Using Thermoelectric Coolers

in Electronics Cooling

Thermoelectric devices are semiconductor modules which use the Peltier effect to create a heat flux between the junctions of two different types of materials. Named after French physicist Athanase Peltier, the effect shows that a temperature differential is created when DC current is applied across two dissimilar materials. (It is one of the three thermoelectric effects; the others are the Seebeck effect and Thomson effect.)

A typical thermoelectric module is manufactured using two thin ceramic wafers with a series of N and P doped bismuth-telluride semiconductor material sandwiched between them. The ceramic material adds rigidity and the necessary electrical insulation. The N type material has excess electrons, while the P type material has a deficit of electrons. One N and one P make up a couple, as shown in Figure 1.

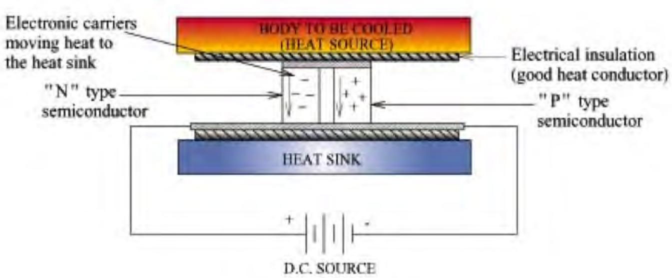

Figure 1. Illustration of a Thermoelectric Module [1].

When a DC current is applied to the circuit, the thermoelectric module can work as a cooler or heater depending on the current's direction. A thermoelectric cooler (TEC), or solid state heat pump transfers heat from one side of the device to the other side against the temperature gradient. Many products use thermoelectric coolers, including small refrigeration systems, CCD cameras, laser diodes and portable picnic coolers. They are also used in the thermal management of microprocessors, memory modules and other electronic devices. Figure 2 shows the Cooler Master V10 TEC CPU heat sink.

Figure 2. Cooler Master V10 TEC CPU Heat Sink [2].

Although a TEC provides a very simple and reliable solution for cooling devices, its poor thermal performance prevents its broader usage. Compared with traditional refrigeration systems, the coefficient of performance (COP) of a TEC is only about 1/5 that of a refrigeration system using a vapor compression cycle. Currently, the uses of TECs in electronics cooling are limited to systems that require temperature stability or sub-ambient operating conditions, or specially designed devices. Laser beam components and high energy optical modules are such examples.

Figure 3 compares a regular heat sink and heat sink with a TEC module. For the sake of simplicity, all the interfacial and contact resistances are ignored.

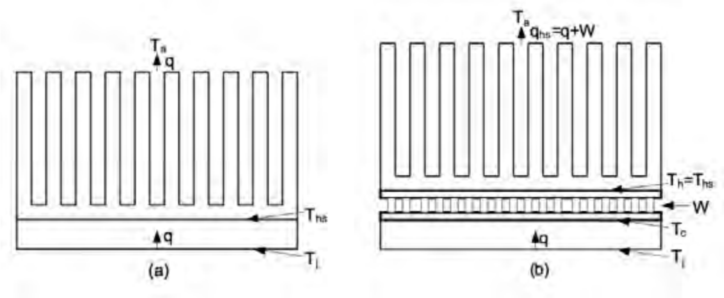

Figure 3. Schematic of (a) a Regular Heat Sink; (b) a Heat Sink with a TEC.

For Figure 3(a), the device's junction temperature can be predicted simply as,

$$T_j = T_a + (R_{jc} + R_{hs})q \qquad (1)$$

Where $\boldsymbol{R_{jc}}$ is the device thermal resistance from junction to case, and $\boldsymbol{R_{hs}}$ is the thermal resistance of the heat sink from base to ambient. For the heat sink with a TEC, the junction temperature of the device is

$$T_j = T_c + R_{jc}q \qquad (2)$$

Where $\boldsymbol{T_c}$ is the TEC cold side temperature.

