MECHANICAL INVESTIGATION OF THERMOELECTRIC COOLING

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Contents

Introduction

Thermoelectric coolers absorb heat on one side from a device to be cooled and dissipate heat to the other side by utilizing electricity through the Peltier effect.[1] Thermoelectric Generators work on the Seebeck effect. The Seebeck effect was discovered by Thomas Seebeck in 1821 when he discovered that when 2 dissimilar metal wires are joined at two ends, and the two junctions are kept at different temperatures, a voltage is developed.[2] Therefore, Thermoelectric devices can be divided in 2 categories which are Thermoelectric coolers(TEC) and Thermoelectric generators(TEG). Thermoelectric coolers find their application in areas where high reliability, noiseless operation, simplicity, compactness and light weight is required.[1] . TEC can generate both cold and heat. Thus, it can stabilize a thermal load temperature in a short time. [8]

In the case of electronics today, the need for the dissipation of heat through cooling is essential for performance, reliability and lifespan of the electronic device. To achieve heat dissipation, either active or passive cooling can be employed. Active cooling is the type of cooling which involves the use of energy for cooling. Passive cooling, on the other hand, is a type of cooling where heat dissipation is caused naturally, without the use of energy, such as free convection in heat sinks.

In electronic devices, maintaining a defined temperature is a problem if passive cooling techniques are employed. Therefore, to maintain a defined temperature, a technique is required to be employed. Thermoelectric coolers can maintain the temperature of electronics components at a defined value.[4]

This report aims at investigating Thermoelectric cooling for cooling application in electronics. The device to be cooled is a Sensor PCB and the heat required to be dissipated is 1W. The temperature of the device to be maintained is 60^{o}C or 333.15K.

1. Review of TEC Technology

1.1 Definition of TEC

TEC stands for Thermoelectric Cooler. Thermoelectric cooling is the process of conversion of electrical energy into heat or as we say, thermal energy. The devices which work on this phenomenon are known to utilize the Peltier effect for the conversion of energy.

When electricity is supplied to a device working on the Peltier effect, it will generate a temperature gradient which can be observed on the two-sides of the said device. Hence, on one side of the device, there is lack of heat which is said to be the cold side and on the other side of the device, there is presence of a higher temperature relative to the cold side. Also, it can be inferred from the above statement that upon the application of a DC current flow to a Peltier device, there is transfer of heat from one side to the other which results in a temperature gradient. A single stage Thermoelectric Cooler can achieve a temperature differential of up to 70ºC/70K. [10]

Thermoelectric Cooling finds its application in the cooling of devices/components/equipment, where high reliability, low weight, small size, safety for hazardous electrical environments and accurate temperature control is required. Also, the life of TEC devices is high compared to the other types of cooling systems such as Vapor Compression.

1.1.1 Seebeck effect:

When a temperature gradient is applied to two opposite sides of a semi-conductor, an electric potential (Voltage) is produced at two ends.[2]

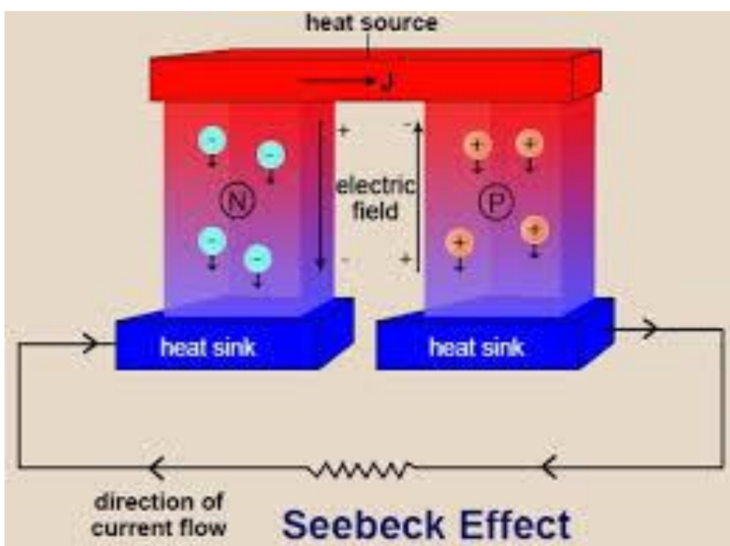


Fig.(1.1) Illustration of the Seebeck effect

1.1.2 Peltier effect: If a voltage is applied to two ends of semi-conductors, there will be a temperature gradient resultant of heat transfer between two sides of the semi-conductor.

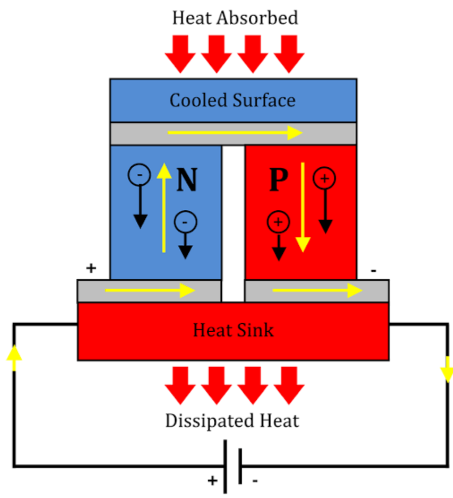


Fig.(1.2) Illustration of the Peltier effect

1.1.3 Thomson effect: Heat is released or absorbed when a current is passed through a TE element with temperature gradient.

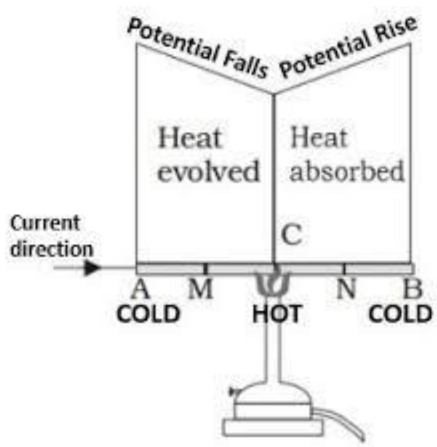


Fig.(1.3) Illustration of the Thomson effect

1.1.4 Joule heating: The resistance to the flow of electric current produces heat which is known as Joule heating.

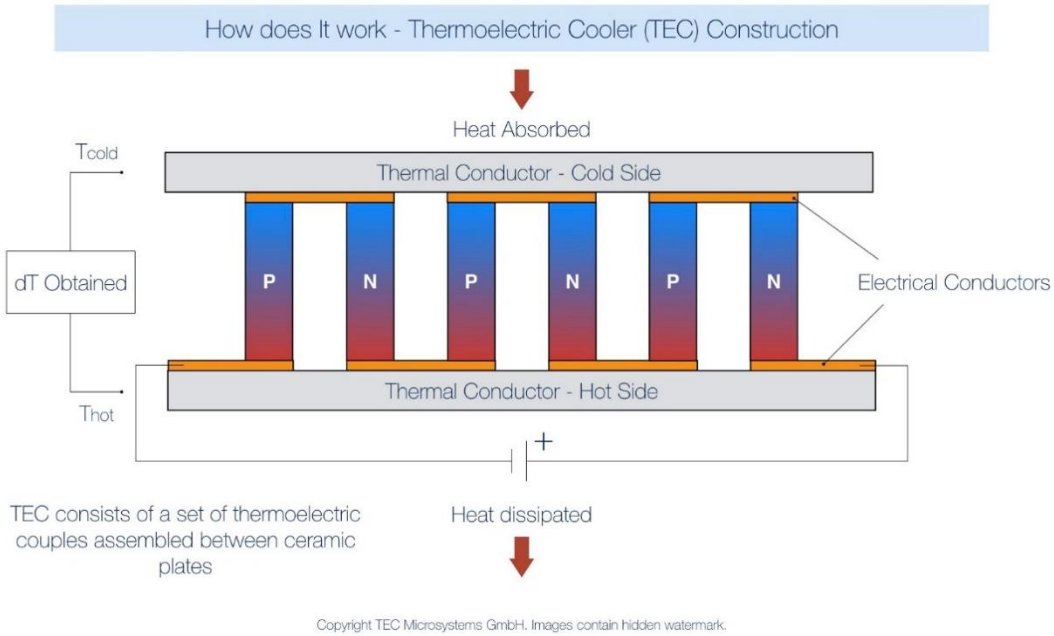


Fig. 1.4: Illustration of Thermo electric cooling

If an efficient heat sink is provided to the hot side of the TEC, the cold side of the TEC can be maintained at a temperature at which the cold side would enable to act as heat absorbing to a device which is at a relatively higher temperature than the cold side temperature.

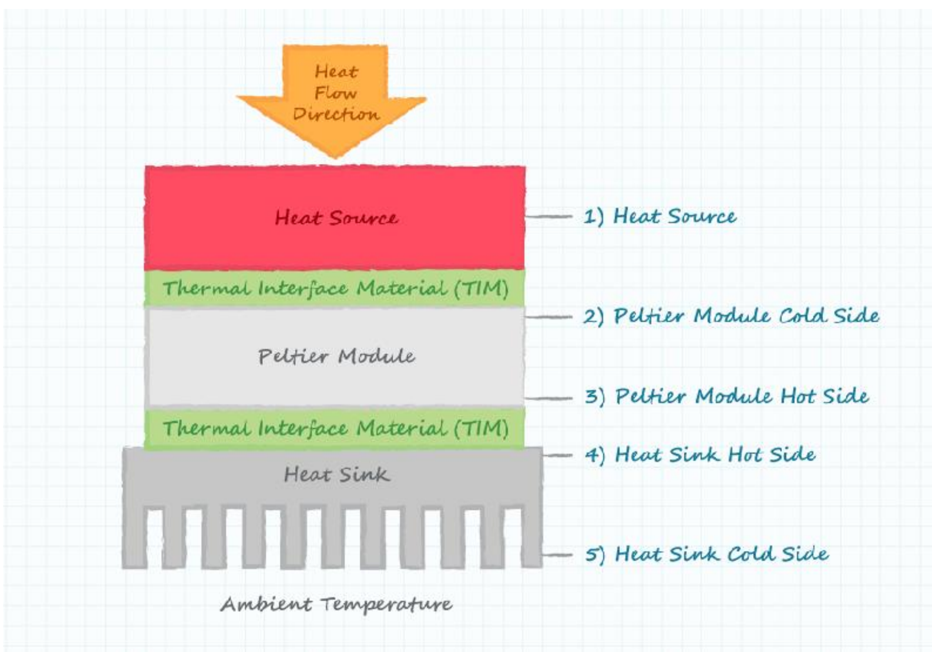


Fig.1.5: Employment of a heat sink to decrease ΔT

1.2 Types of TEC:

1.3 TEC applications:

- Electronic devices: Thermoelectric cooling devices can be employed in electronic devices where they can achieve cooling without the need of relatively bigger moving mechanical parts. The TEC is employed in devices where the temperature needs to be maintained at a certain temperature for efficient operation of the electronic circuitry.

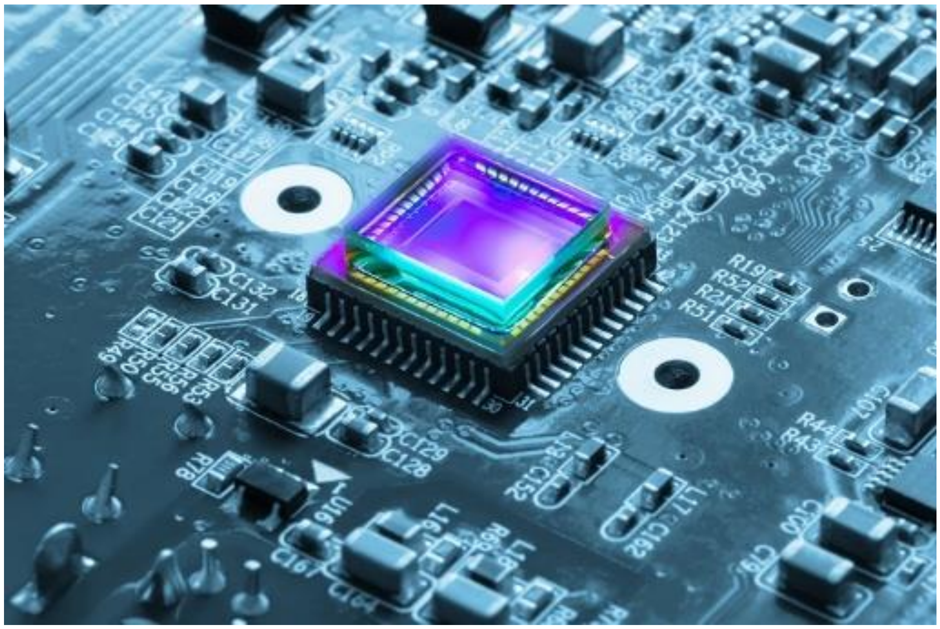


Fig.1.6: TEC can be employed in the cooling of PCBs.

- Refrigerators: Peltier cooling is also employed in refrigerators where cooling in a small space is to be achieved. Imagine a refrigerator as the one shown below which does not have a high heat load compared to the refrigerators employed at home and is portable. A Thermoelectric cooling refrigeration system has the advantage of being light in weight, quiet in operation due to the absence of moving mechanical parts and being reliable. TECs employed in refrigeration systems find their application in the medical field, logistics such as small food containers and compact coolers.

Fig. 1.7: TEC employed in portable coolers.

- Laser equipment: TECs are employed as cooling systems for industrial and medical lasers

1.4 Performance parameters of TECs [1]:

1. The first performance parameter of TEC is the figure of merit, known as the ZT value. The ZT value is a dimensionless parameter, and a function of the Seebeck coefficient, temperature (generally taken as room temperature), electrical resistivity and thermal conductivity. A good thermoelectric material should have a high Seebeck coefficient, high electrical conductivity and low thermal conductivity. The materials with a ZT value above 0.5 could be practically used. **Higher the ZT value, better is the performance of a TEC. [5]**

$$ZT=\frac{\alpha^2}{p_e k}T$$

   where, α, p_e, k and T are the Seebeck coefficient, electrical resistivity, thermal conductivity and temperature respectively.

