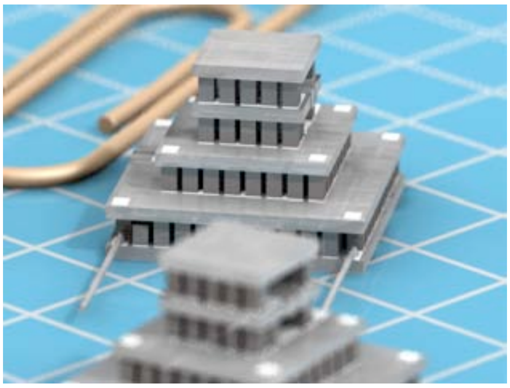
# THERMOELECTRIC COOLERS BASICS



**Introduction**. Although thermoelectric (TE) phenomena was discovered more than 150 years ago, thermoelectric devices (TE coolers) have only been applied commercially during recent decades. For some time, commercial TECs have been developing in parallel with two mainstream directions of technical progress – electronics and photonics, particularly optoelectronics and laser techniques. Lately, a dramatic increase in the application of TE solutions in optoelectronic devices has been observed, such as diode lasers, superluminescent diodes (SLD), various photodetectors, diode pumped solid state lasers (DPSS), charge-coupled devices (CCDs), focal plane arrays (FPA) and others.

**History**. The effect of heating or cooling at the junctions of two different conductors exposed to the current was named in a honor of the French watchmaker Jean Peltier (1785–1845) who discovered it in 1834. It was found that if a current passes through the contacts of two dissimilar conductors in a circuit, a temperature differential appears between them. This briefly described phenomenon is the basis of thermoelectricity and is applied actively in the so-called thermoelectric cooling modules.

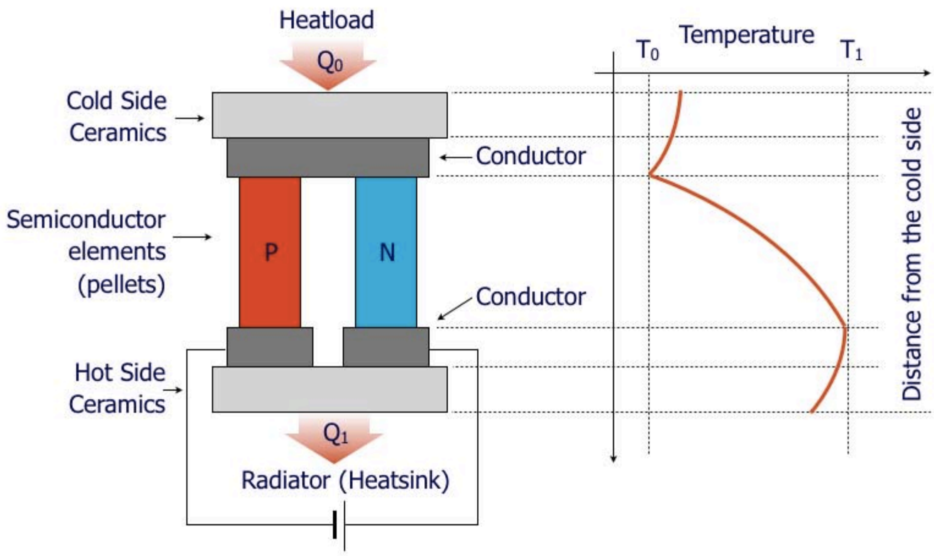



Fig. 1 Simplified Scheme of TE Module and the Temperature Differential along it

In contrast to the Joule heating, which is proportional to the square of the current ($Q=R \cdot I^2$) the Peltier heat (Qp) varies as a linear function of the current and changes its sign with it:

$$Qp=P \cdot q$$

where q is the charge that passes through the junction ($q=I \cdot t$); P is the Peltier coefficient, whose value depends on the contacting materials' nature and the contact temperature. The common way of presenting the Peltier coefficient is the following:

$$P=\alpha \cdot T$$

Here, $\alpha$ - alpha is the Seebeck coefficient defined by both contacting materials, properties and their temperature. T is the junction temperature in Kelvins.

**Thermoelectric Cooler Construction** . A TE module is a device composed of thermoelectric couples (N and P-type semiconductor legs) that are connected electrically in series, in parallel thermally and, fixed by soldering, sandwiched between two ceramic plates. The latter form the hot and cold thermoelectric cooler (TEC) sides. The configuration of thermoelectric coolers is shown in Figures 2 and 3.

