CUI DEVICES

THE COMPLETE GUIDE TO
THERMAL MANAGEMENT

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1. EXECUTIVE SUMMARY

Despite vast improvements in recent times, electronic components do not work with 100% efficiency. Some of the power provided to them is inevitably wasted, usually in the form of heat. While the amount of heat produced by individual components has decreased significantly, they now occupy less space which makes it possible to pack additional components onto printed circuit boards, which in turn are housed in ever-shrinking enclosures. Also operating at much faster speeds, their individual contributions combine to create a thermal nightmare for the electronic designer. As a result, it has never been more important for engineers to understand the fundamental principles of heat transfer and how to design an appropriate thermal management solution to manage it. Failure to do so may lead to components overheating, which can cause irreparable damage.

Conduction is the movement of heat between a hot and cold body without any physical movement and is the most efficient form of heat transfer. Convection, which is the movement of heat from a hot to a cold region by the movement of air, can occur naturally or by artificial means. While convection is less efficient than conduction, the two modes can be combined as a part of an effective cooling solution. Radiation is the movement of heat in the form of an electromagnetic wave, but it is not an efficient cooling mechanism in most scenarios. The thermal impedance of a material is its resistance to heat flow. A material with a low thermal impedance is a good conductor and vice versa.

When it comes to thermal management components, fans, heat sinks, and Peltier devices are the most common and well-recognized. Fans consist of a rotor that spins on a bearing to provide forced airflow in higher power applications that cannot be cooled by the natural convection of air. They are categorized by airflow direction (axial or centrifugal) and come with several bearing options. Fan selection involves system profiling and the calculation of airflow and cooling requirements. Some fans provide additional control features to improve their efficiency and reliability while reducing audible noise.

Not all applications require cooling but for those that do, heat sinks are a simple and yet highly effective thermal management tool. Their function is based on the physical principle that increased surface area improves heat conduction. They ensure that electronic components operate within their rated temperature range, even at worst-case conditions. Determining the size and type of heat sink requires an understanding of the contributions to the total thermal impedance between the silicon junction of a component and the surrounding ambient air. This also includes a knowledge of the function and nature of the role of thermal compounds as well as the ability to interpret and apply multiple parameters specified in the datasheets provided by heat sink manufacturers.

Systems housed in small, sealed environments cannot use forced-air cooling solutions. For these applications, the Peltier module provides a viable alternative. