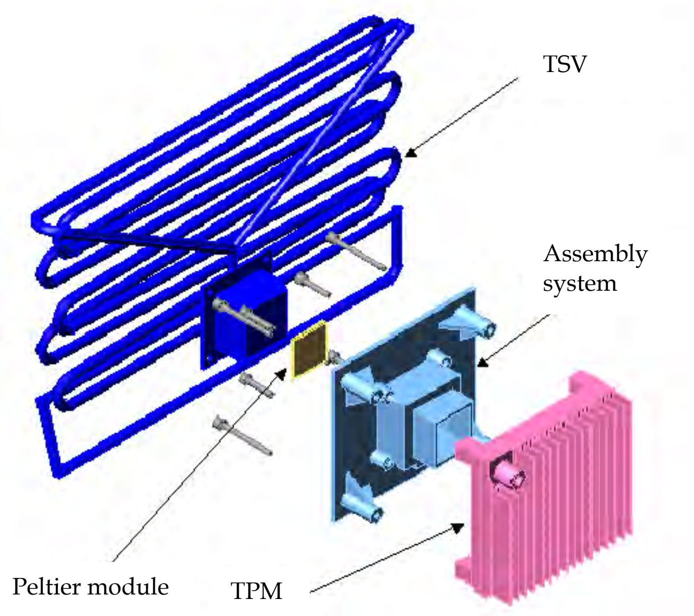

Fig. 10. Thermoelectric device with the heat exchangers TSV and TMP.

Figure 10 shows the sketch of a prototype thermoelectric refrigerator including the two types of thermosyphon explained along this section, for either end of the Peltier module.

Likewise, Figure 11 provides two photographs of this prototype, indicating the cited heat exchangers. This prototype served to conclude that including the developed thermosyphons (TSV and TMP) in a thermoelectric refrigerator, the COP increased by 66% with respect to that obtained with a similar thermoelectric refrigerator endowed with finned dissipators (Vian & Astrain 2009b).

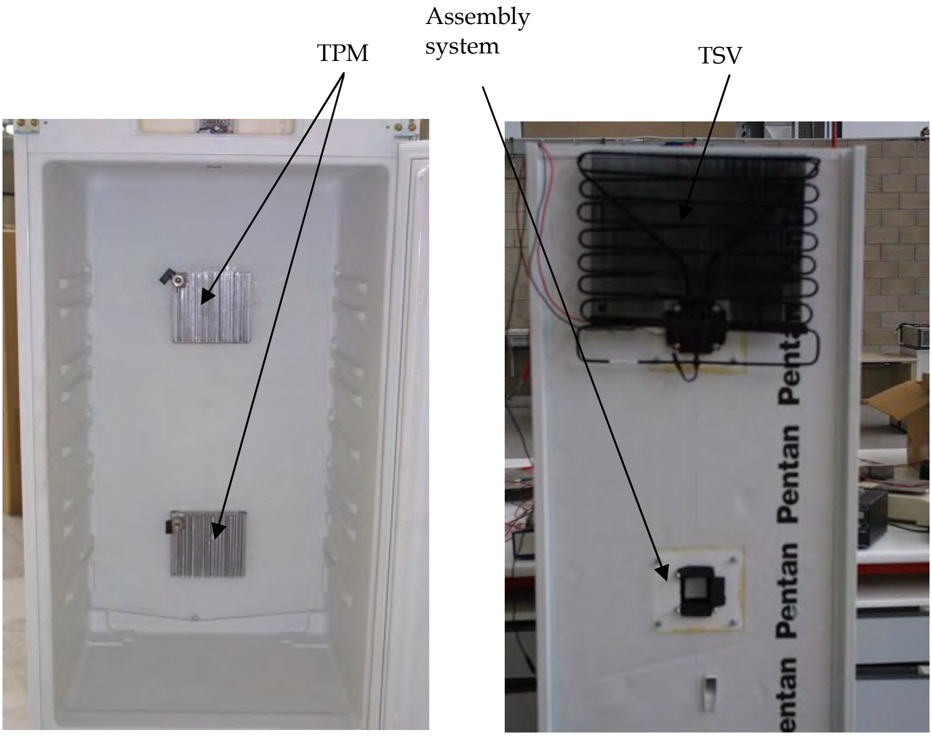

Fig. 11. Photographs of the prototype with heat exchangers TMP and TSV.

4. Thermoelectric self-cooling of devices (TSC)

Recently, a new thermoelectric application has come out (Martinez et al., 2011), which allows the self-cooling of any device that generates a certain amount of heat, such as electrical power converters, transformers, control systems, etc. As can be seen in Figure 12, the Peltier module in this application works as an electric power generator, since it harnesses the thermal gradient between the heat source (device that generates a certain amount of heat and must be cooled) and the ambient to produce electric power, which in turn is used to operate a fan and attain forced convection over a dissipator, thus improving the cooling of the device without electricity consumption. At the same time, the hot side of the module absorbs heat by Peltier effect, which reinforces the cooling process of the device. This work describes the design and experimental study of a prototype of TSC composed of:

- Two thin film heating resistors with dimensions 80 mm x 80 mm x 0.5 mm, each one capable of providing 150 W at 200 ºC, connected in series to a controllable DC power source. These elements serve to generate a controllable and measurable heat flux, and represent the heat source that must be cooled.
- A 220 mm x 160 mm x 32 mm aluminium plate composed of two pieces screwed to each other, the bottom one endowed with two similar cavities, wherein the heating resistors are installed.
- Four Peltier modules Kryotherm TGM-287-1.0-1.5, with dimensions 40 mm x 40 mm x 3.8 mm, and capable of working at 225 ºC.
- An aluminium finned dissipator composed of a square base plate, with side length 155 mm and height 12 mm, and 23 fins with dimensions 155 mm x 23 mm x 1.5 mm.
- One rectangular aluminium prism is installed between the modules and the dissipator in order to separate the device from the dissipator and avoid thermal bridges between them, which would decrease the efficiency of the system. This element is 55 mm long and has a squared base area with side length 80 mm.
- A DC fan type SUNON KDE1208PTS1-6, and a wind tunnel over the dissipator.

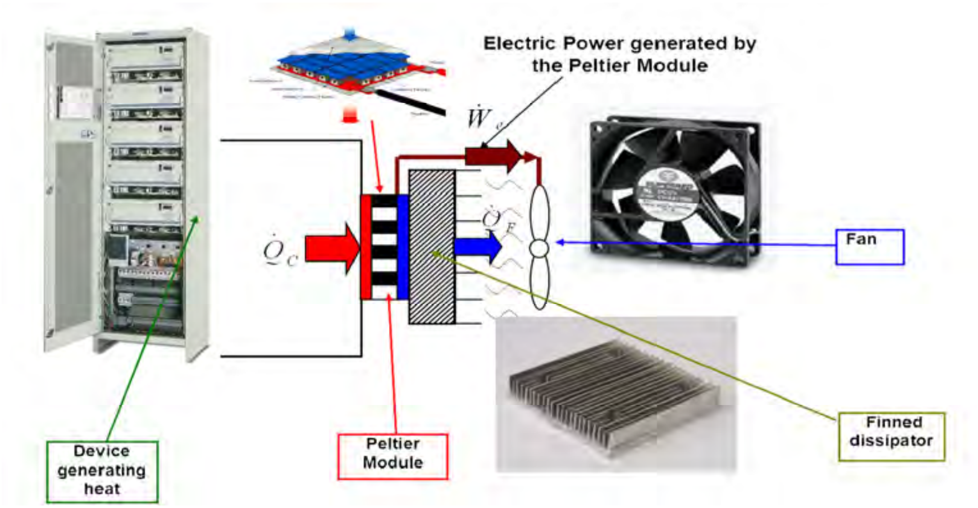

Fig. 12. Sketch of a thermoelectric self-cooling system.

This prototype served to conduct several experimental tests in order to study the thermal resistance between the heat source and the ambient, and compare it to that obtained when only the dissipator was mounted over the heat source (no modules, no fan), and finally compare it to the thermal resistance between the heat source and the ambient when no cooling system was mounted. Figure 13 shows the comparison between these three thermal resistances as functions of the heat flux generated by the heating resistors. As expected, the highest thermal resistance is achieved when no cooling system is attached to the device. More interesting is the fact that the TSC system always outperforms the dissipator alone, especially when the heat flux generated by the device exceeds 130 W. For lower values of heat flux, the electric power generated by the Peltier modules does not suffice to operate the fan. However for heat fluxes higher than 130 W, the electric power generated by the modules makes the fan rotate and, therefore, provides forced convection over the dissipator, which improves the heat transfer efficiency and decreases the thermal resistance between the heat source and the ambient by 30 % without electricity consumption.

