Thermoelectric Cooling Modules

a report by
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Introduction

Although thermoelectric (TE) phenomena were discovered more than 150 years ago, thermoelectric devices (TE modules) have only been applied commercially during recent decades. For some time, commercial TEs have been developing in parallel with two mainstream directions of technical progress – electronics and photonics, particularly opto-electronics and laser techniques.

Lately, a dramatic increase in the application of TE solutions in optoelectronic devices has been observed, such as diode lasers, photodetectors, solid-state pumped lasers, charge-coupled devices (CCDs) and others.

The progress in applications is provided by advantages of TE modules – they are solid state, have no moving parts and are miniature, highly reliable and flexible in design to meet particular requirements.

History

The effect of heating or cooling at the junctions of two different conductors exposed to the current was named in honour 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 (see *Figure 1*).

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

$$Q_p = P \cdot q$$

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, α is the Seebeck coefficient defined by both contacting materials, properties and their temperature. T is the junction temperature in Kelvins.

Thermoelectric Module 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 TE modules is shown in *Figures 2* and *3*.

Commonly, a TE module consists of the following parts.

- Regular matrix of TE elements – pellets. Usually, such semiconductors as bismuth telluride, 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.

- Ceramic plates – cold and warm (and intermediate for multi-stage modules) 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 are used most widely due to the optimal cost/performance ratio and developed processing technique. Other ceramics, such as aluminium nitride (AlN) and beryllium oxide (BeO), are also used. They have much better thermal conductance – five to seven times more than Al_2O_3 – but both are more expensive. In addition, BeO technology is poisonous.

Figure 1: Simplified Scheme of TE Module and the Temperature Differential Along It