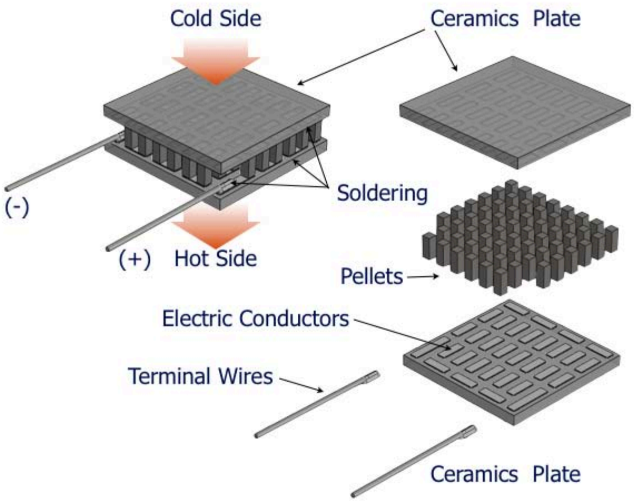



Fig. 2 - Single-stage Thermoelectric Cooler Construction

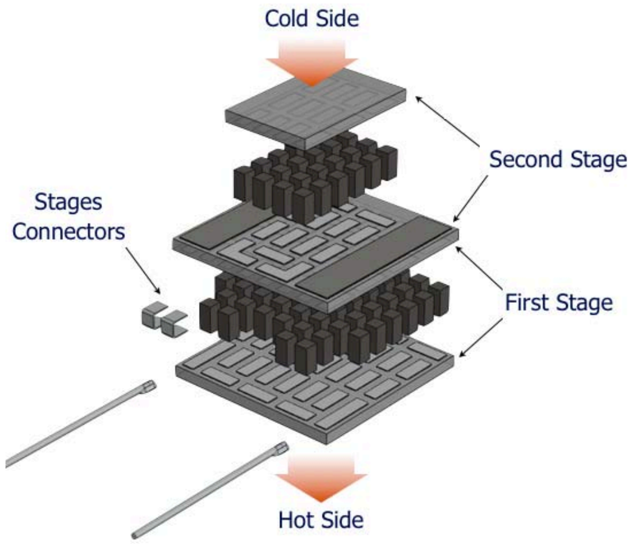



Fig. 3 Two-stage Thermoelectric Cooler Construction

Commonly, a TE module consists of the following parts:

- Regular matrix of TE elements – Pellets. Usually, such semiconductors as bismuth telluride (BiTe), antimony telluride or their solid solutions are used. The semiconductors are the best among the known materials due to a complex optimal TE performance and technological properties. BiTe material is the most typical for TE cooler.

- Ceramic plates – cold and warm (and intermediate for multi-stage coolers) ceramic layers of a module. The plates provide mechanical integrity of a TE module. They must satisfy strict requirements of electrical insulation from an object to be cooled and the heat sink. The plates must have good thermal conductance to provide heat transfer with minimal resistance. The aluminum oxide ($Al_2O_3$)

ceramics is used most widely due to the optimal cost/performance ratio and developed processing technique. Other ceramics types, such as aluminum nitride (AIN) and beryllium oxide (BeO), are also used. They have much better thermal conductance – five to seven times more than Al2O3 – but both are more expensive. In addition, BeO technology is poisonous.

• Electric conductors provide serial electric contacting of pellets with each other and contacts to leading wires. For most of the miniature TE coolers, the conductors are made as thin films (multilayer structure containing copper (Cu) as a conductor) deposited onto ceramic plates. For large size, high-power coolers, they are made from Cu tabs to reduce the resistance.

• Solders provide assembling of the TE module. The most standard solders used include Lead-Tin (Pb-Sn), Antimony-Tin (Sn-Sb) and Gold-Tin (Au-Sn) alloys. The solders must provide good assembling of the TE module. The melting point of a solder is the one of limiting factors for TE Cooler reflow processes and operating temperature. Leading wires are connected to the ending conductors and deliver power from a direct current (DC) electrical source.

A single-stage module consists of one matrix of pellets and a pair of cold and warm sides (see Figure 2). A multi-stage module can be viewed as two (see Figure 3) or more single stages stacked on top of each other. The construction of a multi-stage module is usually of a pyramidal type – each lower stage is bigger than the upper stage. Once the top stage is used for cooling, the lower stage requires greater cooling capacity to pump heat that is dissipated from the upper stage.

**Performance**. Thermoelectric coolers can be characterized by maximal performance parameters with a hot junction temperature (T1). Usually, they are listed in standard specifications of a TE cooler:

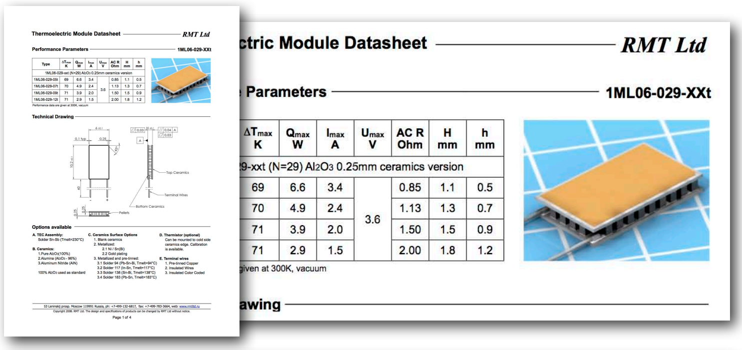
$\Delta T_{max}$ – maximal Temperature Difference along the module at zero heat load, Q=0

Qmax – maximal Cooling Capacity corresponding to $\Delta T_{max}$=0

Imax – the device Current at $\Delta T_{max}$, specified at certain ambient conditions

Umax– the terminal Voltage for Imax with no heat load

Usually manufacturers specify TE cooler performance parameters at 300K (27C) ambient temperature in vacuum or/and at 323K (50C) in Nitrogen conditions. The example from standard thermoelectric cooler datasheet is shown on Figure 4.




| Type | $\Delta T_{max}$ K | $Q_{max}$ W | $I_{max}$ A | $U_{max}$ V | AC R Ohm | H mm | h mm |
|---|---|---|---|---|---|---|---|
| 1ML06-029-xxt (N=29) $Al_2O_3$ 0.25mm ceramics version | | | | | | | |
| 1ML06-029-05t | 69 | 6.6 | 3.4 | 3.6 | 0.85 | 1.1 | 0.5 |
| 1ML06-029-07t | 70 | 4.9 | 2.4 | | 1.13 | 1.3 | 0.7 |
| 1ML06-029-09t | 71 | 3.9 | 2.0 | | 1.50 | 1.5 | 0.9 |
| 1ML06-029-12t | 71 | 2.9 | 1.5 | | 2.00 | 1.8 | 1.2 |

Fig.4 TE Cooler Parameters in Datasheet

All of the performance parameters are in an interdependent relationship with each other. The correct analysis of a TEC operation in the real application could be carried out using performance plots, which are the results of the interdependence between them. It is important to note that TE cooler performance parameters depend from ambient conditions.

**Standard Performance Plots** . A typical specification for thermoelectric cooler contains performance plots, that indicate the inter- dependent relationship between Imax, Umax, Qmax and ΔTmax. The typical examples are shown in Figure 5. Usually TEC performance parameters and standard performance plots are specified by manufacturers at 300K, vacuum ambient conditions.

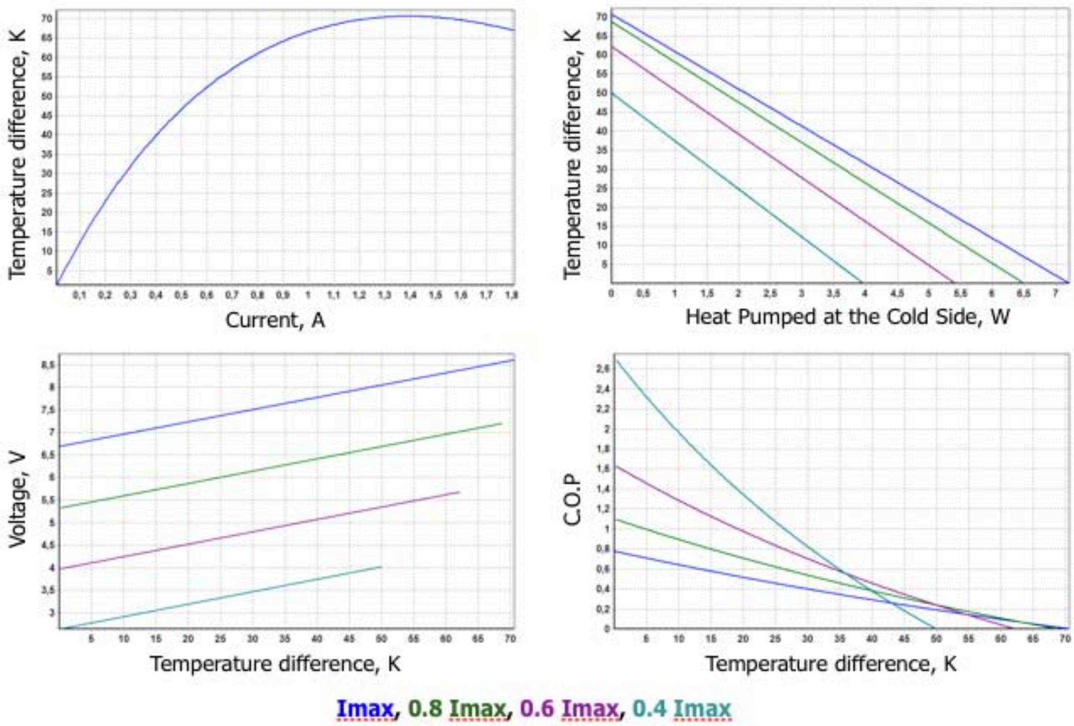



Fig.5 TE Cooler Standard Performance Plots

**Optimal Performance Plots** . They are the characteristics of TEC operation in the maximum coefficient of performance (COP) mode. The COP is defined as TE cooler cooling capacity Q divided by the consumed electric power in operating mode. The example is shown in Figure 6.

**Figure-of-merit**. There are more performance parameters that are usually not presented in standard specifications of commercial TE coolers, but that play a very important role in a module characterization.

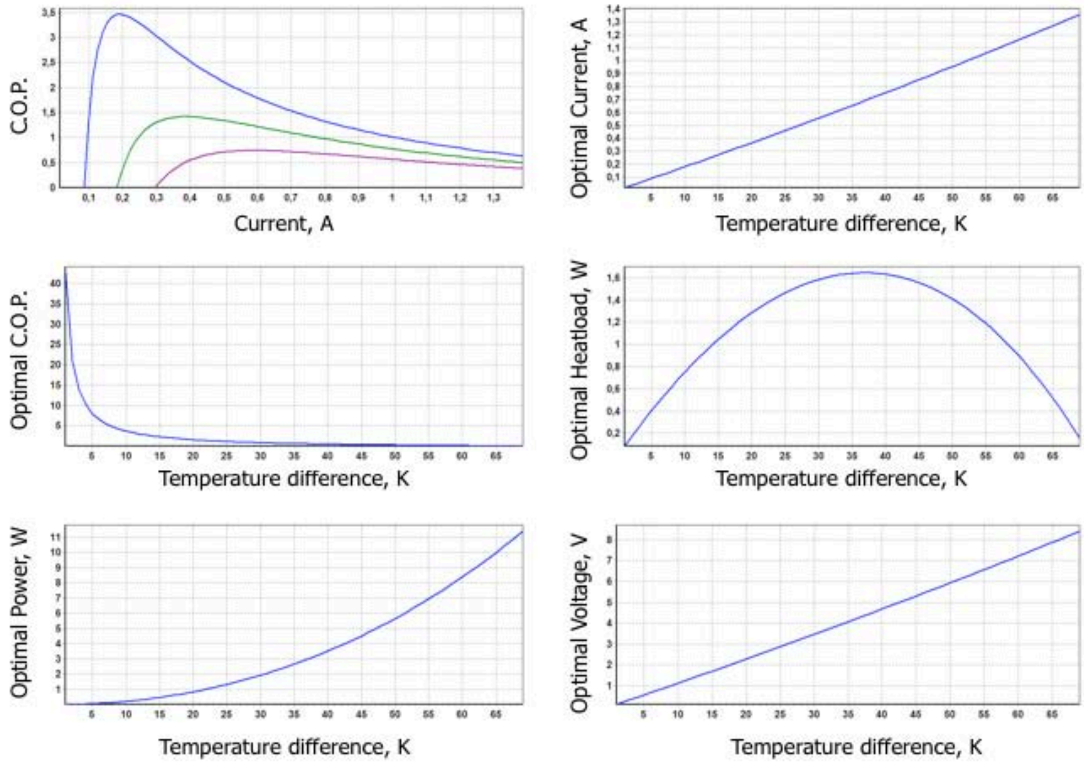
These parameters are the properties of pellet material (thermal conductance (k), electrical resistance (R) and the Seebeck coefficient) combined as follows:

$$Z = \frac{\alpha^2}{kR}$$

The parameter Z is usually referred to as “figure-of- merit”. The typical value of Z in 2.5 - 3.2 $10^{-3}K^{-1}$ range. The known value of Z allows estimating of ΔTmax of a single-stage TEC by the simple formula:

$$\Delta T_{max} = \frac{1}{2} Z \cdot T_0^2$$

where T0 is the cold side temperature. The typical temperature dependence of Z and ΔTmax vs Z is shown in Figure 7.