The heat sink temperature is,

$$T_{hs} = T_h = T_a + R_{hs}(q + W) \qquad (3)$$

And $\boldsymbol{T_h}$ is the TEC hot side temperature.

The COP (coefficient of performance) of the TEC for cooling is defined as,

$$COP = \frac{q}{W} \qquad (4)$$

Where $\boldsymbol{q}$ is the heat removed from the cold side by the TEC and $\boldsymbol{W}$ is the electric energy consumed by the TEC.

Equation 3 can be written as,

$$T_h = T_a + R_{hs}(1 + \frac{1}{COP})q \qquad (5)$$

Let

$$\Delta T_{TEC} = T_h - T_c \qquad (6)$$

The junction temperature of device becomes

$$T_j = T_a + R_{hs}(1 + \frac{1}{COP})q - \Delta T_{TEC} + R_{jc}q \qquad (7)$$

It can be written as

$$T_j = T_a + (R_{hs} + R_{jc})q - \Delta T_{TEC} + \frac{R_{hs}}{COP}q \qquad (8)$$

Compared to the heat sink without the TEC, the junction temperature difference between them is

$$-\Delta T_{TEC} + \frac{R_{hs}}{COP}q\,.$$

Two TECs, the RC12-8 and XKLT2418 from Marlow Industries, are used in the calculation to evaluate the TEC cooling method. A Marlow TEC is shown in Figure 4. The specifications of the two TECs are shown in Table 1.

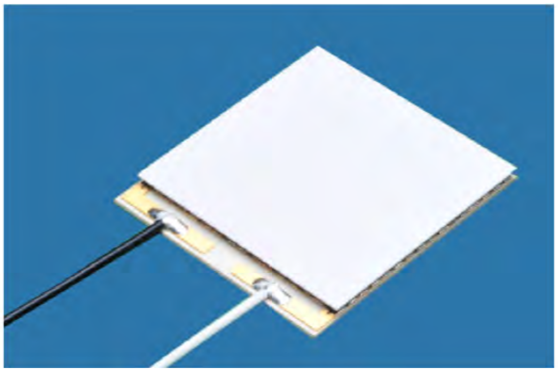

Figure 4. A TEC from Marlow Industries [3].

	RC12-8 40mm x 40mm x 3.6mm		XLT2418 40mm x 40mm x 2.3mm	
Hot Side Temperature (°C)	27	50	27	50
ΔT_{max} (°C)	66	74	56.5	64.0
q_{max} (watts)	71	78	127	141
I_{max} (amps)	7.4	7.4	13.9	13.8
V_{max} (vdc)	14.7	16.4	14.1	15.7

Table 1. TEC Specifications [3].

For the electronic device, assume the junction-to-case thermal resistance is 0.2 ℃/W. The thermal resistance of the heat sink is 0.2 ℃/W and the ambient temperature is 25 ℃. When the heat flux generated by device is 20W, the junction temperature for device without the TEC will be 33 ℃. For the device with TEC, the heat sink will dissipate both the heat generated by device and the TEC. Figure 5 shows the predicted device junction temperature for the heat sink with the TEC at different operating conditions. By using a TEC, the device junction temperature is less than the 33 ℃. It can also be cooled to below the ambient temperature if it is needed. The value of ΔT_{TEC} is directly proportional to the voltage applied on the TEC. The larger the ΔT_{TEC} , the bigger the voltage and energy consumed by the TEC.

Figure 6 shows the calculated COP for the TEC. Clearly the COP drops fast with the increase of ΔT_{TEC} . Figure 7 shows the total heat dissipated by the heat sink. As the device junction temperature becomes low, more heat is dissipated by the heat sink including the heat generated by the TEC. At a certain temperature, the heat created by the TEC will surpass the heat created by the device itself. Because the RC-128 is designed for low power applications and the XLT2418 is specially designed for high power applications, the RC-128 typically has better performance than the XLT2418 when the heat removed from device is fixed at 20W.