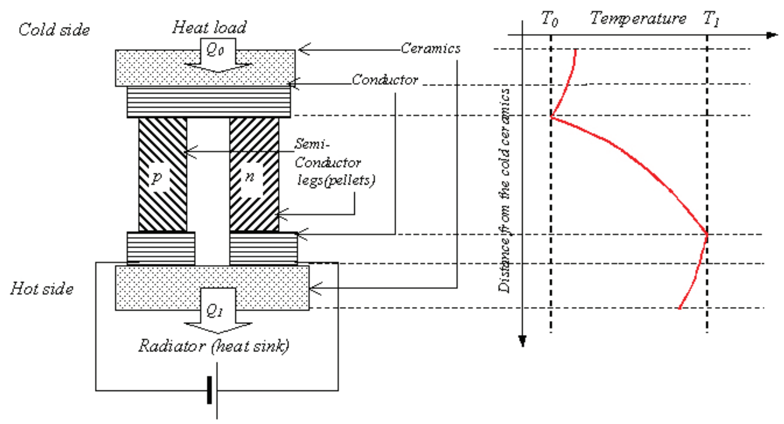


Figure 2: Single-stage Module Construction

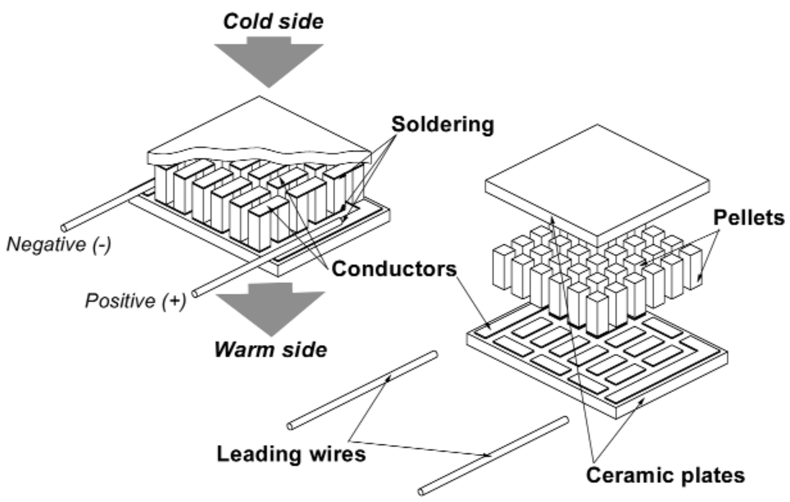
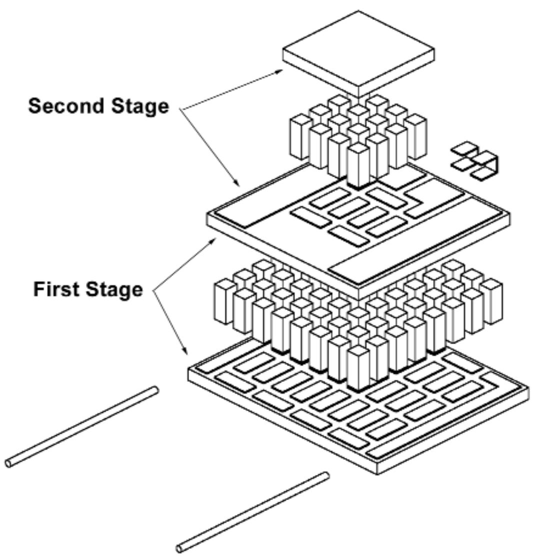


Figure 3: Two-stage Module Construction



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

- Solders provide assembling of the TE module. The solders used include antimony-tin and lid-tin alloys. The solders must provide good assembling of the TE module. The melting point of a solder is the limiting factor of operation temperature of the module. For long lifetime module, operation temperature must be lower than the solder's melting point as much as possible.

- 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.[1] 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

TE modules can be characterised by maximal performance parameters with a hot junction temperature (T_1). Usually, they are listed in standard specifications of a module:

ΔT_{max} – maximal temperature difference along the module at no heat load Q=0

Q_{max} – the cooling capacity corresponding to $\Delta T_{max}=0$

I_{max} – the device current at ΔT_{max}

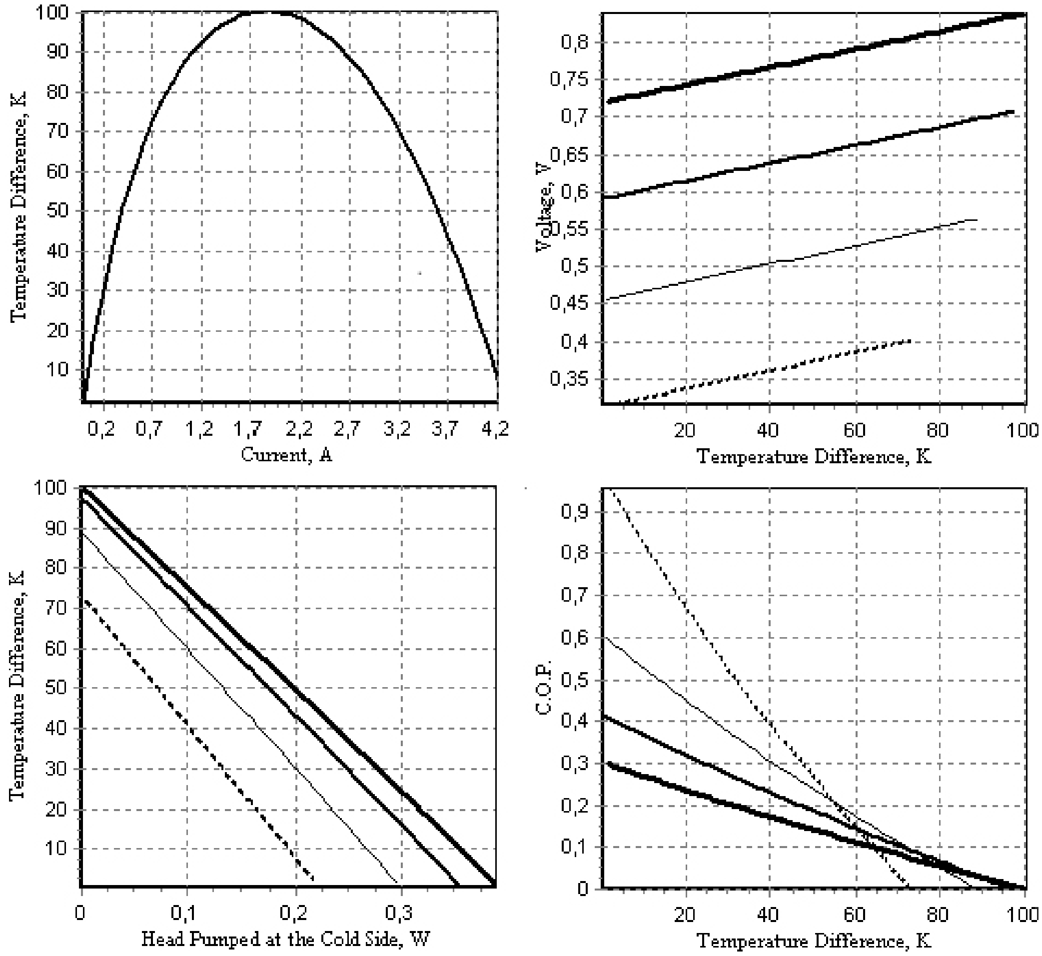
U_{max} – the terminal voltage for I_{max} with no heat load

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.

1. L I Anatychuk, Thermoelements and Thermoelectrical Devices, *p.151, Kiev, 1979.*

Figure 4: Example of Maximum Performance Plots



Maximum Performance Plots

The basic performance plots indicate the inter-dependent relationship between I_{max}, U_{max}, Q_{max} and ΔT_{max}. The typical examples are shown in *Figure 4*.

Optimal Performance Plots

They are characteristics of TEC operation in the maximum coefficient of performance[2] (COP) mode. The COP is defined as cooling capacity Q divided by the consumed electric power. Typical examples are shown in *Figure 5*.

Figure-of-merit

There are more performance parameters that are usually not presented in standard specifications of commercial TE modules, but that play an important role in a module characterisation.

These parameters are the properties of pellet material (thermal conductance (k), electrical resistance (R) and the Seebeck coefficient) combined[1,2] as follows:

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

The parameter Z is usually referred to as figure-of-merit. The typical value of Z is 2.5 to 3.0 $10^{-3}\ K^{-1}$. The known value of Z allows estimating of ΔT_{max} of a single-stage TEC by the simple formula:

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

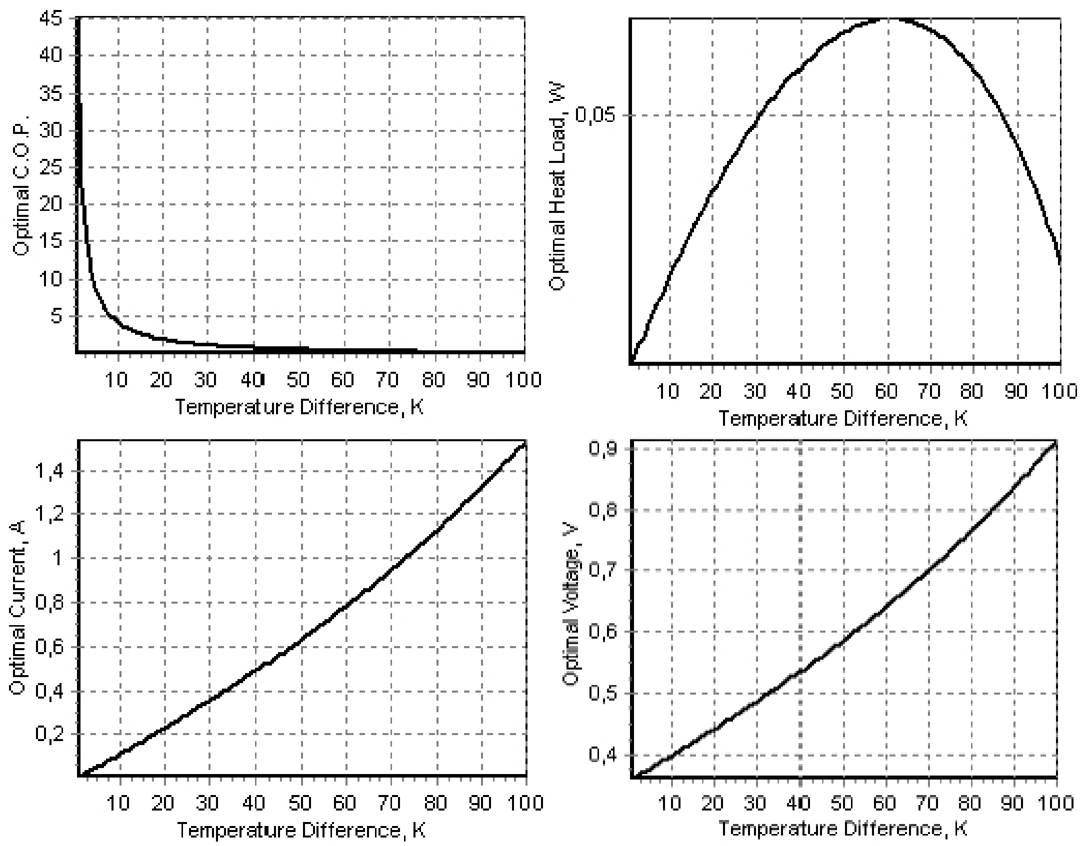
where T_0 is the sold side temperature. The typical temperature dependence of Z and ΔT_{max} vs Z is shown in *Figure 6*.

Reliability

Commercial TE modules provide long operation lifetime in the range of 100,000 to 200,000 hours. 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[3] are required.

2. *A L Vayner,* Thermoelectric Coolers, *Moscow, 1983, pp. 30–35.*
3. *L G Stokholm, "Reliability of thermoelectric cooling systems",* Proceedings of Xth International Conference on Thermoelectrics, *Cardiff, UK, 1991, p. 228.*

Figure 5: Example of Optimal Performance Plots



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, GP–468–CORE (Reliability Assurance for Optoelectronic Devices).

The minimal standard set of the test methods is:

- the mechanical shock test;
- the vibration test;
- the shear force test;
- the high-temperature storage test; and
- the temperature cycle endurance test.

Failure Criteria

The suggested failure criteria that are in practice for reliability tests are the following:

- a drop in TEC maximum cooling capacity ΔT_{max} of below its specified rating; and
- an increase in TEC resistance, usually of 5% or higher.

Controlling both the criteria is achievable in the method of *Z*-metering[4], which is fast and quite accurate, realised by the test device *Z*-Meter. The latter provides the measurement of the figure-of-merit *Z* and therefore the ΔT_{max} 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.

Selection of TE Module for an Application

Every specific application where a TE module is required is characterised 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 T_a/hot junction T_h temperatures);
- Q – operating cooling capacity;

4. *H H Woodbury, L M Levinson and R S Lewandowski, "Z-Meters",* CRC Handbook of Thermoelectrics, *CRC Press, Inc., 1995, pp. 181–189.*

- 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:

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

A detailed analysis must be carried out with the help of performance plots.

In *Table 1,* a list of typical commercial TE modules is shown. A user can find that, concerning the required temperature difference, the single-stage TE modules provide ΔT_{max} in a range of 65K to 72K, and two and more stage types can give more (see *Figure 7*).

Among each group (single and multi-stage types), there are modules with different cooling capacity Q. When more power is required, the bigger dimensions of the TE module can provide the necessary heat pump.