Imax, 0.8 Imax, 0.6 Imax, 0.4 Imax

Fig.6 TE Cooler Optimal Performance Plots

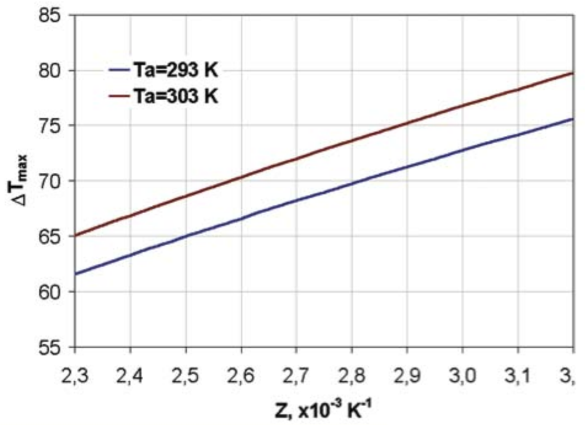



Fig.7 dTmax vs Figure-of-Merit

**Reliability**. Commercial TE coolers provide long operation lifetime in the range of 250,000 to 350,000 hours at normal conditions. It is the result of a highly developed technology of manufacturing and high-quality raw materials. In many applications, TEC is a critical component because it affects the temperature of the whole device and can have an influence on its correct operation, as well as an impact on heat dissipation. That is why severe reliability test procedures are required.

**Reliability Test Standards**. For these purposes, there are many national and international test standards. They are unified for a range of electronic and optoelectronic device qualifications. In the international market, Bellcore standards are the most common, namely, GR–468 (Reliability Assurance for Optoelectronic Devices).

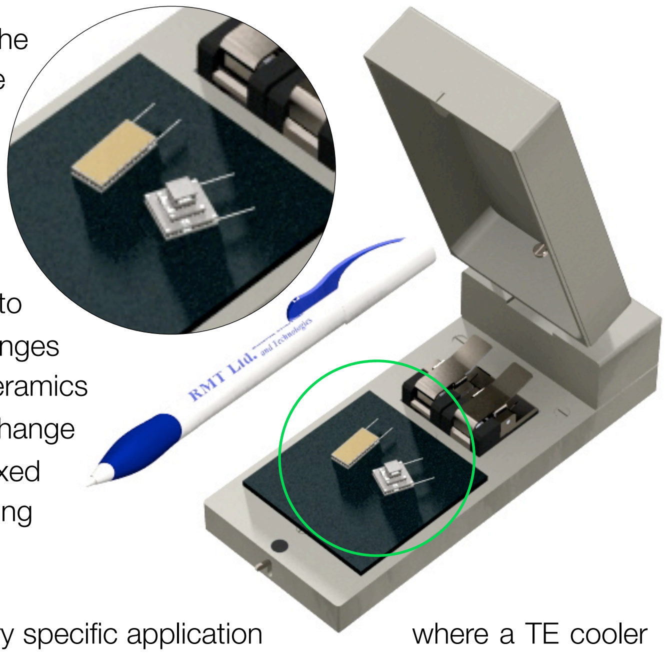
The minimal standard set of the test methods contains mechanical shock test, the vibration test, shear force test, the high-temperature storage test, the temperature cycle endurance test

**Failure Criteria**. The suggested failure criteria that are in practice for reliability tests are the following:

-drop in TEC maximum cooling capacity ΔTmax of below its specified rating
-and an increase in TEC resistance of 5% or higher.

Controlling both the criteria is achievable in the method of Z-metering, which is fast and quite accurate, realized by the test device Z-Meter. The latter provides the measurement of the figure-of-merit Z and therefore the ΔTmax and alternating current resistance (AC R) measurement.

Parameters Z and AC R are extremely sensitive to the TEC quality and to any failure. Any slight changes in a module – destruction of pellets, junctions, ceramics and so on – immediately result in the noticeable change of Z (decrease) and AC R (raise) against initial fixed values. The detailed information about Z-Meter using and QC methods is available by by this link.