2. Cooling capacity, Q_c is the second performance parameter of the TEC. [6]

$$Q_c = 2N(\alpha I T_c - \frac{1}{2} I^2 \frac{\rho}{G} - kG\Delta T) \tag{1}$$

N = Number of thermocouples in the Peltier module,
I = Current supplied in Amperes,
T_c = Cold side temperature of the Peltier module,
ρ = specific resistance
G= Geometry factor, ratio of area to length of the thermoelement.
k = coefficient of thermal conductivity
The cooling capacity is the capacity of heat that can be absorbed by the TEC module, at a given operating current, voltage, hot side and cold side temperatures.

3. The third performance parameter of the TEC module is the COP. COP is the co-efficient of performance which relates the Cooling capacity and the Power intake of the TEC module. **A higher COP generally means a power efficient TEC module.**

$$COP=\frac{Q_C}{P}$$

where, Q_c is the cooling capacity of the TEC module and P is the power provided to the TEC module.

1.5 Technical challenges and limitations:

- The efficiency of Thermo Electric Coolers is limited to 10-15%. The reason for this low value of efficiency is that if more heat is moved, more current is required to move the heat. Therefore, the phenomenon of Joule heating occurs, which is directly proportional to the square of the current being provided. This creates the waste heat generated on its own, which requires a larger area for heat dissipation.
- The maximum efficiency of TECs is limited from the perspective of the figure of merit which is a function of the Seebeck co-efficient, Electrical conductivity, temperature and thermal conductivity.
- The reason being, the Seebeck coefficient, electrical conductivity and thermal conductivity are inter-related, which means that in the process of increasing one variable, it does affect the other variable negatively effecting in very little or no net increase in the ZT value.
- The figure of merit for materials used in the Peltier modules has been observed to be around 1 for many years. [4]
- The highest ZT value reported in research is 3 at a temperature of 550K. [16]
- The COP is a function of the figure of merit ZT. [4]
- For cooling, there is a compromise between the minimum surface temperature obtained and the efficiency of the TEC since to attain a bigger temperature difference, more power input is drawn which consequently increases the consumption and therefore decreasing the efficiency.

- If natural convection is used at the hot side for heat dissipation, it is suitable for the operating current to be 2 amps or less since a current more than this will cause Joule heating which would need to be assisted by forced convection. [25]
- Thermal insulation is necessary to provide in the case of a Peltier device so as to avoid short circuiting of heat which means the direct transfer of heat from the hot side to the cold side.
- Compared to the conventional cooling technologies employed such as Vapor-compression cooling systems, for a given cooling capacity, the cost of Thermoelectric cooling is higher than that of the conventional cooling systems.

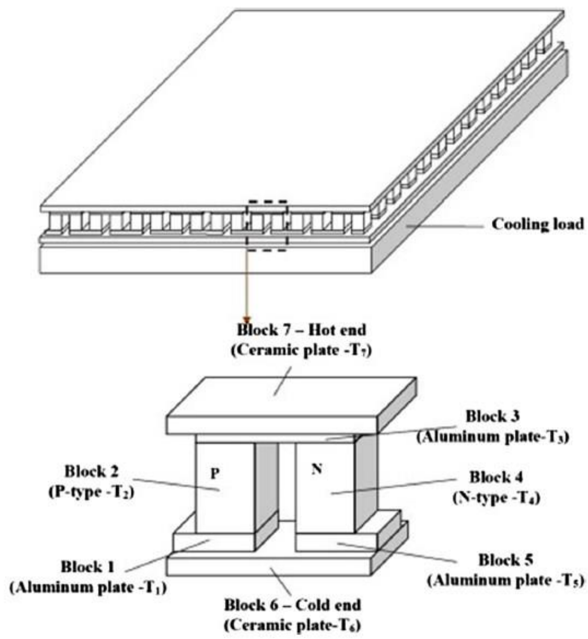


Fig.(1.8): Physical model of a TEC [1]

Design Margin:

- Choosing the Peltier element having greater heat pump capacity than required. ($Q_{max}>Q_c$)
- Operating current should be well below I_{max} of the Peltier element in use. ($I_{max}>I_{op}$)
- Either increase the size of the heat sink or add fan to keep the hot side temperature of the Peltier device as low as possible so that dT (T_{hot}-T_{cold}) is favorable for high COPs or else the Peltier element will end up drawing more current which is undesirable.

1.6 Mathematical models:

1.6.1 Standard simplified model:

- Derived based on the global balance of thermoelectric effects and heat transfer.
- The Thomson value in this equation is zero since the Seebeck coefficient is constant.
- The accuracy of the value obtained after solving this equation is less accurate compared to the improved simplified TE model where the Thomson effect is not zero and is practical to be considered.
- The distribution of the Joule effect is assumed to be symmetrical.
- The electrical conductivity, thermal conductivity, Seebeck co-efficient are taken as constant and the temperature is assumed to be the average value of the hot side and the cold side temperature.[12]
- Reliable in steady state where the effect of Joule heating is not a main factor to be considered. [3]

$$Q_c = \alpha I T_c - \frac{1}{2} I^2 R - k\Delta T \tag{2}$$

Where, Q_c= Cooling capacity,
α = Seebeck coefficient,
T_c= Cold side temperature,
I = Current
R=electrical resistance,
K=thermal conductance,
ΔT= temperature difference between hot and cold sides

1.6.2 Improved standard simplified model:

- The Thomson effect is considered in this mathematical model.
- The uniform distribution of the Thomson effect is ensured on the two sides of the semiconductor device. [14]
- The Seebeck coefficient being not a constant value, it has two different values at the cold and hot sides of the semiconductor device.
- Still an approximated mathematical model, where the Seebeck co-efficient are assumed to be a single value when the dT is low.
- More accurate than the standard simplified model due to consideration of the Thomson effect.
- The Thomson effect tends to counter the Joule heating. [3]
- It is advantageous in the cooling mode, not in the heating mode. [3]

$$Q_c = \alpha I T_c - k\Delta T + \frac{1}{2} I^2 R + \frac{1}{2} \tau I \Delta T \tag{3}$$

Where, Q_c= Cooling capacity,

α = Seebeck coefficient,

T_c= Cold side temperature,

I = Current

R=electrical resistance,

K=thermal conductance,

τ= Thomson coefficient

ΔT= temperature difference between hot and cold sides

1.6.3 Complex TE models:

- Local energy balance equations utilized in this kind of mathematical model.
- All Thermoelectric effects are generated due to the bond between heat and charge transport.
- These transports are quantified on the entropy, energy and mass equations.[13]
- Heat and current flow is parallel to each other.[17]
- Results demonstrate an increase in cooling power and efficiency due to the Thomson effect.
- The transportation of energy in the Thermoelectric leg is described as:

$$Q(x) = \alpha I T(x) - \frac{\rho \lambda I}{\tau} + \frac{\left(-Q_f + \frac{\rho \lambda I}{\tau}\right) * \frac{Q_T}{Q_F}}{\left(\exp\left(\frac{Q_T}{Q_F}\left(1 - \frac{x}{L}\right)\right) - \exp\left(\frac{Q_T x}{Q_F L}\right)\right)} * \frac{1}{T(x)} \tag{4}$$

Where, x denotes the position on the leg of the thermoelement,

Q_F denotes the Fourier heat,

Q_T denotes the Thomson heat,

1.6.4 Analytical model

- The assumption in this model is that the leg section and the TE coefficients are constant along the length of the TE leg in the steady state condition.[13]
- The Thomson effect is included in this model.
- For the cooling capacity,

$$Q(x) = \alpha I T(x) - \frac{kI}{\tau\sigma} + \frac{\left(-Q_f + \frac{kI}{\tau\sigma}\right) * \frac{Q_T}{Q_F}}{\left(\exp\left(\frac{Q_T}{Q_F}\left(1 - \frac{x}{L}\right)\right) - \exp\left(\frac{Q_T x}{Q_F L}\right)\right)} \tag{5}$$

Where, x denotes the position on the leg of the thermoelement,

Q_F denotes the Fourier heat,

Q_T denotes the Thomson heat,

L denotes the length of the thermoelement

τ denotes the Thomson coefficient.

2 Design Parameters

2.1 Typical requirement set:

- For this project, it is assumed that the heat to be dissipated by the PCB would be 1W.
- Therefore, on the basis of this assumption, an approximation is made which includes the necessary requirements of the cooling system for an efficient heat dissipation process.
- The cooling capacity is taken as 1W. Therefore, the selection of a Peltier device should be made where the Q_{max} value of the device should be more than the cooling capacity required.
  For the cooling capacity of 1W, a dT value is assumed for the calculation of Q_{max}.
- For the assumed value of dT, which is the difference in temperature at the cold and hot sides of a TEC, the temperature at the cold end is assumed and desired to be 60 degrees Celsius. Hence, $T_c = 60^oC$ or 333.15 K
- A further assumption is made on the basis considering the COP of a Peltier module. Since the input power to the Peltier module is limited, it is desirable to have dT as low as possible so that the COP is not low which facilitates for less power consumption and since the temperature difference is not high, it enables to choose a heat sink having an area the same as the Peltier module surface area.
- Therefore, a dT value of 20 Kelvin is assumed which would be a starting assumption for further calculations and experimentation. Hence, $T_h = 80^oC$ or 353.15K
- Now we can calculate the value of Q_{max} based on this assumption.
- The formula to calculate the value of Q_{max} is: $Qmax = \frac{Q_c}{1-\frac{dT_r}{dT_m}}$, where, Q_c= Cooling capacity, dT_r=required temperature difference and dT_m=maximum temperature difference.[7]
- Based on the values assumed above, the calculated required Q_{max} is: 1.16W.
- It is not the case the Q_{max} is the optimal value of the cooling requirement. It is viewed as the minimum value to meet the application requirement. The optimal value of Q_{max} may have a value which would be 4 to 10 times the value of the required Q_{max}.[7]
- The table below provides an overview for the assumed optimal values of Q_{max}.

Sr.no	TEC Description	Q_{max} (Watts)	I_{max} (Amps)	U_{max} (Volts)	dT_{max} (K)	Length (mm)	Width (mm)	Thickness (mm)
1	TB-31-1.0-2.5 (Kryotherm)	4.5	1.9	3.9	70	14.8	14.8	4.8
2	TB-31-1.0-2.0	5.6	2.3	3.9	70	14.8	14.8	4.3
3	TB-31-1.0-1.5	7.3	3.1	3.8	69	14.8	14.8	3.8
4	CP50141 (T_h=27°C)Digikey	5.5	5	2.1	68	15	15	4.05
5	CP10-35-05 (Laird) T_h=50°C	9.2	3.9	4.0	75	12.3	12.3	3.2
6	CP10-31-08 (Laird) T_h=50°C	5.8	2.5	4.0	75	12.3	12.3	4.0
7	CP08-31-06 (Laird) T_h=50°C	4.9	2.1	4.0	75	24.6	24.6	3.4
8	OT24,31,F1,1010 (Laird) T_h=50°C	5.8	2.5	4.0	73	10	10	2.6
9	HOT12-65-F2A-1312 (Laird) T_h=50°C	5.9	1.2	8.4	77	13.16	13.16	3
10	CP081030-M (CUI) T_h=50°C	4.2	0.8	8.8	75	10	10	3
11	CP30138	7.2	3	3.8	72	15	15	3.8
12	CP50141	6.1	5	2.1	75	15	15	4

Table(2.1): Thermo-electric cooler Qmax and Optimal Qmax estimation.

2.2 Operating conditions:

- The most commonly recommended input current for a TEC is 60% to 80% of the Imax for that TEC. Input current of greater than 80% of Imax usually results in minimal increases in both heat pumping and Delta T while significantly increasing both power consumption and waste heat generated. Input current of lower than 60% (of Imax) is also common to create a more efficient system (input power versus heat pumping created).
- Provision of thermal isolation to the Peltier device to prevent short circuiting b/w both sides of the device. (basically the transfer of heat from the hot side to the cold side)

2.3 Design Process

The steps described is the procedure in the design process for a Thermoelectric Cooler setup.[9]

1. Estimate the heat load
2. Define the working temperature range
3. Choose a TEC satisfying the requirements
4. Choose a TEC controller for the same (Optional)
5. Choose the object temperature sensor and the optional sink sensor (for the TEC controller)
6. Choose a heat sink for the Peltier element.
7. Choose a fan to provide circulation of air over the heat sink.
8. Choose a power supply for TEC controller. (Mandatory if controller is to be employed)
9. Testing and improvements.

3 Determination of TEC(s) for the requirement.

- For the given requirement of the transfer of heat of 1W, a number of TECs were reviewed for their performance.
- Some of the manufacturer's data sheets had a limitation in the working temperatures of the TECs which was below the stated hot side temperature of 80ºC.
- Datasheets from Laird provided ample knowledge regarding the operating conditions and the change in values given the operation parameters.
- Referring to these datasheets, the thermo-electrical parameters of the modules were calculated
- Given below is the mathematical model for the TEC which is found in literature (insert references) and the set of equations required to calculate the thermoelectric parameters of the Peltier module.

$$Q_c = 2N(\alpha I T_c - \frac{1}{2} I^2 \frac{\rho}{G} - kG\Delta T) \qquad (1)$$

Where,
N = Number of thermocouples in the Peltier module,
I = Current supplied in Amperes,
T_c = Cold side temperature of the Peltier module,
ρ = specific resistance
G= Geometry factor, ratio of area to length of the thermoelement.
k = coefficient of thermal conductivity

- The regular set of data in the datasheet of TEGs (for example, Hi-Z technology)4 includes the thermal conditions for which the parameters are specified: the temperature of the "hot" side Th, the temperature of the "cold" side Tc, power at the matched load Wm (load is matched to internal resistance), load voltage at the matched load Vm, and maximum efficiency η opt. Some manufacturers give η m—efficiency for the matched load. [11]
- Using the data given in datasheets, one can calculate the parameters.
- Thermo-physical properties: <u>Thermo-physical properties</u> of a Thermoelectric device concern the temperature dependent physical properties of a module such as the <u>Seebeck coefficient, Resistivity, Thermal conductance, thermal resistance</u>.
- Thermo-electric properties: The <u>thermo-electric properties</u> of a Thermoelectric module concern the temperature dependent electrical properties of the module such as the <u>maximum operation voltage</u>(V_{max}), the <u>maximum operating current</u>(I_{max}), the <u>maximum temperature difference</u>(dT_{max}), <u>the maximum cooling capacity</u>(Q_{max}).

The calculation of the Z value (figure of merit) is as follows:

The parameters obtained in this calculation are dependent on the specified hot side temperature of the module. These parameters are subject to variation since for every variation in the hot side temperature of the module, the Imax, Vmax, Qmax and DTmax of the module will vary. Hence, these parameters along with N (number of thermocouples) and G (geometry factor) will effect in the calculation of the fundamental thermophysical parameters (Seebeck coefficient, specific resistivity and coefficient of thermal conductivity)

Insert the graph of Qc versus dT, assume a dT of 20 degrees with T_h = 80 degrees

3.1 Calculation for the figure of merit (ZT) of a TEC.

- Calculate the temperature dependent Seebeck coefficient α_m :

$$\alpha_m = \frac{V_{max}}{T_h} \tag{6}$$

where,
α_m = Seebeck coefficient (V/K)
V_{max} = Maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts
T_h = Hot side temperature specified in the datasheet, Kelvin

- Calculate electrical resistance R_o

$$R_o = \frac{V_{max}^2}{2Q_{max}} \tag{7}$$

Where,
R_o = electrical resistivity, Ohms (Ω)
V_{max} = Maximum Voltage the TEC can withstand specified in the datasheet, Volts
Q_{max} = Maximum cooling capacity of the TEC at 0 temperature difference.

- Calculate the ratio of thermal to electrical resistance for dT_{max}

$$\frac{R_q}{R_0} = \frac{2\, dT_{max}}{V_{max}^2 (1 - dT_{max} \,/\, T_h)^2} \tag{8}$$

Where,
V_{max} = Maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts
dT_{max} = Maximum temperature difference specified in the datasheet
T_h = Hot side temperature of the Peltier module

- Calculate the thermal resistance R_q (°K/W)

$$R_q = R_0 * \frac{R_q}{R_0} \tag{9}$$

- Calculate the quality factor Z

$$Z = \frac{R_q}{R_0} \alpha_m^2 \tag{10}$$

Where,
Z = Quality factor, (/°K)
α_m = Seebeck coefficient (V/K)

- Furthermore, to calculate the ZT value or the figure of merit, the Quality factor and the average temperature of the hot and cold sides is employed.
where,

$$T = \frac{T_h + T_c}{2} \tag{11}$$

Where T_h and T_c are the hot side and cold side temperatures respectively.

3.2 Fundamental thermo-physical properties calculation.

- Calculate the temperature dependent Seebeck coefficient.

$$\alpha_m = \frac{V_{max}}{T_h} \tag{6}$$

where,
α_m = Seebeck coefficient (V/K)

V_{max} is the maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts

T_h = Hot side temperature specified in the datasheet, Kelvin

- Calculate the parameter ρ_m

$$\rho_m = \frac{(T_h - \Delta T_{max})V_{max}}{T_h * I_{max}} \tag{12}$$

Where,

T_h is the hot side temperature of the TEC,

ΔT_{max} is the maximum temperature difference

V_{max} is the maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts

I_{max} the maximum direct current which will produce the maximum possible DeltaT across the Peltier element.

- Calculate the parameter k_m

$$k_m = \frac{(T_h - \Delta T_{max})V_{max}I_{max}}{2 * T_h * \Delta T_{max}} \tag{13}$$

Where,

T_h is the hot side temperature of the TEC,

ΔT_{max} is the maximum temperature difference

V_{max} is the maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts

I_{max} is the maximum direct current which will produce the maximum possible temperature difference across the Peltier element.

- Now that we have these values, we can calculate the thermo-physical parameters viz. Seebeck coefficient, specific resistivity and coefficient of thermal conductivity.

- To calculate the Seebeck coefficient, N(number of thermocouples) is a factor to be known. N can be found by looking at the description of the part number given by the manufacturer. Different manufacturers have different methods of specifying part numbers therefore, an examination of the part number(add ref1), the datasheet(add ref1), the universal system of specification(add ref) of TECs and assumption based on the literature review(add ref) was done to understand the number of thermocouples in the device.

  Now, Seebeck coefficient is calculated by the given expression.

$$\alpha_m = 2 * \alpha * N \tag{14}$$

Where, N = number of thermocouples in the module.
α = Fundamental Seebeck coefficient.
α_m = Temperature dependent Seebeck coefficient

- To calculate the specific resistivity of the module (ρ), we use the following expression.

$$\rho_m = \frac{2 * \rho * N}{G} \tag{15}$$

Where, ρ is the specific resistivity of the module,
ρ_m is the temperature dependent specific resisitivity,
N is the number of thermocouples,
G is the factor of geometry

- To calculate the thermal conductivity of the module,

$$k_m = 2 * N * k * G \tag{16}$$

Where, k is the thermal conductivity of the module,

k_m is the thermal conductivity calculated dependent on hot side temperature and the temperature difference,

N is the number of thermocouples in the module,

G is the factor of geometry.

Using these equations, one can determine the thermo-physical parameters of the TEC which is needed in addition with operating current and cold side temperature to calculate the Cooling capacity of the module.

The expression to calculate the cooling capacity as seen in Eqn 1 is:

$$Q_c = 2N(\alpha I T_c - \frac{1}{2} I^2 \frac{\rho}{G} - kG\Delta T)$$

3.3 Thermo-electric parameters.

It is also possible to calculate the thermo-electric parameters such as V_{max}, I_{max}, ΔT_{max}(same as dT_{max}) and Q_{max} for a defined hot side temperature.
These parameters are specified in the datasheets but they are specified for pre-defined hot side temperature(s) by the manufacturer.
Hence, for a varying hot side temperature, the equations and the procedure shown below can be followed.

These parameters can be calculated using eqns (14), (15), (16) and are shown below.

- Calculate V_{max}
  It is possible to calculate the maximum voltage for a given operating temperature using eqn(1.2) and eqn(1.10)

$$\alpha_m = \frac{V_{max}}{T_h} \tag{6}$$

$$\alpha_m = 2 * \alpha * N \tag{14}$$

Substituting eq(10) in eq(2), we get,

$$2 * \alpha * N \quad = \frac{V_{max}}{T_h} \tag{17}$$

$$V_{max} = 2 * T_h * \alpha * N \tag{18}$$

- Calculate I_{max} and ΔT_{max}

  To calculate I_{max} and ΔT_{max}, we utilize eq(12) to get an expression for I_{max} and then we substitute the expression for I_{max} in eq(15) to obtain the value of ΔT_{max}

  Once we have obtained a value for ΔT_{max} after solving the equation, we can obtain the value of I_{max} by utilizing the value of ΔT_{max} in the expression for I_{max}

  Shown below are the equations and procedure to obtain the values for I_{max} and ΔT_{max}

$$\rho_m = \frac{2 * \rho * N}{G} \tag{15}$$

$$\rho_m = \frac{(T_h - \Delta T_{max})V_{max}}{T_h * I_{max}} \tag{12}$$

Substituting the expression of ρ_m in eq(15) to eq(12), we get,

$$\frac{2 * \rho * N}{G} = \frac{(T_h - \Delta T_{max})V_{max}}{T_h * I_{max}} \tag{19}$$

$$I_{max} = \frac{(T_h - \Delta T_{max})V_{max} * G}{2 * T_h * \rho * N} \tag{20}$$

Now, for ΔT_{max}

$$k_m = 2 * N * k * G \tag{16}$$

$$k_m = \frac{(T_h - \Delta T_{max}) V_{max} I_{max}}{2 * T_h * \Delta T_{max}} \tag{13}$$

Substituting the expression of k_m in eq(16) to eq(13), we get,

$$2 * N * k * G = \frac{(T_h - \Delta T_{max}) V_{max} I_{max}}{2 * T_h * \Delta T_{max}} \tag{21}$$

Substituting the expression obtained for I_{max} in the above expression, we get,

$$2 * N * k * G = \frac{(T_h - \Delta T_{max}) V_{max}}{2 * T_h * \Delta T_{max}} * \frac{(T_h - \Delta T_{max}) V_{max} * G}{2 * T_h * \rho * N} \tag{22}$$

Which forms,

$$\frac{8 * N^2 * {T_h}^2 * K * \rho}{{V_{max}}^2} = \frac{(T_h - \Delta T_{max})^2}{\Delta T_{max}} \tag{23}$$

Since all the parameters except ΔT_{max} are already known, the value for ΔT_{max} can be obtained by solving the equation (23) shown above.

Once we have obtained the value of ΔT_{max}, we substitute it in the expression for I_{max}.

Therefore, we can calculate the thermo-electric parameters for a given hot side temperature.

3.4 Calculation for ZT, thermo-physical and thermoelectric parameters of a TEC

This calculation is for Laird ET19,23,F1N,0608,11,W2.25HiTemp Series.

Vmax (Volts)	DTmax (K)	Qc (W)	Qmax (W)	Th (K)	Imax (A)
3.4	87	1	3.5	358.15	1.9

Table(3.1): Thermo-electric parameters of the module for calculation.

- Calculate the temperature dependent Seebeck coefficient α_m :

$$\alpha_m = \frac{V_{max}}{T_h} \tag{6}$$

where,
α_m = Seebeck coefficient (V/K)
V_{max} = Maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts
T_h = Hot side temperature specified in the datasheet, Kelvin

Therefore,

$$\alpha_m = \frac{3.4}{358.15}$$

Which gives a value of 0.0095 V/°K

- Calculate electrical resistance R_o

$$R_o = \frac{V_{max}^2}{2Q_{max}} \tag{7}$$

Where,
R_o = electrical resistivity, Ohms (Ω)
V_{max} = Maximum Voltage the TEC can withstand specified in the datasheet, Volts
Q_{max} = Maximum cooling capacity of TEC.
Therefore,

$$R_o = \frac{3.4^2}{2 * 3.5}$$

Which gives a value of 1.65 Ω

After a check in the datasheet for the resistance value provided by the manufacturer, it is found to be 1.66 Ω.

- Calculate the ratio of thermal to electrical resistance for dT_{max}

$$\frac{R_q}{R_0} = \frac{2\, dT_{max}}{V_{max}^2 (1 - dT_{max} \,/\, T_h)^2} \tag{8}$$

Where,
V_{max} = Maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts
dT_{max} = Maximum temperature difference specified in the datasheet
T_h = Hot side temperature of the Peltier module

Therefore,

$$\frac{R_q}{R_0} = \frac{2 * 87}{3.4^2 (1 - 87 \,/\, 358.15)^2}$$

Which gives a value of <u>26.3 $^oK/V^2$</u>

- Calculate the thermal resistance R_q

$$R_q = R_0 * \frac{R_q}{R_0} \tag{9}$$

After obtaining the value of R_o and R_q/R_o, and utilising in the above equation, we get,

$$R_q = 1.65 * 26.5$$

Which gives a value of R_q to be <u>43.4 $^oK/W$</u>

- Calculate the quality factor Z

$$Z = \frac{R_q}{R_0} \alpha_m^2 \tag{10}$$

Where,
Z = Quality factor, ($/^oK$)
α_m = Temperature dependent Seebeck coefficient (V/K)

Utilising values obtained from above,

$$Z = 26.5 * 0.0095^2$$

Which gives a value of 0.0024 $/^oK$.

- We now calculate the figure of merit (ZT) value which is a product of the quality factor and the average of the temperatures of the hot and cold sides of the module at DTmax.

$$T = \frac{T_h + (T_h - DT_{max})}{2}$$

The value of T obtained is 309.65K

Utilising this value and multiplying with the quality factor as obtained above, we get,

$$ZT = 0.74$$

Note that the ZT value is a function of the hot side temperature. Therefore, it is bound to vary at different operating temperatures.

3.4.1 Fundamental thermo-physical properties of TEC.

- Calculate the temperature dependent Seebeck coefficient from eqn (6)

$$\alpha_m = \frac{V_{max}}{T_h} \tag{6}$$

$$\alpha_m = \frac{3.4}{358.15}$$

where,

$\alpha_m = 0.0095$ V/K°

V_{max} is the maximum voltage the TEC can withstand for the given temperature difference specified in the datasheet, Volts

T_h = Hot side temperature specified in the datasheet, Kelvin

- Calculate the parameter ρ_m from eqn(12)

$$\rho_m = \frac{(T_h - \Delta T_{max})V_{max}}{T_h * I_{max}} \tag{12}$$

$$\rho_m = \frac{(358.15 - 87) * 3.4}{358.15 * 1.9}$$

Which gives us $\rho_m = 1.35\ V/A$

- Calculate the parameter k_m from eqn(13)

$$k_m = \frac{(T_h - \Delta T_{max})V_{max}I_{max}}{2 * T_h * \Delta T_{max}} \tag{13}$$

$$k_m = \frac{(358.15 - 87) * 3.4 * 1.9}{2 * 358.15 * 87}$$

Where, $k_m = 0.028\ W/K$

- Now that we have these values, we can calculate the thermo-physical parameters viz. Seebeck coefficient, specific resistivity and coefficient of thermal conductivity.

- To calculate the Seebeck coefficient, N(number of thermocouples) is a factor to be known. N can be found by looking at the description of the part number given by the manufacturer.

- For the TEC selected for this calculation, Laird ET19,23,F1N,0608, the number of thermocouples are 23.

- The geometry factor for this TEC is calculated by the expression,[23]

$$G = \frac{I_{max}}{50} \tag{24}$$

The I_{max} for this TEC is 1.9A. Therefore, G is calculated to be 0.038

The number of thermocouples and the geometry factor help to describe the size of the device - more thermocouples means more pathways to pump heat. [23]

Now, the fundamental Seebeck coefficient is calculated by eqn(14).

$$\alpha_m = 2 * \alpha * N \tag{14}$$

$$0.0095 = 2 * \alpha * 23$$

Which gives $\alpha = 2.06 * 10^{-4}\ V/K$

- To calculate the specific resistivity of the module (ρ), we use eqn(15).

$$\rho_m = \frac{2 * \rho * N}{G} \tag{15}$$

$$1.35 = \frac{2 * \rho * 23}{0.023}$$

Where, $\rho = 1.1 *\ 10^{-3}$ V/A

- To calculate coefficient of thermal conductance of the module,

$$k_m = 2 * N * k * G \tag{16}$$

$$0.028 = 2 * 23 * k * 0.038$$

Where, $k = 1.6 * 10^{-2}\ W/K$

3.4.2 Calculation of Cooling power (Q_c) of the TEC

Using these equations, one can determine the thermo-physical parameters of the TEC which is needed in addition with operating current and cold side temperature to calculate the Cooling capacity of the module.

The expression to calculate the cooling capacity as seen in Eqn 1 is:

$$Q_c = 2N(\alpha I T_c - \frac{1}{2} I^2 \frac{\rho}{G} - kG\Delta T)$$

The ΔT value we have is 358.15-333.15 (The difference of hot side and cold side temperatures in Kelvin) which is 25K.

The value of T_c is 333.15K. The value for I is 0.62A.

After substituting these values in the expression above, we get,

$$Q_c = 2 * 23(0.0002 * 0.62 * 333.15 - \frac{1}{2} 0.62^2 \frac{0.001}{0.038} - 0.016 * 0.038 * 25)$$

$$Q_c = 0.99W$$

The specifications shown on the manufacturers website show a value of 1.02W for the given input parameters as shown in the figure below.

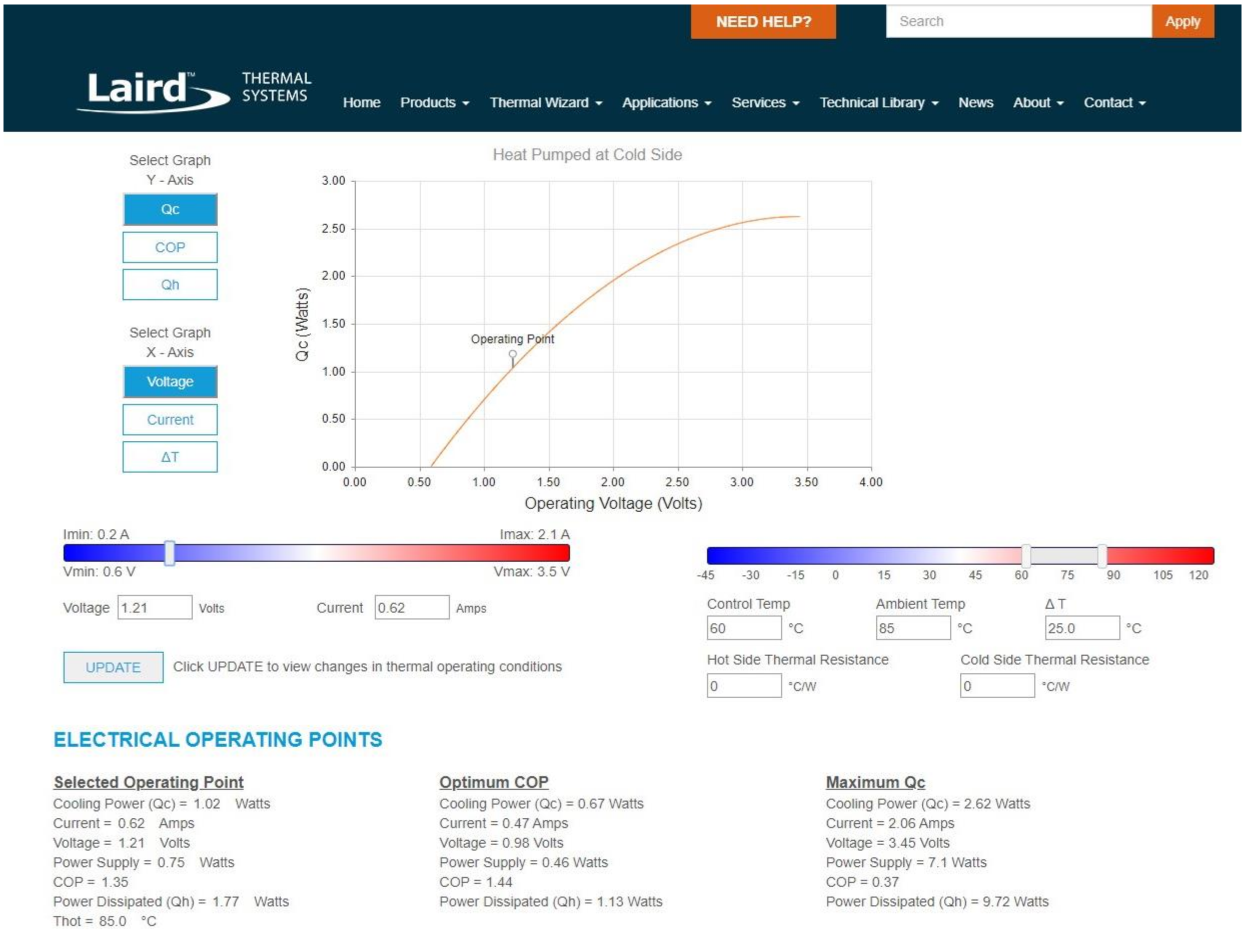


Fig.(3.1) Manufacturer's graph for Laird ET19,23,F1N,0608

3.4.3 Calculation of Thermo-electric parameters

It is also possible to calculate the thermo-electric parameters such as V_{max}, I_{max}, ΔT_{max}(same as dT_{max}) and Q_{max} for a defined hot side temperature.
These parameters are specified in the datasheets but they are specified for pre-defined hot side temperature(s) by the manufacturer.
Hence, for a varying hot side temperature, the equations and the procedure shown below can be followed.

These parameters can be calculated using eqns (18), (23), (20) and are shown below.

For Laird ET19,23,F1N,0608, the parameters obtained in the equations from above are listed in the table(n) below which will be utilised to calculate the thermo-electric parameters for a given hot side temperature.

N (no. of thermocouples)	G(Geometry factor)	α (V/K) Seebeck coefficient	k (W/K) Thermal conductance	$\rho(V/A)$ Resistance of the module	$T_h(K)$ Hot side temperature
23	0.038	$2.06 * 10^{-4}$	$1.6 * 10^{-2}$	$1.1 * 10^{-3}$	358.15

Table(3.2): Thermo-physical properties of the module

- Calculate V_{max}

  We know from eq(20),

$$V_{max} = 2 * T_h * \alpha * N \tag{18}$$

$$V_{max} = 2 * 358.15 * 0.000206 * 23$$

$which\ gives\ us$, $V_{max} = 3.4V$

- Calculate I_{max} and ΔT_{max}

  To calculate I_{max} and ΔT_{max}, we utilize eq(12) to get an expression for I_{max} and then we substitute the expression for I_{max} in eq(15) to obtain the value of ΔT_{max}

  Once we have obtained a value for ΔT_{max} after solving the equation, we can obtain the value of I_{max} by utilizing the value of ΔT_{max} in the expression for I_{max}

  Now, for ΔT_{max}

$$\frac{8 * N^2 * {T_h}^2 * K * \rho}{{V_{max}}^2} = \frac{(T_h - \Delta T_{max})^2}{\Delta T_{max}} \tag{23}$$

Substituting the value obtained for V_{max} and the values from table(n), we get,

$$\frac{8 * 23^2 * 358.15^2 * 0.016 * 0.0011}{3.4^2} = \frac{(358.15 - \Delta T_{max})^2}{\Delta T_{max}}$$

$Solving\ this\ equation\ gives,$ $\Delta T_{max} = 87K$

Once we have obtained the value of ΔT_{max}, we substitute it in the expression for I_{max}.

$$I_{max} = \frac{(T_h - \Delta T_{max})V_{max} * G}{2 * T_h * \rho * N} \tag{20}$$

$$I_{max} = \frac{(358.15 - 87) * 3.4 * 0.038}{2 * 358.15 * 0.0011 * 23}$$

Solving this equation gives, $I_{max} = 1.9A$

Therefore, we can calculate the thermo-electric parameters for a given hot side temperature.

Laird

HiTemp ET Series ET19,23,F1N,0608,11-W2.25

Thermoelectric Modules

The HiTemp ET Series of Thermoelectric Modules (TEMs) are designed to operate in high temperature environments.

This product line is available in multiple configurations and is ideal for applications that operate in temperatures above 80°C. Assembled with Bismuth Telluride semiconductor material, thermally conductive Aluminum Oxide ceramics and high temp solder construction, the ET Series is designed for higher current and larger heat-pumping applications.

FEATURES

- High-temperature operation
- Reliable solid state
- No sound or vibration
- Environmentally-friendly
- RoHS-compliant

APPLICATIONS

- Automotive cooling
- Telecom cooling
- Outdoor environments
- Medical heating/cooling

TECHNICAL SPECIFICATIONS		
Hot Side Temperature (°C)	85	110
Qmax (W)	3.5	3.6
Delta Tmax (°C)	87	94
Imax (Amps)	1.9	1.9
Vmax (Volts)	3.4	3.6
Module Resistance (Ohms)	1.66	3.25

Fig(3.2): Manufacturer's datasheet.

Comments: Using the equations as shown above, for a given hot side temperature, the thermoelectric parameters can be calculated.

4. Selection of Thermoelectric Coolers for operation

Vmax (V)	Imax (A)	Qmax (W)	DTmax	Th (K)	Sm(V/K)	Km(W/K)	Rm(Ohms)	Se(V/K)	Ro(Ohms)	Rq/Ro	Rq(K/W)	Z (/K)	ZT	Part numbers (Manufacturers)
2,1	5	6	75	323,15	0,0065	0,054	0,32	0,0065	0,36	57,7	20,9	0,0024	0,70	CP50141 (CUI Devices)
3,8	3,1	7,3	69	300	0,0127	0,066	0,94	0,0127	0,99	16,1	15,9	0,0026	0,69	TB-31-1.0-1.5 (Kryotherm)
3,8	3,6	8,4	69	300	0,0127	0,076	0,81	0,0127	0,86	16,1	13,9	0,0026	0,69	TB-31-1.0-1.3 (Kryotherm)
8,8	0,8	4,2	75	323,15	0,0272	0,036	8,45	0,0272	9,22	3,3	30,3	0,0024	0,70	CP081030-M (CUI Devices)
3,4	1,9	3,5	87	358,15	0,0095	0,028	1,35	0,0095	1,65	26,3	43,4	0,0024	0,74	ET19,23,F1N,0608,11,W2.25 HiTemp series (Laird Tech)
4,56	1,8	4,5	87	358,15	0,0127	0,036	1,92	0,0127	2,31	14,6	33,7	0,0024	0,74	ET1.8-31-F1-0707 (Laird Tech)
5,1	1,9	5,4	87	358,15	0,0142	0,042	2,03	0,0142	2,41	11,7	28,1	0,0024	0,74	ET19,35,F1N,0612,11,W2.25 HiTemp series (Laird Tech)
4	2,1	4,9	75	323,15	0,0124	0,043	1,46	0,0124	1,63	15,9	26,0	0,0024	0,70	CP08-31-06 (CUI Devices)
3,7	2,1	4,5	67	298,15	0,0124	0,045	1,37	0,0124	1,52	16,3	24,8	0,0025	0,66	CP08-31-06 (CUI Devices)
4	3,9	9,2	75	323,15	0,0124	0,080	0,79	0,0124	0,87	15,9	13,8	0,0024	0,70	CP10-31-05 (CUI Devices)
8,4	1,2	5,9	77	323,15	0,0260	0,050	5,33	0,0260	5,98	3,8	22,5	0,0025	0,72	OptoTEC series HOT 12-65-F2A-1312 (Laird Tech)
8,5	1,5	7,4	77	323,15	0,0263	0,063	4,32	0,0263	4,88	3,7	17,9	0,0025	0,72	OptoTEC series OT 15-66-F0-1211 (Laird Tech)
9,7	0,8	4,29	87	358,15	0,0271	0,034	9,18	0,0271	10,97	3,2	35,4	0,0024	0,74	ET08-66-F0-1009 (Laird Tech)
4,56	1,5	3,6	87	358,15	0,0127	0,030	2,30	0,0127	2,89	14,6	42,2	0,0024	0,74	ET15-31-F2A-0909 (Laird Tech)
3,9	2,3	5,6	70	300	0,0130	0,049	1,30	0,0130	1,36	15,7	21,3	0,0026	0,70	TB-31-1.0-2.0 (Kryotherm)
3,9	1,9	4,5	70	300	0,0130	0,041	1,57	0,0130	1,69	15,7	26,5	0,0026	0,70	TB-31-1.0-2.5 (Kryotherm)
15,9	7,6	75	70	300	0,0530	0,662	1,60	0,0530	1,69	0,9	1,6	0,0026	0,70	TB-127-1.4-1.2 (Kryotherm)
4,1	2,5	6	65	323,15	0,0127	0,063	1,31	0,0127	1,40	12,1	17,0	0,0020	0,57	RC3-2.5 (Marlow)
4,9	1,8	5,8	73	323,15	0,0152	0,047	2,11	0,0152	2,07	10,1	21,0	0,0023	0,67	NL1025T (Marlow)
4,4	1,8	5,2	64	300	0,0147	0,049	1,92	0,0147	1,86	10,7	19,9	0,0023	0,62	NL1025T (Marlow)
9.6	1.5	7.6	87	358.15	0.0268	0.063	4.85	0.0268	6.06	3.3	20	0.0024	0.74	ET15-65-F2A-1312 (Laird Tech)
4.7	1.2	3.12	87	358.15	0.0131	0.025	2.97	0.0131	3.54	13.7	48.6	0.0024	0.74	ET12-32-FO-0606 (Laird Tech)
3.5	2.0	3.9	87	358.15	0.0098	0.030	1.32	0.0098	1.57	24.8	38.9	0.0024	0.74	ET20-24-F2A-0709 (Laird Tech)

Table 4.1: The thermoelectric parameters calculated for each of the TECs.