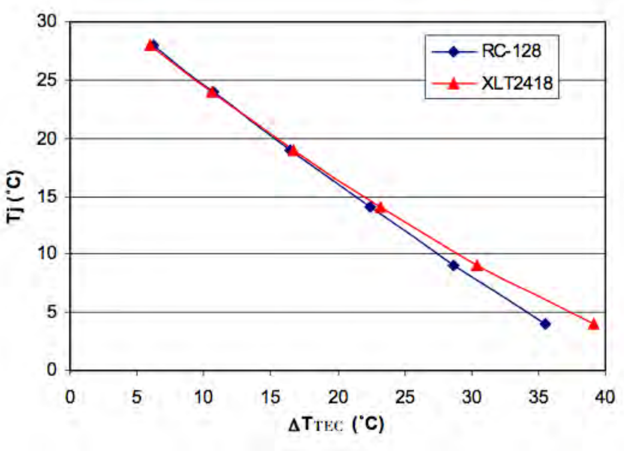

Figure 5.

T_j vs. ΔT_{TEC} ($R_{jc} = 0.2^{\circ}C/W$, $R_{hs} = 0.2^{\circ}C/W$, $q = 20W$).

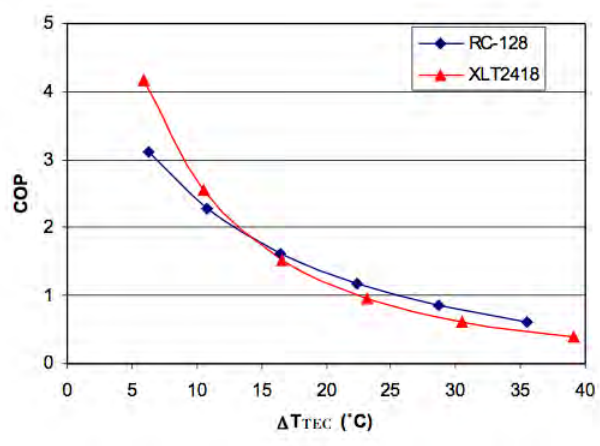

Figure 6.

COP vs. ΔT_{TEC} ($R_{jc} = 0.2^{\circ}C/W$, $R_{hs} = 0.2^{\circ}C/W$, $q = 20W$).

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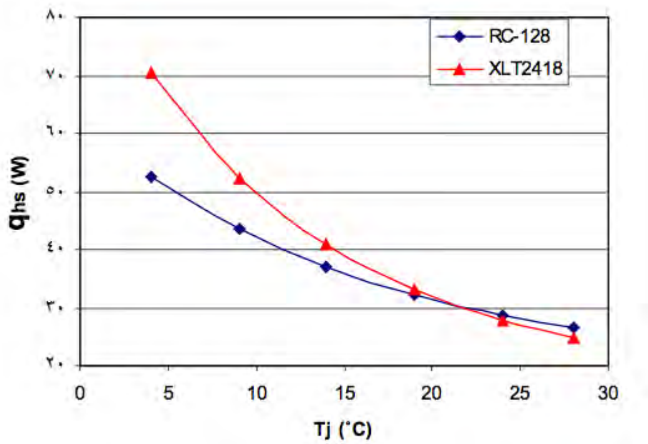

Figure 7.

q_{hs} vs. ΔT_{TEC} ($R_{jc} = 0.2^{\circ}C/W$, $R_{hs} = 0.2^{\circ}C/W$, $q = 20W$).