**Selecting a TE Cooler for an Application**. Every specific application where a TE cooler is required is characterized by a set of operation parameters and restrictions, which dictate the necessity of accurate selection of the optimal TEC type among a wide range of single and multi-stage TECs. These parameters are:

ΔT – operating temperature difference (at known ambient Ta temperature)

Q – operating cooling capacity;

I – applied or available current;

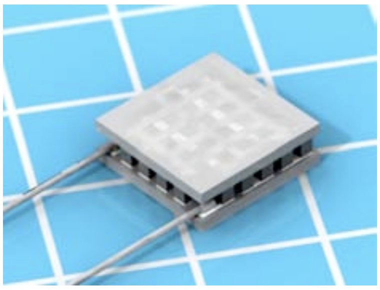
U – terminal voltage; and dimensional restrictions and others.

A user can make a rough but fast estimation of operating temperature difference and cooling capacity as:

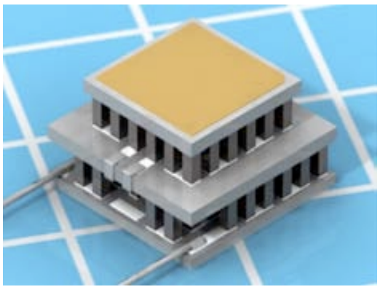
$$Q = Q_{max}(1-\frac{\Delta T}{\Delta T_{max}}) \text{ and } \Delta T = \Delta T_{max}(1-\frac{Q}{Q_{max}})$$

In Table 1 an example list of commercial miniature thermoelectric coolers is shown. A user can find that, concerning the required temperature difference, the single-stage TE coolers provide ΔTmax in a range of 65K to 72K, two and more stage types provide more (see Figure 8).

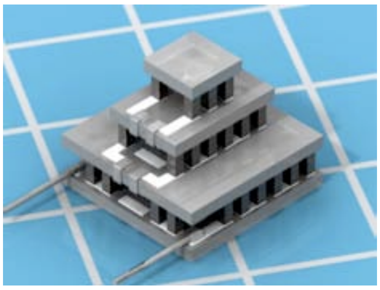
| Typical Commercial TE Coolers (RMT Ltd) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| TE Cooler Type | dTmax K | Qmax W | Imax A | Umax V | AC R Ohm | H mm | A mm | B mm | C mm | D mm |
| Single-stage Thermoelectric Coolers | | | | | | | | | | |
| 1MD04-003-03 | 68 | 0.49 | 2.3 | 0.37 | 0.12 | 0.9 | 1.2 | 1.9 | 1.2 | 2.6 |
| 1MD04-010-05 | 71 | 1.05 | 1.5 | 1.20 | 0.63 | 1.1 | 2.5 | 3.0 | 2.5 | 3.9 |
| 1MC06-018-15 | 72 | 1.45 | 1.2 | 2.2 | 1.55 | 2.6 | 6.0 | 6.0 | 8.0 | 6.0 |
| 1ML06-029-09 | 71 | 3.85 | 2.0 | 3.55 | 1.50 | 2.1 | 6.0 | 10.2 | 6.0 | 10.2 |
| 1MDL06-042-05 | 70 | 9.7 | 3.5 | 5.10 | 1.17 | 1.1 | 6.0 | 10.2 | 6.0 | 12.0 |
| 1MC06-070-05 | 69 | 15.80 | 3.41 | 8.60 | 2.05 | 1.6 | 12.0 | 12.0 | 12.0 | 12.0 |
| 1MC06-126-05 | 71 | 28.30 | 3.4 | 15.50 | 3.70 | 1.6 | 16.0 | 16.0 | 16.0 | 16.0 |
| Two-stage Thermoelectric Coolers | | | | | | | | | | |
| 2MC04-039-12 | 98 | 0.51 | 0.5 | 3.6 | 6.00 | 4.1 | 4.8 | 4.8 | 6.4 | 6.4 |
| 2MC06-010-10 | 94 | 0.37 | 1.3 | 0.90 | 0.58 | 3.7 | 3.2 | 3.2 | 4.0 | 4.0 |
| 2MC06-021-05 | 100 | 1.20 | 2.8 | 2.10 | 0.60 | 2.7 | 2.0 | 4.0 | 8.0 | 6.0 |
| 2MC06-051-08 | 95 | 2.25 | 1.6 | 4.55 | 2.35 | 3.3 | 4.0 | 7.0 | 8.0 | 10.0 |
| Three-stage Thermoelectric Coolers | | | | | | | | | | |
| 3MC06-024-12 | 115 | 0.26 | 1.0 | 1.95 | 1.65 | 5.9 | 2.5 | 2.5 | 6.0 | 6.0 |
| 3MC06-044-10 | 114 | 0.60 | 1.2 | 3.50 | 2.55 | 5.3 | 2.0 | 4.0 | 10.0 | 8.0 |
| 3MD04-113-15 | 112 | 0.49 | 0.34 | 8.40 | 20.20 | 6.8 | 3.2 | 3.2 | 7.4 | 7.4 |
| Four-stage Thermoelectric Coolers | | | | | | | | | | |
| 4MD04-116-15 | 126 | 0.19 | 0.35 | 8.25 | 20.44 | 8.9 | 2.6 | 2.6 | 7.4 | 7.4 |
| 4MC06-105-10 | 123 | 0.64 | 1.1 | 7.20 | 6.05 | 6.9 | 2.0 | 4.0 | 12.0 | 12.0 |
| TE Coolers Performance parameters specified at 300K, Vacuum<br>AxB, CxD, mm - Dimensions of Cold and Hot Sides; H - TEC Height | | | | | | | | | | |