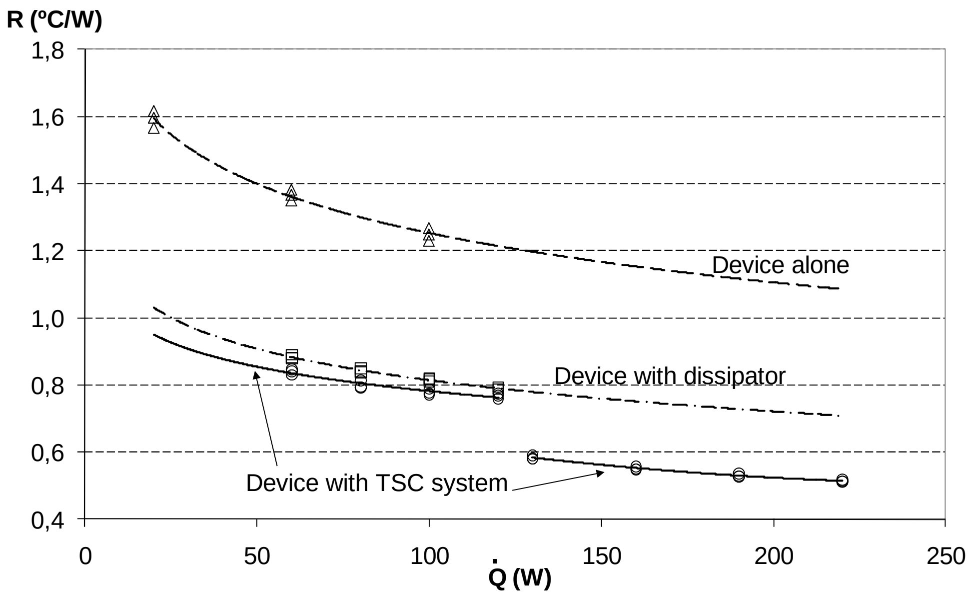

Fig. 13. Thermal resistances between heat source and ambient versus heat flux generated.

5. Conclusions

Thermoelectric technology has evolved significantly in the last decade, fundamentally due to the improvement of thermoelectric materials, which boosted the commercialization of novel applications in the civil market. However, efficiencies of thermoelectric devices that provide heating, cooling and generation of electric power are still low. In this sense, the scientific community considers essential the optimization of heat exchangers that must be mounted at either end of the Peltier modules.

This chapter has shown the major influence of the heat exchangers on the efficiency of thermoelectric devices, and indicates that this efficiency rises as the thermal resistances of both heat exchangers decreases. Particularly, for thermoelectric generators, a decrease by 10 % in both thermal resistances leads to an average increase in the electric power generated by around 8 %.

The optimization of finned dissipators used in thermoelectric refrigerators allows the reduction of their thermal resistances, which in turn increases the COP of these thermoelectric devices. However, finned dissipators do not represent the most efficient heat exchangers, since constriction thermal resistances restrict, to a great extent, the global thermal resistance of the dissipator.

Two different heat exchangers are presented, one for the hot side and the other for the cold side of the Peltier modules. On one hand, the TSF (phase-change thermosyphon) reduces the thermal resistance between the hot side of the module and the ambient by 51 %, which means an increase in the COP of thermoelectric refrigerators by 36.5 %. Subsequently, this TSF was improved and a thermosyphon with natural convection (TSV) came out, thus eliminating all moving parts. On the other hand, for the cold side of the Peltier modules, the described TMP joins thermosyphon and capillarity lift technologies and improves by 37 % the thermal resistance of a similar-in-size finned dissipator. Finally, a prototype that included the developed thermosyphons TSV and TMP showed an improvement on the COP by 66 % with respect to that attained with a similar prototype but including finned dissipators.

In the last part of the chapter, the novel concept of thermoelectric self cooling has been introduced, which can be applied to any device that generates a certain amount of heat, such as electrical power converters, transformers and control systems. When the thermoelectric self cooling system is installed, the thermal resistance between the heat source and the environment decreases by up to 30 % without electricity consumption.

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