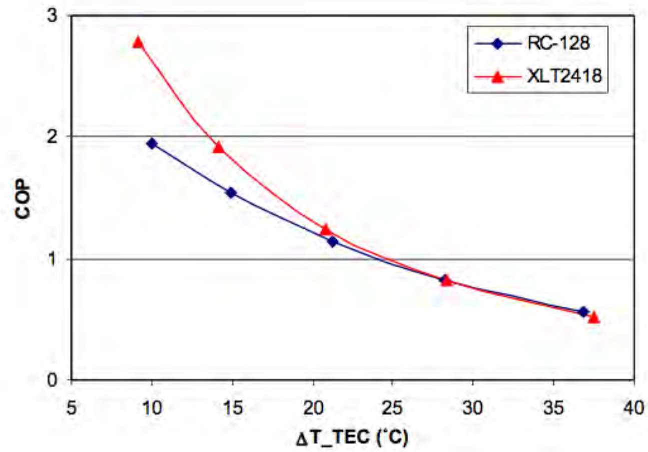

Figure 9.

COP vs. ΔT_{TEC} ($R_{jc} = 0.2^{\circ}C/W$, $R_{hs} = 0.2^{\circ}C/W$, $q = 30W$).

When the heat flux generated by the device is 30W, the device junction temperature for the heat sink without a TEC will be 37℃. Figure 8 shows the predicted device junction temperature for a heat sink with TEC at different operating conditions. With an increase of device heat flux, the TEC is less effective. The XLT2418 shows better performance than the RC-128 because it is designed for higher heat flux applications.

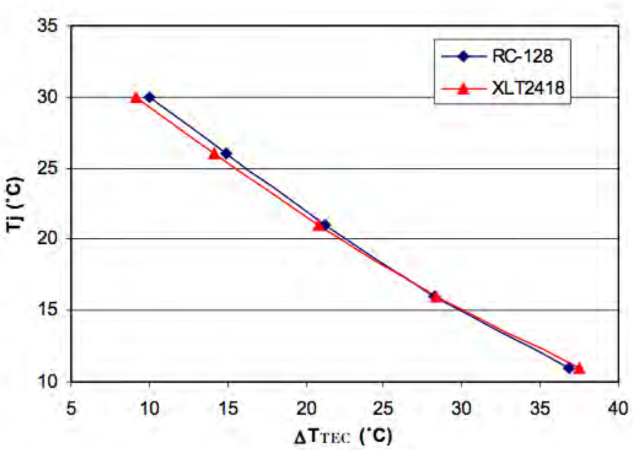

Figure 8.

T_j vs. ΔT_{TEC} ($R_{jc} = 0.2^{\circ}C/W$, $R_{hs} = 0.2^{\circ}C/W$, $q = 30W$).

Figure 9 shows the calculated COP for a TEC at 30W. When compared with the COP of a 20W case at the same junction temperature, the COP at 30W is much lower. That indicates that the TEC is less effective at higher heat flux.

From the above calculations, it is obvious that a TEC's COP decreases with an increase of heat flux and $\Delta \boldsymbol{T}_{TEC}$. TECs have limited heat transfer ability at certain $\Delta \boldsymbol{T}_{TEC}$ and their cooling performance worsens as heat flux approaches that limit. If the COP is too low, more waste heat will be generated by the TEC, which will put a heavy burden on the heat sink and increase its temperature. Increasing the heat sink temperature will degrade the TEC's performance even more.

The device junction temperature $\boldsymbol{T}_j$ is also affected by a heat sink's thermal resistance, as demonstrated in Equation 8. This is because the heat generated by a TEC must be dissipated to ambient through the heat sink.

In cooling applications where TECs are used, it is important to comply with the following design rules:

1. Use a TEC at the operation point where the heat flux is much less than its maximum heat flux.

2. Optimize the design to decrease $\Delta \boldsymbol{T}_{TEC}$ to allow better COP.

3. Use a high performance heat sink.

4. Use active temperature control, which will reduce the temperature swing.The cooling system will also last longer and save more energy in a long run.

The electric and thermal performance of current TECs is still low compared with other refrigeration methods. Researchers in physics and material science are actively looking for new materials and packaging methods to improve TECs' efficiency. With advances in technology, TECs will find more applications in electronic cooling in the future.

References:

1. http://www.melcor.com/tec_intro.html
2. http://www.coolermaster-usa.com/
3. http://www.marlow.com/