If also considering the usual restrictions in the power supply, the correct selection can become rather a complicated task.

In order to accelerate and optimise 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 modelling of a concrete TE module behaviour in particular operating conditions.

Examples of such software are now advised, for example, by the firms Melcor, Kryotherm and RMT.

Application Tips

In practice, the performance and operational lifetime of TE modules depends considerably on many factors as follows.

Mounting

Mounting is the first procedure before any application of a TE module (see *Figure 8*). The mounting method and applied materials must provide good thermal

Figure 6: ΔT_{max} as a Function of Figure-of-merit Z

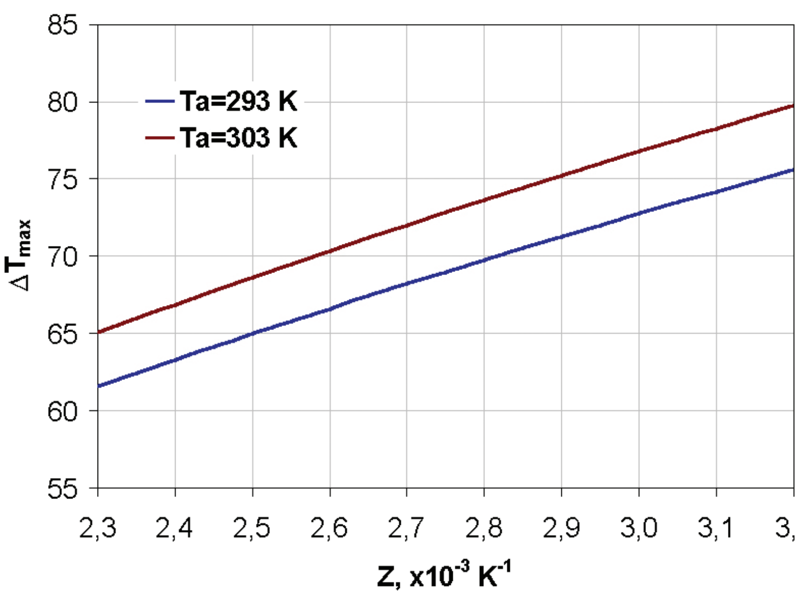


Figure 7: Maximum Performance Parameters of Commercial TE Modules of RMT

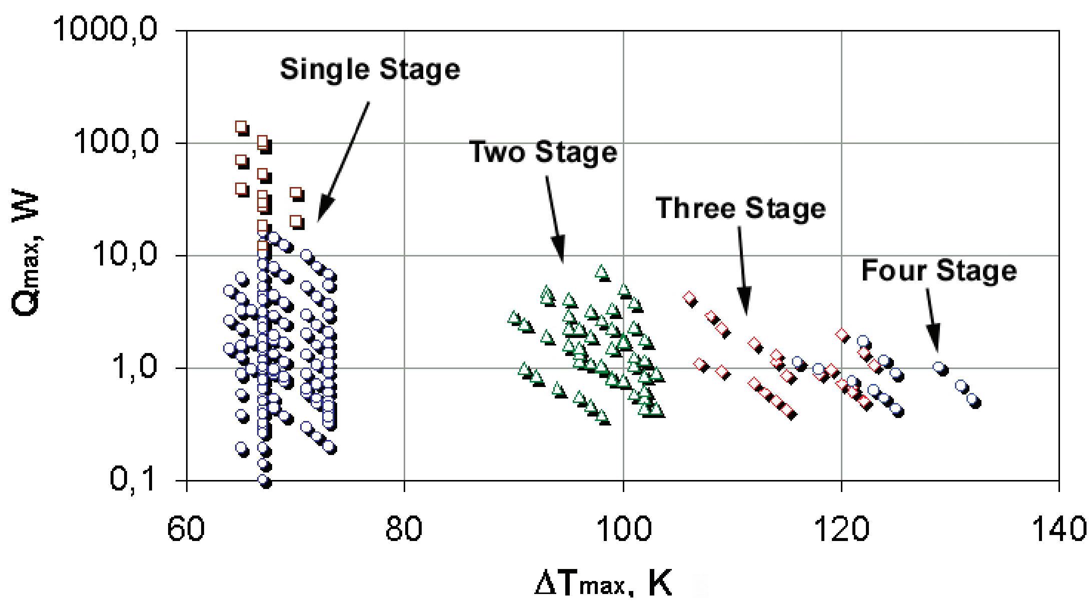


Figure 8: TE Module Mounted onto TO8 Header

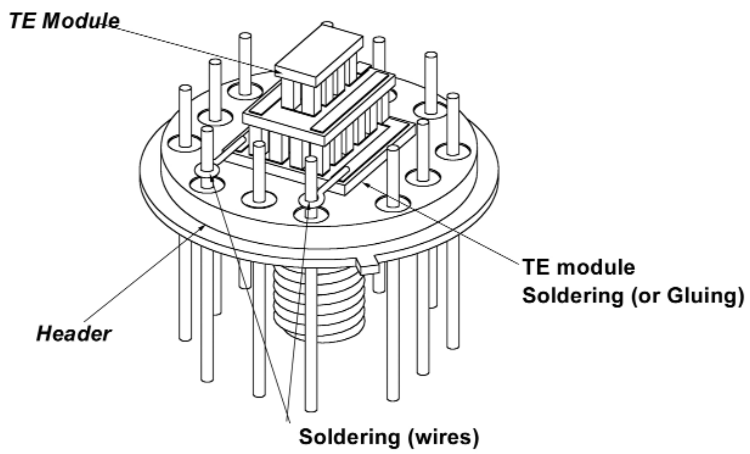


Table 1: Typical Commercial TE modules (of RMT Ltd)

Model	ΔT_{max},K	Q_{max},W	I_{max},A	U_{max},V
		Single Stage		
1MT 03-004-13	67	0.10	0.40	0.45
1MT 03-008-13	67	0.19	0.40	0.90
1MT 03-012-13	67	0.29	0.40	1.35