4.1 Explanation of the table

Vmax is the maximum operation voltage of the TEC. The unit is Volts. Imax is the maximum operating current of the TEC. The unit is Amperes(A). Qmax is the maximum cooling capacity at the given maximum supply voltage and current. The unit is Watts(W)

DTmax is the largest temperature difference that can occur in a TEC when Qc is equal to 0. Qc is the cooling capacity of the TEC at a given supply voltage and current. DT is the difference in temperature between the hot and cold sides of the TEC. (DT=Th-Tc)

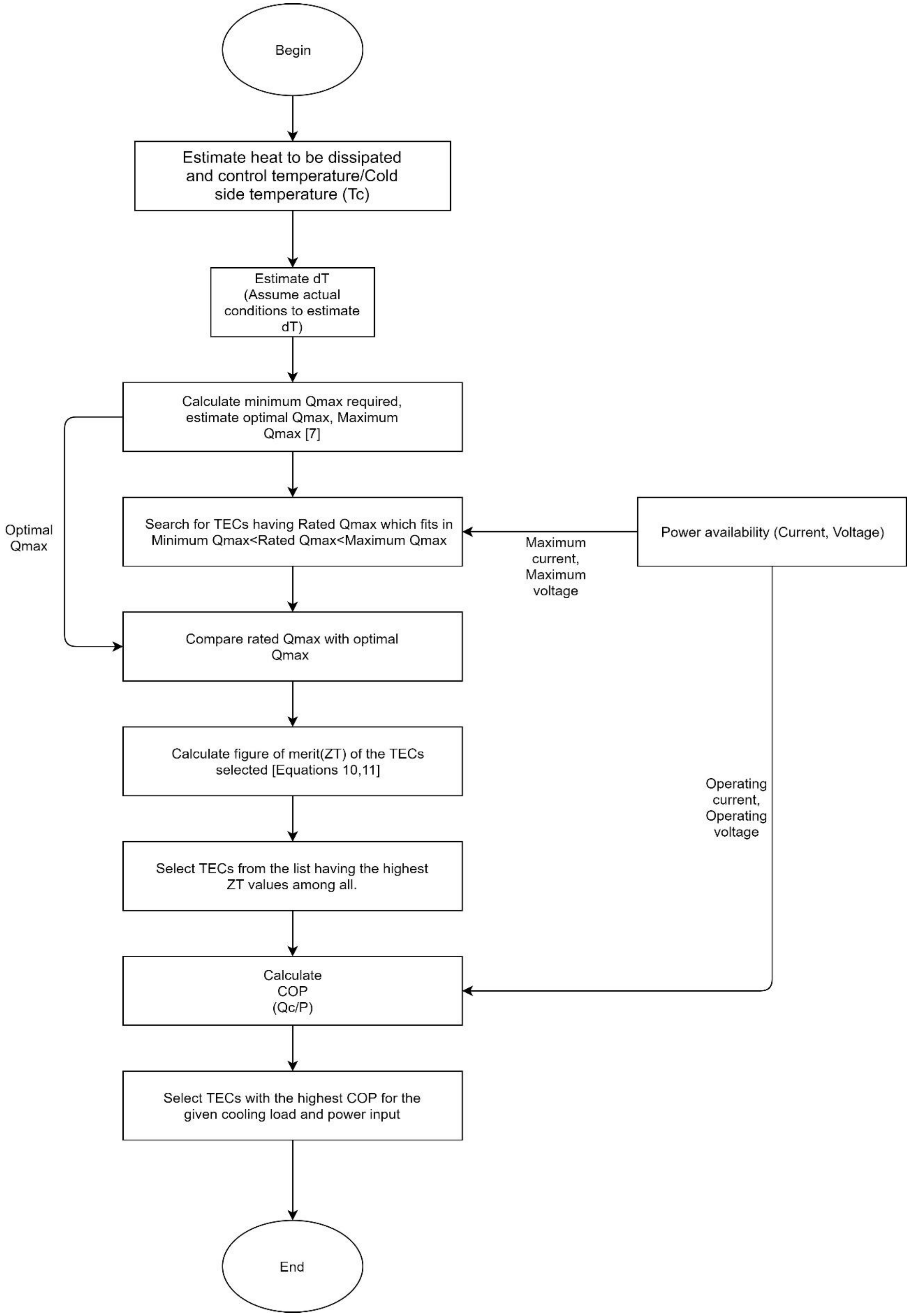
Sm is the device Seebeck coefficient calculated as the ratio of Vmax to Th. The unit is (V/K). Km is the thermal conductance of the device. The unit is (W/K). Ro and Rm are the electrical resistances, the unit of which is Ohms. (Kindly note that Rm and Ro are same)

Rq is the thermal resistance of the device, the unit being (K/W). Z is the quality factor of the device, the unit being K-1. ZT is the figure of merit of the TEC device and it is dimensionless.

The cooling capacity required is 1W. Therefore, Qc=1W. The selection of TECs is done on the assumption that the value of Qmax of the Peltier device should be 2-3 times the required cooling capacity as stated in literature.

The Thermoelectric Coolers marked in green are the TECs selected for this assignment as they can operate at temperatures of more than 353 Kelvin (80^{o} C). The other TECs have the limitation of maximum operating temperature being lesser than the expected hot side temperature which, in this assignment is expected to be equal to or more than 353 Kelvin (80^{o} C). Also, the figure of merit values (ZT) of the selected TECs is higher than other TECs as can be seen in the table.

4.2 Flowchart for selection of Thermoelectric Cooler



4.3 Result comparison of mathematical model and manufacturer's graphs

For <u>Laird ET19,23,F1N,0608</u>, the Cooling power Q_c was calculated using the mathematical model in eqn(1) as <u>0.99W</u>, at a <u>hot side temperature</u> of <u>85°C/358K</u>.

The graph obtained from the manufacturer's website shows the Cooling power Q_c as <u>1.02W</u>, for a <u>temperature difference</u> of <u>25°C/25K</u>.

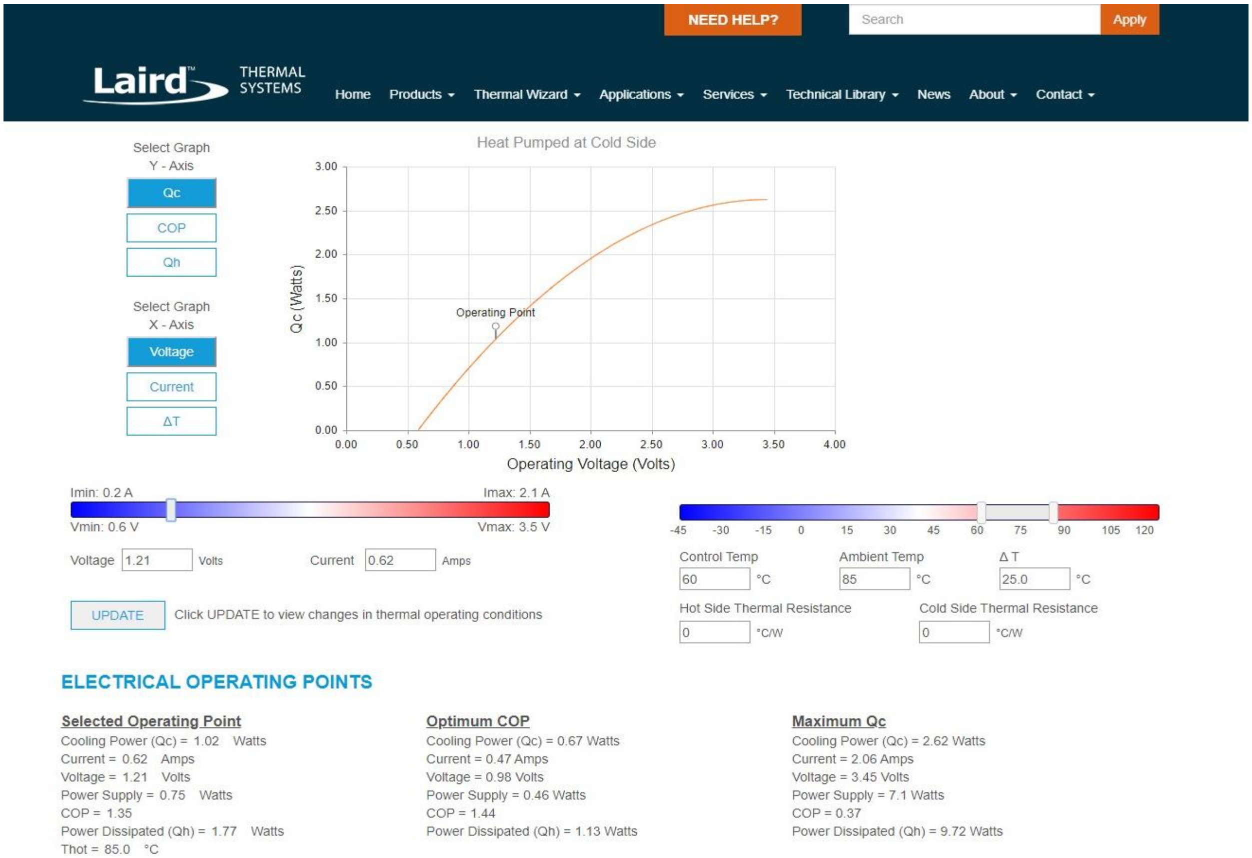


Figure 4.1: The manufacturer's graph for <u>Laird ET19,23,F1N,0608</u>

For Laird ET08, 66, F0, 1009, the Cooling power Q_c was calculated using the mathematical model in eqn(1) as 0.97W.

The graph obtained The graph obtained from the manufacturer's website shows the Cooling power Q_c as 1.01W, for a temperature difference of 20^{o}C/20K.

Figure 4.2: The manufacturer's graph for Laird ET08, 66, F0, 1009

For CP50141, the Cooling power Q_c was calculated using the mathematical model in eqn(1) as 1W at a current value of 1.17A at a potential difference of 0.50V for a temperature difference of 20ºC/20K. The hot side temperature here is 50ºC/323.15K

The graph obtained from the manufacturer's website shows that for a cooling power of 1W, for a temperature difference of 20ºC/20K, the current and voltage required roughly can be made out to be 1.2A and 0.6V respectively.

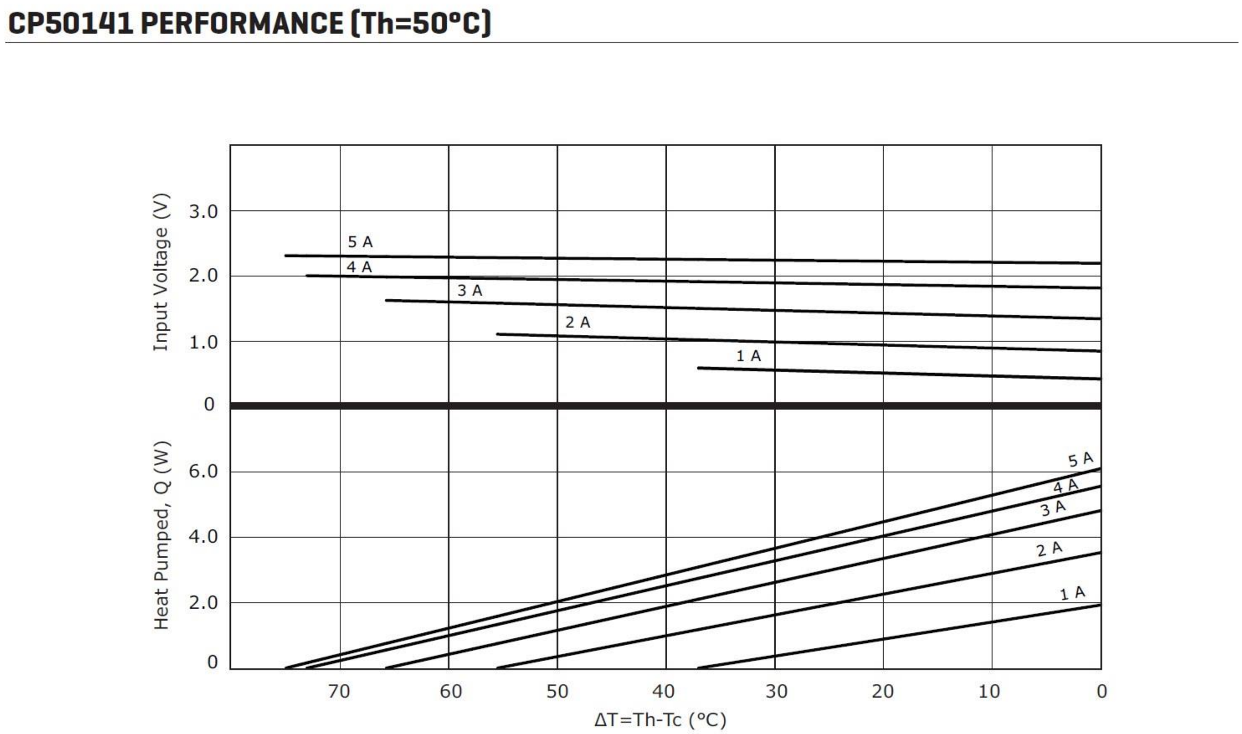


Figure 4.3: The manufacturer's graph for CP50141

4.4 Selection based on Operation parameters, Cost and availability.

1. Selection based on operating temperature: The requirements stated that the cold side temperature/control temperature for the cold side of the Thermoelectric device is 60ºC/333.15K. Owing to this, in the practical scenario, it would be beneficial to make a choice of Thermoelectric coolers having their operating temperatures higher than the hot side temperature. In this case, the hot side temperature is expected to be 80º/353.15K. Therefore, from the list shown in table 4.1, a number of TECs were eliminated on the basis of lower maximum operating temperatures.
   The inclusion of CP50141: The maximum operating temperature limited to 80º/353.15K. Since this TEC available has its cost lower than the other TECs available, it would be beneficial to see how much effect this TEC has on the Heat sink requirements for heat

dissipation and also, if possible, the overall cost of the setup. It can be presented as a low cost option. (After discussion, it was decided to investigate a TEC which has max operation temperature limited to 80 degrees)

2. Selection based on figure of merit(ZT): The figure of merit determines the efficiency of the Thermoelectric module[5]. It is wise to choose a TEC having a higher figure of merit when compared to other TEC options. A high ZT value signifies a high Coefficient of Performance[5] which means that for a given cooling capacity, the power required by a TEC would be lower as compared to TECs which have a lower ZT.