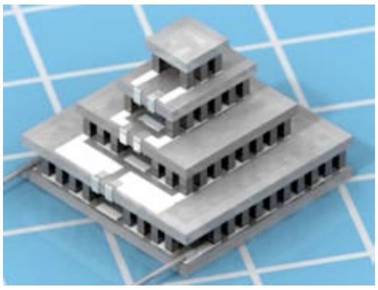
Single-stage TE Cooler



Two-stage TE Cooler



Three-stage TE Cooler



Four-stage TE Cooler

Fig.8 Typical Commercial miniature TE Coolers

Among each group (single and multi-stage types), there are modules with different cooling capacity Q. Thermoelectric cooler cooling capacity depends from the number of pellets and their geometry. Low height pellets or/and larger pellets cross-section provide higher cooling capacity value for thermoelectric cooler. In the same time they increase the operating current and total power consumption. Small pellets cross-section and tall pellets increase maximum temperature difference and reduce TEC power consumption, but cooling capacity is reduced too.

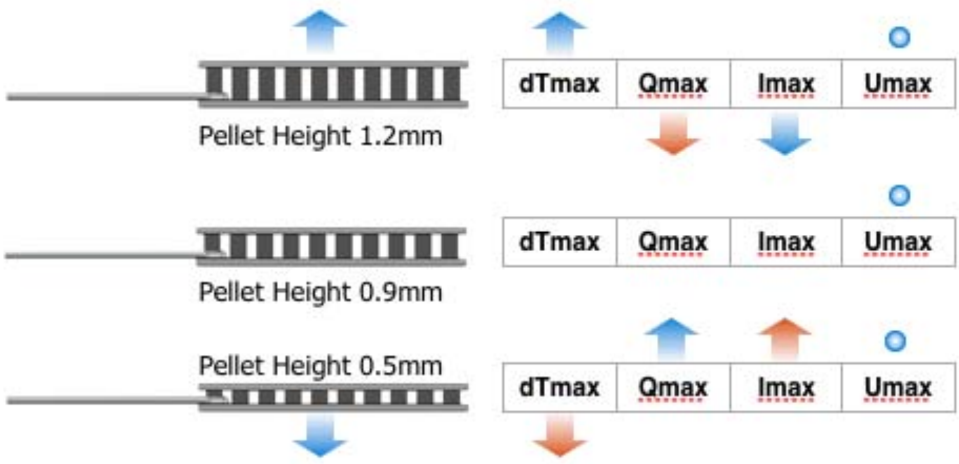
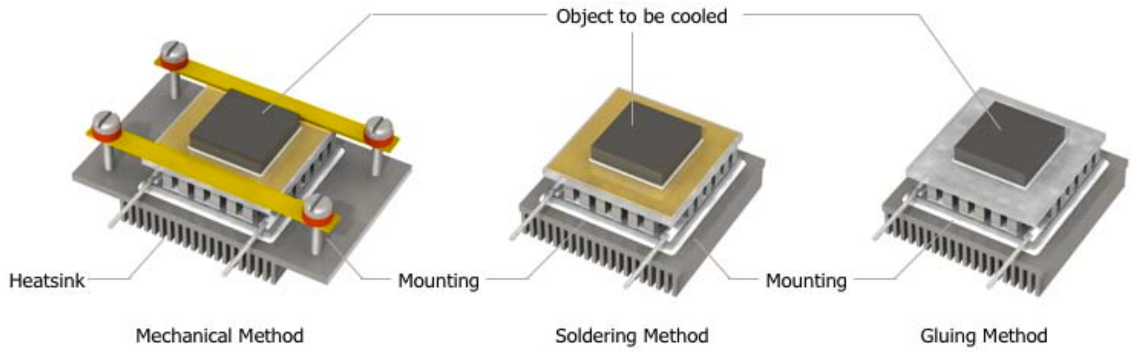