1MC 04-004-05	68	0.44	1.60	0.50
1MC 04-018-15	68	0.53	0.40	2.20
1MC 04-032-15	68	0.94	0.40	4.00
1MT 04-128-12	65	6.20	0.80	14.50
1MT 05-004-13	67	0.26	1.10	0.45
1MT 05-008-13	67	0.52	1.10	0.90
1MT 05-032-13	67	2.10	1.10	3.60
1MT 05-128-13	67	8.45	1.10	14.50
1MC 06-008-15	73	0.72	1.30	1.00
1MC 06-012-15	73	1.08	1.30	1.50
1MC 06-018-15	73	1.63	1.30	2.20
1MC 06-032-15	73	2.89	1.30	3.90
1MC 06-032-05	68	7.71	3.60	3.90
1MC 06-060-05	68	14.40	3.60	7.30
1MT 06-128-13	67	12.50	1.60	14.50
1MT 07-004-13	67	0.50	2.00	0.45
		Two Stage		
2MC 06-015-15	98	0.38	1.00	1.30
2MC 06-039-15	102	0.85	1.10	3.60
2MC 06-077-15	100	1.82	1.10	7.00
2MC 06-077-05	93	4.80	2.90	7.00
2MC 10-009-15	101	0.58	3.00	0.80
2MC 10-019-20	103	0.90	2.30	1.80
2MC 10-037-20	102	1.78	2.30	1.80
2MC 10-041-20	96	2.26	2.10	3.50
2MC 10-075-20	101	3.80	2.20	3.50
		Three Stage		
3MC 10-038-20	122	0.51	2.10	3.30
3MC 10-078-20	123	1.05	2.10	6.60
3MC 10-095-20	109	2.23	1.70	6.60
3MC 06-046-15	115	0.42	0.90	3.50
3MC 06-080-15	122	0.50	1.00	6.70
3MC 06-080-05	114	1.31	2.60	6.70
		Four Stage		
4MC 06-105-15	125	0.43	0.80	6.80
4MC 10-089-20	132	0.52	1.80	6.50
4MC 10-097-20	125	0.89	1.60	6.50

contacts and minimum heat resistance.