3. Selection based on Cost: The cost of the TECs can be categorized into operating cost per unit of cooling capacity. Hence, the TECs which have a higher COP(higher ZT value) are selected so that the Cost per unit cooling capacity can be minimized as much as possible. Also, in the process of purchase, cost of the setup is an important factor. The TECs having their operating temperature higher than 80^{o}/353.15K cost more than the TECs having their operating temperature limited to 80^{o}/353.15K. But, since the priority lies with operation and not with cost, the TECs having a lower cost within the pool were selected.

4. Selection based on availability: The availability in the market is a deciding factor for the procurement of Thermoelectric Coolers. Some of the TECs which were selected based on the points as explained above were either not available or were discontinued from production.

4.5 Summary of selection

- The selection of devices/materials/components is a process where one has to choose some of the devices available at the manufacturer on the basis of the main requirement of the module.
- Secondly, from the list of the chosen devices/materials/components from the customer's database, we further eliminate some of the options based on the efficiency, cost and the operating conditions.
- Lastly, after performing physical experiments on the modules obtained, we have substantial data which can assist in further dialing down the selection to 1/2 modules.
- In this case, the main requirement of the module is to remove heat from the Printed Circuit Board (PCB) so that the temperature of the PCB could be brought down to a specified temperature for efficient operation of the PCB.
- After constructing a list of TECs available in the market, one can eliminate or modify some options by referring to the datasheet and obtaining data from the calculations to align with the operating conditions and gauging the efficiency of the device.
- The next step is the physical experimentation of the performance of the TECs in actual operating conditions.

5. Heat Transfer

5.1 Requirement of a Heat sink:

Efficient heat sink is required so that it can transfer equal or more amount of heat. If less heat is removed than gained, it will effect in an increase in temperature at the hot side of the module. If the temperature at the hot side of the module increases and the current and voltage are kept constant, the temperature difference will also remain constant, which signifies that the temperature would increase at the cold side of the module. If the cold side temperature needs to be kept constant, more power will need to be pumped into the TEC so that the cold side temperature remains constant. But, as the hot side temperature increases, the temperature difference increases as well which requires an increase in input power. This in turn reduces the Coefficient of Performance (COP) of the TEC. Therefore, a heat sink which is able to dissipate heat from the hot side of the TEC is necessary. [19]

5.2 Heat input from the TEC

- As a starting point for heat sink design(the minimum area required), it is calculated that the heat sink would require to dissipate 1.6W of heat at a temperature of 80^{o}C.
- The calculation for the source of 1.6W of heat is based on the characteristics of Laird.
- For LairdET19,23,F1N,0608 Thermoelectric module, to maintain a temperature difference of 20K, at a cold side temperature of 60^{o}C/333.15K, Cooling power of 1W, Current of 0.6A needs to be provided at 1V potential difference. The power input is hence, 0.6W. [Refer Appendix]
- The amount of heat produced at the hot side is the sum of the input power and the heat pumped (Qc). All input power given to a TEC always comes out as heat. [20]
- In this scenario, the heat pumped (Qc), is 1W and the input power is 0.6W. The total heat to be dissipated from the Thermoelectric Cooler is 1.6W

5.3 Heat Transfer Calculation

- Since the thickness in the case of conduction heat transfer is 0.01m (10mm), it is not sufficient to induce a drop in the temperature. Therefore, the temperature at the surface of the heat sink exposed to air is assumed to be same as the temperature at the hot side of the TEC.
- In this case, the area required for heat transfer by convection and radiation needs to be calculated since convective and radiative heat transfer could play a major role in heat dissipation compared to conductive heat transfer.

- Convective heat transfer and radiative heat transfer occur from the surface exposed to the surroundings. To formulate the convective and radiative heat transfer in combination, the expression signifies that they act in parallel.
- The expression for the combined heat transfer is:

$$Q_{tot} = Q_{conv} + Q_{radn} \tag{25}$$

Where, Q_{tot} is the total heat transfer,

Q_{conv} is the convective heat transfer,

Q_{radn} is the radiative heat transfer.

- Expanding this term gives,

$$Q_{tot} = [h * A * (T_s - T_a)] + [\varepsilon * \sigma * A * ({T_s}^4 - {T_a}^4)] \tag{26}$$

The term $[h * A * (T_s - T_a)]$ stands for convective heat transfer
h is the convective heat transfer coefficient, unit being W/m^2K
A is the area required for heat transfer, m^2
T_s is the surface temperature of the object, Kelvin.
T_a is the ambient temperature, Kelvin.

And the term $[\varepsilon * \sigma * A * ({T_s}^4 - {T_a}^4)]$ is for radiative heat transfer.
ε is the emissivity of the object which is the measure of an object's ability to emit infrared energy. [21]
σ is the Stefan Boltzmann constant, $5.67 * 10^{-8}\ W/m^2K^4$
A is the area required for heat transfer, m^2
T_s is the surface temperature of the object, Kelvin.
T_a is the ambient temperature, Kelvin.

- For 1.6W of heat to be dissipated, the above equation can be utilized to calculate the area required for heat transfer.
- The material for the heatsink is AL6061, as it is commonly used for heat transfer applications.

- The convective heat transfer coefficient, $h\ (W/m^2K)$, for free convection is determined from the following table.

Flow type	(W/m^2 K)
Forced convection; low speed flow of air over a surface	10
Forced convection; moderate speed flow of air over a surface	100
Forced convection; moderate speed cross- flow of air over a cylinder	200
Forced convection; moderate flow of water in a pipe	3000
Forced Convection; molten metals	2000 to 45000
Forced convection; boiling water in a pipe	50,000
Forced Convection - water and liquids	50 to 10000
Free Convection - gases and dry vapors	5 to 37
Free Convection - water and liquids	50 to 3000
Air	10 to 100
Free convection; vertical plate in air with 30°C temperature difference	5
Boiling Water	3.000 to 100.000
Water fowing in tubes	500 to 1200
Condensing Water Vapor	5.0 - 100.0
Water in free convection	100 to 1200
Oil in free convection	50 to 350
Gas flow on tubes and between tubes	10 to 350

Table(5.1) Convection coefficient for various conditions [22]

Material	Emissivity
Alumel (Unoxidized)	0.10 - 0.25
Alumel (Oxidized)	0.60
Aluminum (Polished)	0.10 - 0.05
Aluminum (Oxidized)	0.10 - 0.40
Aluminum (Rough)	0.10 - 0.30
Aluminum (Anodized)	0.60 - 0.95
Aluminum Oxide	0.40
Asbestos	0.95
Asphalt	0.90 - 1.00
Basalt	0.70
Bismuth	0.50
Brass (Polished)	0.05
Brass (Oxidized)	0.50 - 0.60
Brass (Burnished)	0.30
Carbon (Unoxidized)	0.40 - 0.90
Carbon (Filament)	0.50
Carbon (Soot)	0.50 - 0.95
Carbon (Coke)	0.95 - 1.00
Carbon (Graphite)	0.70 - 0.80
Carborundum	0.80 - 0.90
Ceramic	0.90 - 0.95
Clay (Fired)	0.95
Concrete	0.95
Chrome (Oxidized)	0.60 - 0.85

Table(5.2) Emissivity of materials with surfaces [24]

- For this case, the condition of free convection for vertical plate in air with 30°C temperature difference is assumed. Here, the convection heat transfer coefficient is $5\ W/m^2K$.
- The temperature of the surface of the heatsink exposed to air, T_s is 353K (80°C) as the same as the hot side temperature of the Peltier module.
- The ambient temperature, T_a is 300K (27°C).
- The emissivity of the object, ε , is 0.9.
- σ is the Stefan Boltzmann constant, $5.67 * 10^{-8}\ W/m^2K^4$

Substituting these values in equation (26), we get,

$$1.6 = [5 * A * (353 - 300)] + [0.9 * 5.67 * 10^{-8} * A * (353^4 - 300^4)]$$

Solving for A, we get value of 0.002484 m^2, which is 2484 mm^2.

The diameter of the PCB to be cooled is 40mm. The surface area of the PCB is 1256 mm^2

5.4 FEA model

A simulation was performed on Creo Parametric for heat transfer. The heat sink is connected to the hot side of the Thermoelectric Cooler through a thermal gap pad.

The dimensions of the components are:

- Sensor PCB diameter: 40mm
- TEC assembly dimensions as from the manufacturers datasheet (Laird ET19,23,F1N,0608): 8.2mm * 6mm * 1.2mm (Length * Breadth * Height)
- Heat sink diameter: 56mm

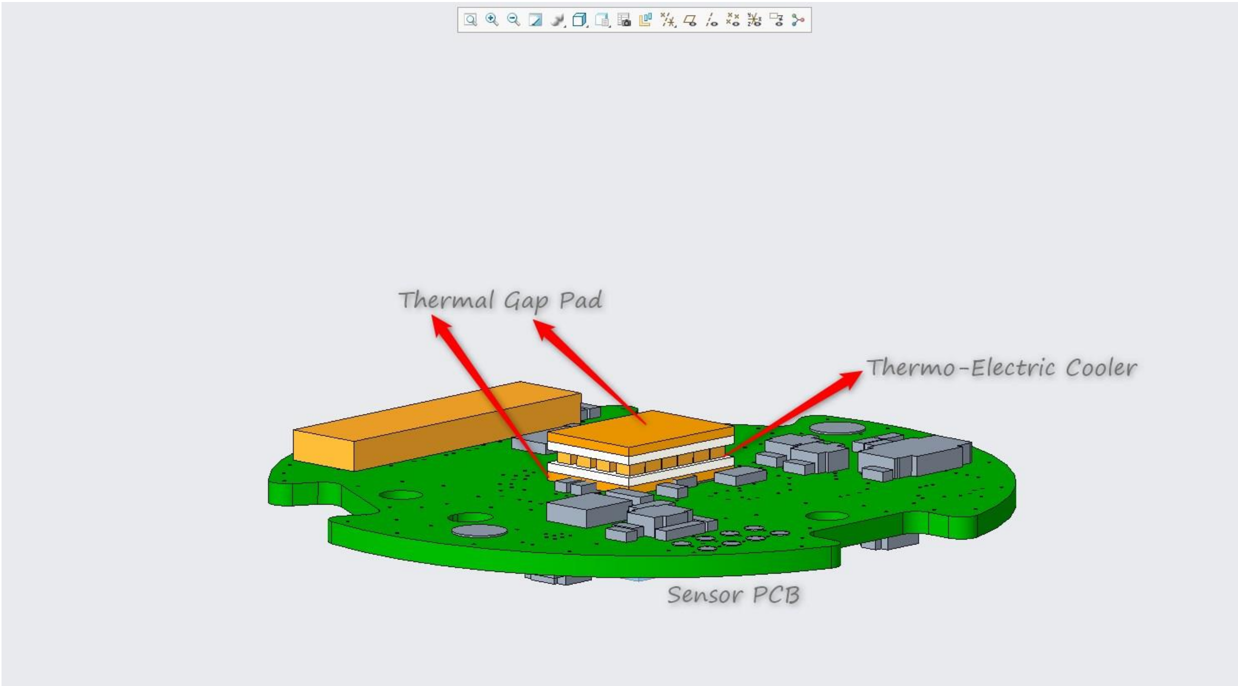


Fig.(5.1): Creo 3D model without Heat sink

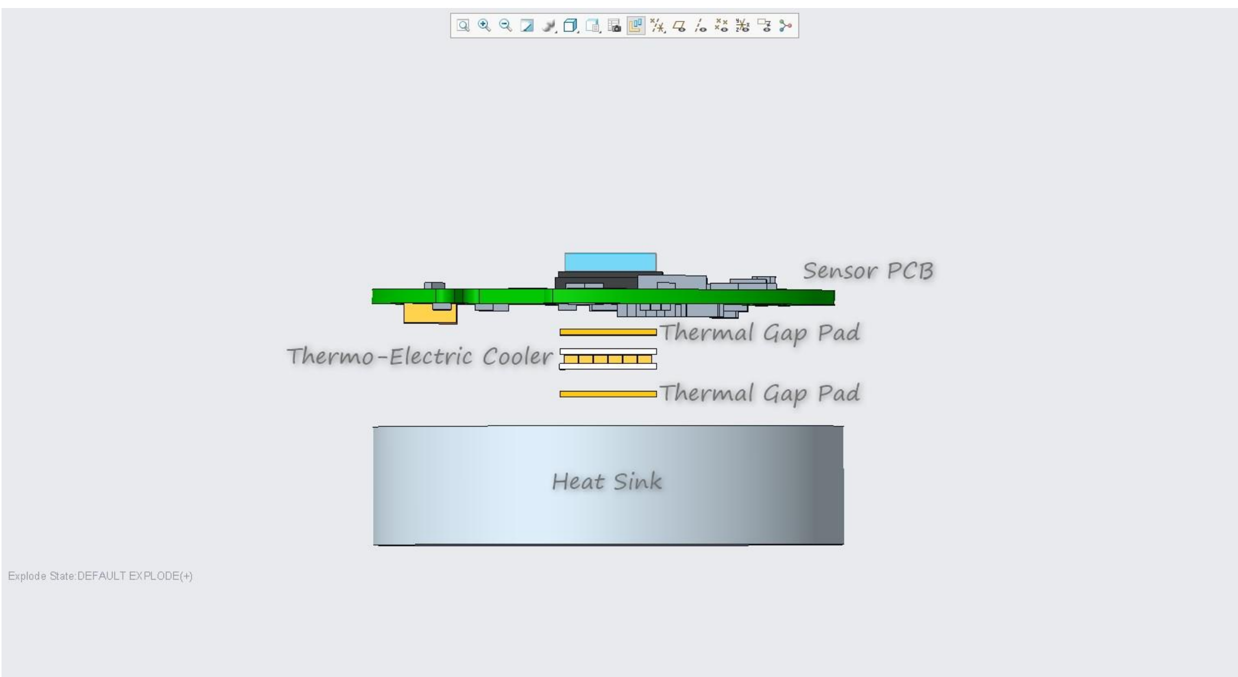


Fig.(5.2) Creo 3D model with Heat sink.