Fig.9 TE Cooler pellets height and parameters dependency

If also considering the usual restrictions in the power supply, the correct selection can become rather a complicated task. In order to accelerate and optimize this procedure, most of the suppliers advise a kind of assistance. In addition, some of them advise users about software that allows them to search among TECs and decide on the optimal choice using computer database analysis of existing TE module types with detailed modeling of a concrete TE module behavior in particular operating conditions. TEC Microsystems recommends TECCad Software, available free for download by the this link.

**Thermoelectric Coolers Mounting.** In practice, the performance and operational lifetime of thermoelectric cooler depends considerably on many factors, and proper mounting method is the very important one. Mounting is the first procedure before any application of a TE cooler. The mounting method and applied materials must provide good thermal contacts and minimum heat resistance.



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**Mechanical mounting.** The TE cooler is placed between two heat exchangers. This sandwich is fixed by screws or in another mechanical way. The advantage of fixing by screws lies in the possibility to make a fast and easy disassembling if required. It is suitable for large coolers, for example, with external surfaces measuring 30 x 30mm or more. Miniature types require different assembling methods.

**Soldering**. This is a universal method for most of the miniature TE coolers. This method involves preparation of the TE module with metal-covered outside surfaces (cold and warm sides). During soldering, a TE cooler is heated for a short time, but up to a high temperature. Therefore:

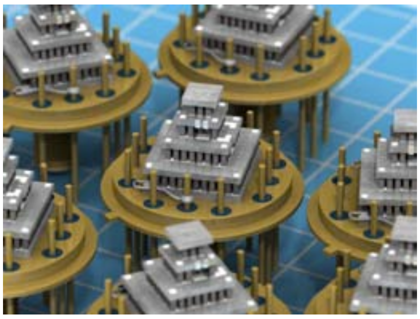
- the melting point of the outside solder must always be lower than the internal solder of the module;
- soldering duration needs to be as short as possible to reduce the overheating time.

Usually, it is not recommended to apply soldering for TECs with linear dimensions of sides measuring more than 18mm because of thermal stress. In this case a very careful materials choice is required.

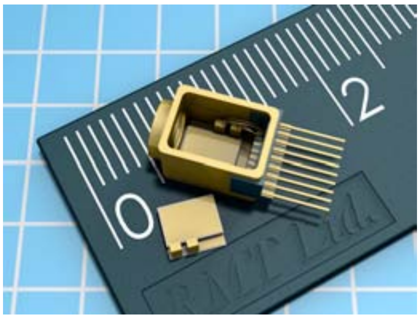
**Gluing**. It is used widely due to simplicity. Usually, epoxy compounds filled with thermoconductive material, such as graphite powder, silver, silicon nitride (SiN) and others, are used.

However, there are general restrictions as follows:

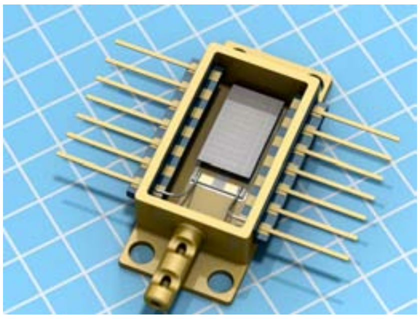
- Some epoxies have low operation temperatures, making them unsuitable for high-temperature TE coolers.
- It is not a proper method for high-vacuum applications because epoxy involves problems with outgassing.



4-Stage TE Coolers on TO-8 Headers Mounting by lead-free Soldering



TO-style TOSA assembly. TEC is mounted by epoxy gluing



Soldering or Gluing are typical for TEC mounting in Butterfly packages

## Materials and References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