- Mechanical mounting – the TE module 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 modules, 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 modules. 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; and

  – soldering duration needs to be as short as possible to reduce overheating time.

  We do not recommend applying soldering for TECs with linear dimensions of sides measuring more than 15mm because of thermal stress.

- Gluing 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 modules.

- It is not a proper method for high-vacuum applications because epoxy involves problems with outgassing.

Power Supply

The TE module is a DC device. Specified TE module performance is valid if a DC power supply is used.

- Rippled DC power – in many cases, actual DC power supply has a rippled output. This AC component is detrimental. Degradation of TEC performance due to the ripple (see *Figure 9*) can be approximated by:

$$\frac{\Delta T'_{max}}{\Delta T_{max}} = \frac{1}{1+N^2/2}$$

Table 2: Manufacturers and Suppliers of Thermoelectric Cooling Modules

Fandis	Italy	Markets TE modules, heatsinks and fans and manufactures TE air conditioners.	http://www.fandis-tm.com
Ferrotec America	US	Manufactures thermoelectric modules. Single and multi-stage units and silicone edge seal available.	http://www.ferrotec-america.com
HiTech Technologies	US	Manufactures thermoelectric modules. Temperature ranges from -150°C to +200°C.	http://www.hitechtec.com
Huayu	China	Manufactures thermoelectric modules.	http://www.huayutec.com
Hui Mao Cooling Equipment	China	Manufactures thermoelectric modules, temperature ranges to +250°C and power to 200W.	http://www.huimao.com
Komatsu Electronics	Japan	Manufactures thermoelectric modules, controllers and cold and hot plates.	http://www.komatsu-electronics.co.jp
Kryotherm	Russia	Manufactures Peltier modules. Temperature range is -150°C to +80°C.	http://www.kryotherm.spb.ru
Osterm	Russia	Manufactures thermoelectric modules.	http://www.zts.com/osterm
Qinhuangdao Fulianjing Electronic	China	Manufactures TE modules.	http://www.fulianjing.com
RMT Ltd	Russia	Manufacturer of TE coolers, thermoelectric assemblies and test devices.	http://www.rmtltd.ru
SCTB NORD	Russia	Manufacturer of TE coolers.	http://www.sctbnord.com
SIREC srl	Italy	Manufactures thermoelectric modules.	http://www.sirec-it.com
Supercool AB	Sweden	Markets TE modules. Manufactures thermoelectric assemblies, systems and temperature controllers.	http://www.supercool.se
Thermion	Ukraine	Manufactures thermoelectric cooler modules.	http://www.zts.com/thermion
Marlow Industries	US	Manufactures single and multi-stage thermoelectric modules.	http://www.marlow.com
Melcor	US	Single and multi-stage TE coolers (to 200°C), power supplies and temperature controllers.	http://www.melcor.com
Taihuaxing Trading/ Thermonamic Electronics	China	Manufacturer of thermoelectric cooling and power-generating modules.	http://www.sitechina.com/thermoelectric/home.html
TE Technology	US	Manufactures thermoelectric cooler modules, assemblies, temperature controllers and TE module test systems.	http://www.tetech.com
Tellurex	US	Manufactures thermoelectric heating and cooling modules.	http://www.tellurex.com
ThermoElectric Cooling America	US	Thermoelectric cooling for electronic enclosures, air conditioners, cold plates, liquid chillers and temperature controllers for Peltier devices.	http://www.thermoelectric.com
ThermoLyte	US	Manufactures TE modules.	http://shore.net/~temodule/tlyte.htm

where N = ripple amplitude around the average current.