Since Creo does not offer a Thermoelectric Module simulation, a thermal simulation for the heat sink was performed.

For the thermal simulation, convection condition and radiation condition were simulated independent of each other since the software is not equipped for combined heat transfer of convection and radiation.

Hence, the heat inputs for convection and radiation were different and were calculated using eqn(25).

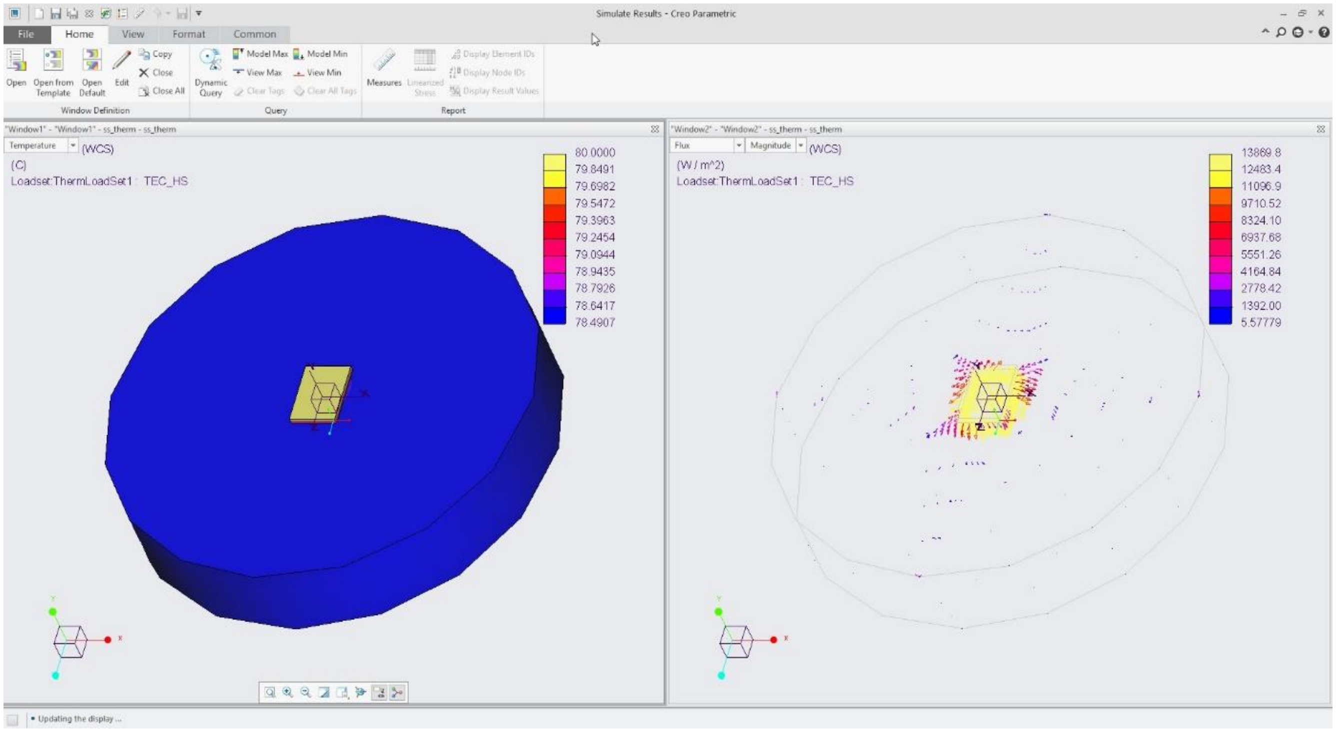


Fig.(5.3) Simulation results for convection model with Heat sink.

The simulation was convection performed with the following boundary conditions:

- Heat input on the hot side of the Thermoelectric Cooler: 0.65W
- Convection coefficient: 5 W/m^2K
- Ambient temperature: 27ºC/300K
- Temperature on hot side of Thermoelectric Cooler: 80ºC/353K

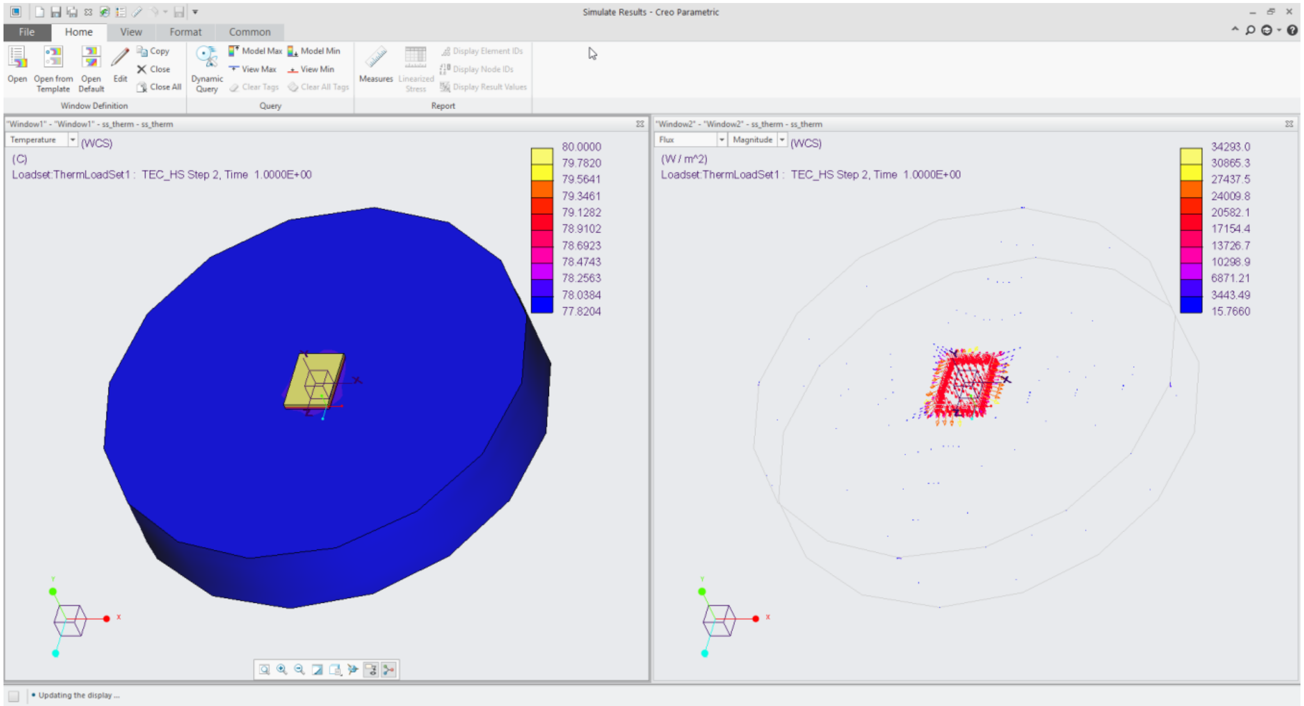


Fig.(5.4) Simulation results for radiation model with Heat sink.

The simulation for radiation was performed with the following boundary conditions:

- Heat input on the hot side of the Thermoelectric Cooler: 0.92W
- Emissivity of the surface: 0.9
- Ambient temperature: 27°C/300K
- Temperature on hot side of Thermoelectric Cooler: 80°C/353K
- Stefan Boltzmann constant: $5.67 * 10^{-8}\ W/m^2K^4$

5.5 Comments on Results

The simulations were performed with the expected actual boundary conditions. The results display a temperature gradient from the hot side of the Thermoelectric Cooler to the surface of the Heatsink exposed to air in both cases. It can be inferred that since there exists a temperature gradient, heat is being dissipated. The results of the simulation are expected to be verified by experimentation.

Conclusion

A Thermoelectric cooler with an efficient heat sink enhances the transfer of heat compared to an individual heat sink for heat dissipation.

The results obtained show that for a given input current at a given input voltage, the Thermoelectric Cooler chosen can effectively dissipate heat, cool down the Sensor PCB to 60^{o}C/333.15K and maintain the temperature value. This is only possible if the heat sink is able to dissipate the heat from the hot side of the TEC efficiently to the surroundings. If the heat sink is not efficient, it will result in reduced transfer of heat which would effect in the hot side temperature rise. If the temperature at the hot side rises, the temperature of the cold side of the Thermoelectric Cooler will rise too, since the Thermoelectric Cooler is operating at a defined temperature difference based on the input power. If the cold side temperature needs to be maintained at the same temperature even when the temperature difference increases, more power input is needed to maintain the cold side temperature at a constant value which decreases the Coefficient of Performance of the system.

Therefore, the additional heat generated by the Thermoelectric Cooler needs to be dissipated by the Heat sink. If the power input available is limited to an extent and a low COP is not desirable, it is recommended to design a heat sink capable of dissipating the heat from the hot side of the Thermoelectric Cooler.

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Appendix

Laird

HiTemp ET Series ET19,23,F1N,0608,11-W2.25

Thermoelectric Modules

The HiTemp ET Series of Thermoelectric Modules (TEMs) are designed to operate in high temperature environments.

This product line is available in multiple configurations and is ideal for applications that operate in temperatures above 80°C. Assembled with Bismuth Telluride semiconductor material, thermally conductive Aluminum Oxide ceramics and high temp solder construction, the ET Series is designed for higher current and larger heat-pumping applications.

FEATURES

- High-temperature operation
- Reliable solid state
- No sound or vibration
- Environmentally-friendly
- RoHS-compliant

APPLICATIONS

- Automotive cooling
- Telecom cooling
- Outdoor environments
- Medical heating/cooling

TECHNICAL SPECIFICATIONS		
Hot Side Temperature (°C)	85	110
Qmax (W)	3.5	3.6
Delta Tmax (°C)	87	94
Imax (Amps)	1.9	1.9
Vmax (Volts)	3.4	3.6
Module Resistance (Ohms)	1.66	3.25

SUFFIX	THICKNESS (PRIOR TO THINNING)	FLATNESS & PARALLELISM	HOT FACE	COLD FACE	LEAD LENGTH
11	0.065" ±0.002"	0.002"/0.002"	Lapped	Lapped	2.25"

SEALING OPTIONS

SUFFIX	SEALANT	COLOR	TEMPERATURE RANGE	DESCRIPTION
RT	RTV	Clear	-60 to +204 °C	Non-corrosive, silicone adhesive
EP	Epoxy	Black	-55 to +150 °C	Low density syntactic foam epoxy encapsulant

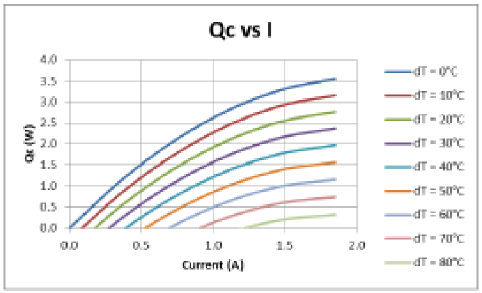
ETS-DS- ET19,23,F1N,0608,11-W2.25 0418

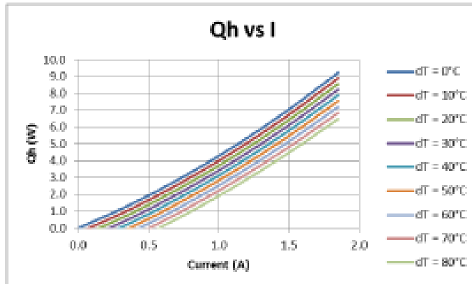
Laird

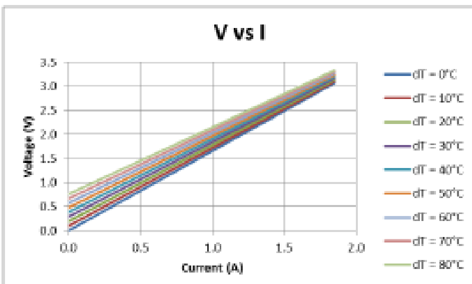
ET19,23,F1N,0608,11-W2.25

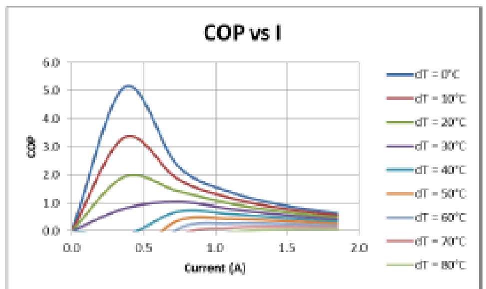
Thermoelectric Modules

PERFORMANCE CURVES AT Th = 85° C

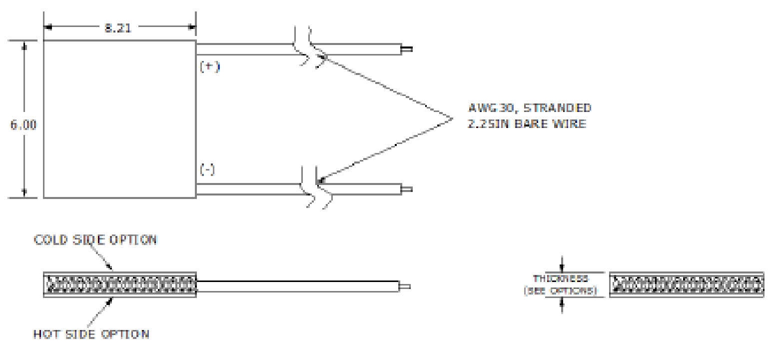








MECHANICAL DRAWING



Ceramic Material: Alumina Nitride(AlN)
Solder Construction: 232°C SbSn

NOTES:

- **Maximum Operating Temperature: 150°C**
- **Do not exceed Imax or Vmax when operating module**
- **Reference assembly guidelines for recommended installation**

RoHS

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ETS-DS- ET19,23,F1N,0608,11-W2.25 0418

Additional Resources: Product Page | 3D Model

SERIES: CP50 | DESCRIPTION: PELTIER MODULE

FEATURES

- arcTEC™ structure on select models
- solid state device
- precise temperature control
- quiet operation

RoHS

MODEL	input voltage[1] max (Vdc)	input current[2] max (A)	internal resistance[3] typ (Ω±10%)	output Qmax[4] T_h=27°C (W)	output Qmax[4] T_h=50°C (W)	output ΔTmax[5] T_h=27°C (°C)	output ΔTmax[5] T_h=50°C (°C)
CP50141	2.1	5.0	0.31	5.5	6.1	68	75
CP50241	3.8	5.0	0.56	10.0	11.1	68	75
CP50301541	4.2	5.0	0.63	11	12.3	68	75
CP50341[6]	8.6	5.0	1.29	23.0	25.7	70	77
CP50441[6]	15.4	5.0	2.3	41.0	45.8	70	77

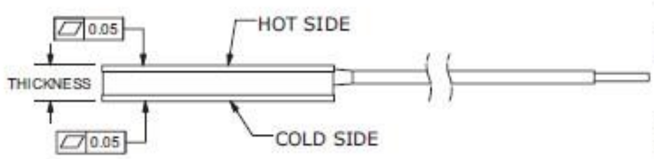
Notes:
1. Maximum voltage at ΔT max and T_h=27°C
2. Maximum current to achieve ΔT max
3. Measured by AC 4-terminal method at 25°C
4. Maximum heat absorbed at cold side occurs at I_{max}, V_{max}, and ΔT=0°C
5. Maximum temperature difference occurs at I_{max}, V_{max}, and Q=0W (ΔT max measured in a vacuum at 1.3 Pa)
6. Designed with arcTEC™ structure

SPECIFICATIONS

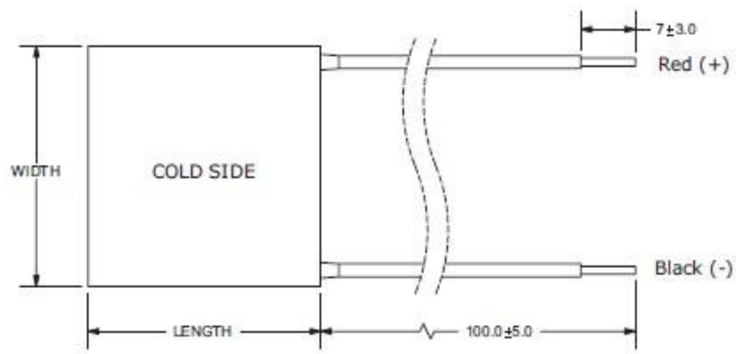
parameter	conditions/description	min	typ	max	units
solder melting temperature	connection between thermoelectric pairs	235			°C
assembly compression				1	MPa
hot side plate				80	°C
RoHS	yes				

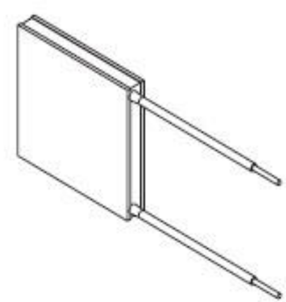
MECHANICAL DRAWING

units: mm



	MATERIAL	PLATING
ceramic plate	96% AL_2O_3	
wire leads	20 AWG	tin
sealer	silicon rubber 703 RTV (between cold and hot side plates)	
joint cover	silicon rubber 703 RTV	
marking	P/N & S/N printed on cold side surface	

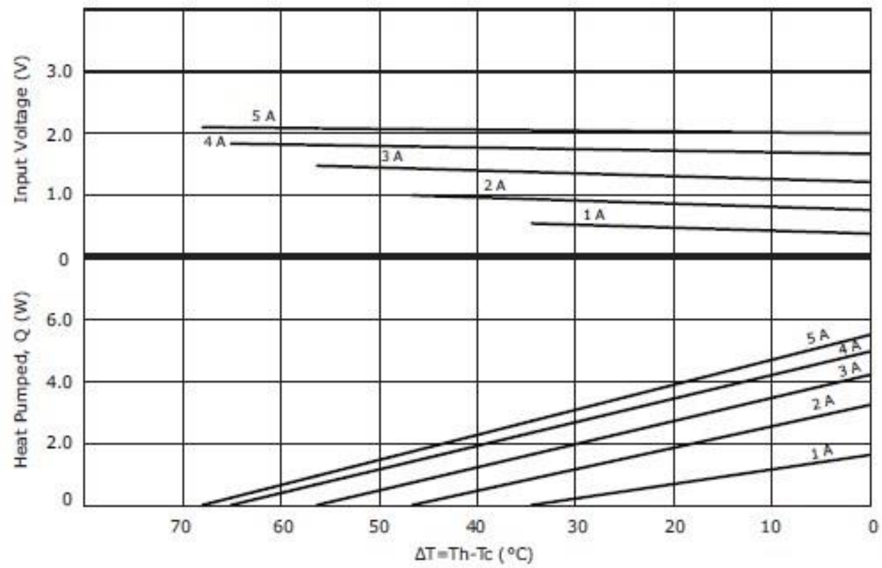




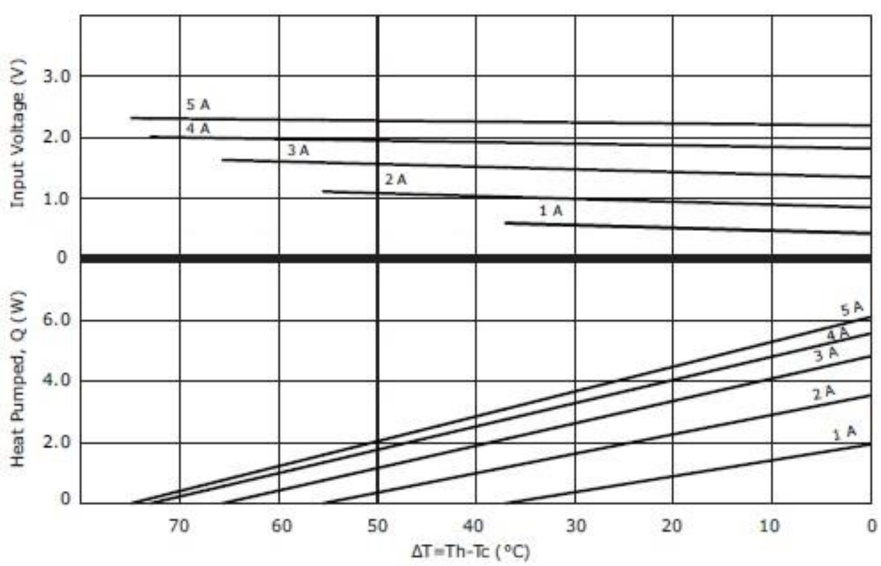
MODEL NO.	LENGTH (mm)	WIDTH (mm)	THICKNESS (mm)
CP50141	15 ±0.3	15 ±0.3	4.0 ±0.1
CP50241	20 ±0.3	20 ±0.3	4.0 ±0.1
CP50301541	30 ±0.3	15 ±0.3	4.0 ±0.1
CP50341[1]	30 ±0.3	30 ±0.3	4.0 ±0.1
CP50441[1]	40 ±0.3	40 ±0.3	4.0 ±0.1

Notes: 1. Wire lead strip length on models CP50341 & CP50441 is 10 ±3.0 mm.

CP50141 PERFORMANCE (Th=27°C)



CP50141 PERFORMANCE (Th=50°C)



HiTemp ET Series ET15,65,F2A,1312
Thermoelectric Modules

The HiTemp ET Series of Thermoelectric Modules (TEMs) are designed to operate in high temperature environments.

This product line is available in multiple configurations and is ideal for applications that operate in temperatures above 80°C. Assembled with Bismuth Telluride semiconductor material, thermally conductive Aluminum Oxide ceramics and high temp solder construction, the ET Series is designed for higher current and larger heat-pumping applications.

FEATURES

- High-temperature operation
- Reliable solid state
- No sound or vibration
- Environmentally-friendly
- RoHS-compliant

APPLICATIONS

- Automotive cooling
- Telecom cooling
- Outdoor environments
- Medical heating/cooling

TECHNICAL SPECIFICATIONS		
Hot Side Temperature (°C)	85	110
Qmax (W)	7.66	7.86
Delta Tmax (°C)	87	94
Imax (Amps)	1.5	1.5
Vmax (Volts)	9.6	10.4
Module Resistance (Ohms)	6.15	6.81

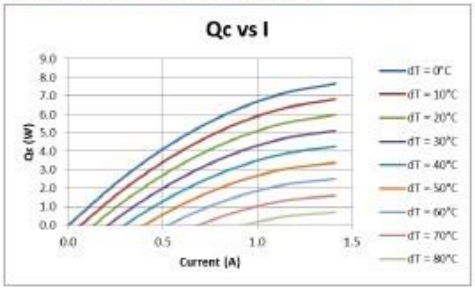
SUFFIX	THICKNESS (PRIOR TO THINNING)	FLATNESS & PARALLELISM	HOT FACE	COLD FACE	LEAD LENGTH
11	0.096" ±0.002"	0.002"/0.002"	Lapped	Lapped	2.25"

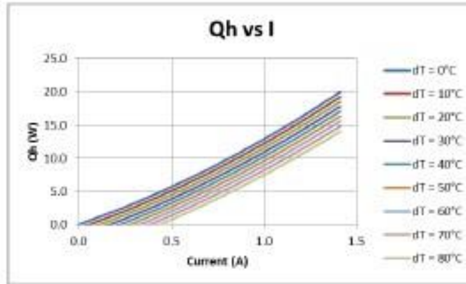
SEALING OPTIONS

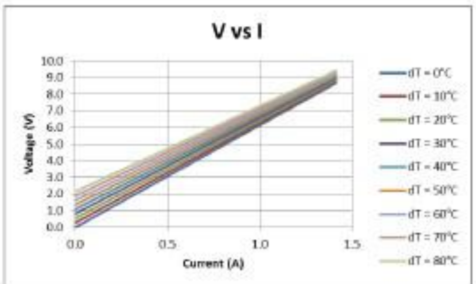
SUFFIX	SEALANT	COLOR	TEMPERATURE RANGE	DESCRIPTION
RT	RTV	Clear	-60 to +204 °C	Non-corrosive, silicone adhesive
EP	Epoxy	Black	-55 to +150 °C	Low density syntactic foam epoxy encapsulant

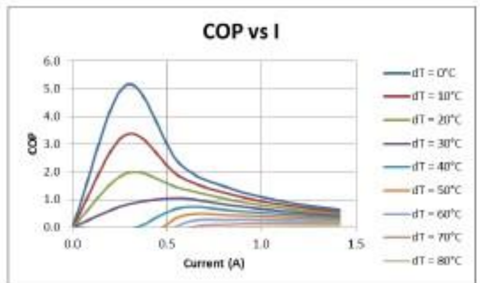
ETS-DS-ET15,65,F2A,1312 0518

PERFORMANCE CURVES AT Th = 85° C

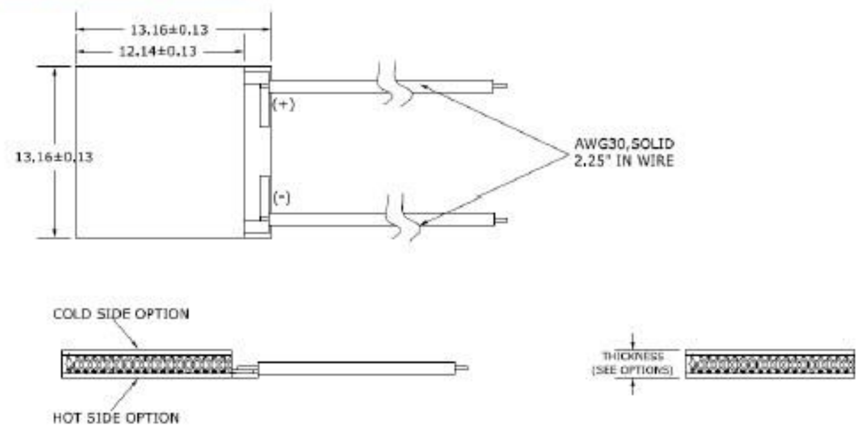








MECHANICAL DRAWING



Ceramic Material: Alumina(Al2O3)
Solder Construction: 232°C SbSn

NOTES:

- **Maximum Operating Temperature: 150°C**
- **Do not exceed Imax or Vmax when operating module**
- **Reference assembly guidelines for recommended installation**

✓RoHS

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