- Power modulation – in practice, pulse wide modulation (PWM) is used widely. This method is particularly unsuitable for a TEC as a power source. It leads to degradation of TEC performance (see *Figure 10*).

$$\frac{\Delta T'_{max}}{\Delta T_{max}} = \frac{(1+N(2Q-1))^2}{1+2N(2Q-1)+N^2}$$

Q, N = duty cycle and amplitude of modulation.

Manufacturers and Prices

Although we have observed a fast rise in commercial applications of TE modules, only few tens of manufacturers operate in the world market. An approximate list is shown in *Table 2*.

Among the manufacturers and suppliers, we can mention the very strong positions of a few well-known American companies (Melcor and Marlow, for example) who have been in the market for many years and have maintained leading positions.

Another group consists of the Commonwealth of Independent States (CIS) companies – mainly Russian and Ukrainian. Most of them are young and started only a decade ago but are based on a high TE technology level and scientific basis from the former CIS's TE scientific school[5–7], which started from Ioffe's investigations. Most of the companies are experienced in high-performance modules, such as miniature and multi-stage, which meet the current photonics needs.

Chinese companies are also relatively young. They have demonstrated a fast expansion in the TE market and dominate in low-cost types.

Production of TE modules is also developing rapidly in Japan and Europe. Some of these companies are involved in co-operation with other leading manufacturers.

5. *A F Ioffe,* Semiconductor Materials, *Moscow, 1960.*
6. *L S Stilbans,* Semiconductor Thermocoolers, *Leningrad, 1967.*
7. *G N Dulnev,* Thermal Exchange in the Radioelectrical Devices, *Leningrad, 1963.*

Figure 9: ΔT_{max} as Function of Rippled Power Supply

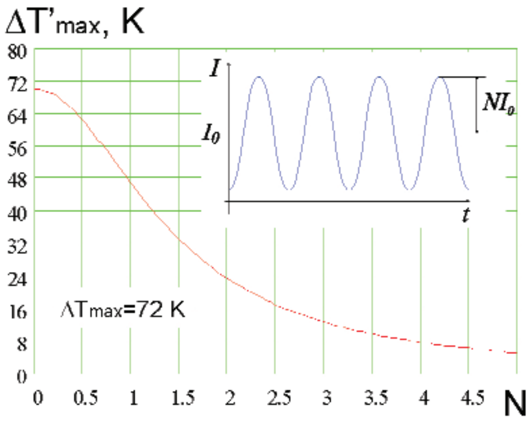
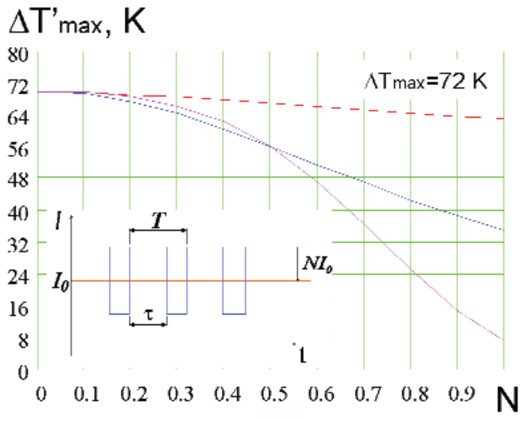


Figure 10: ΔT_{max} in Case of PWM Power Supply



It is very difficult to detail the prices of commercial TE modules. Only powered modules, such as 40 x 40mm^2 and 30 x 30mm^2, are standard and produced by many manufacturers, so their prices can be compared. However, there is a large nomenclature of TE modules for photonics. Every specialised supplier advises a list of hundreds of types. For example, only RMT offers more than 400 standard TEC types.

The leading manufacturing companies have been making great efforts to reduce the cost of TE modules during recent years. Further reductions of prices are predicted for the near future due to the increasing number of commercial TECs on the market, as well as stronger competition. ■

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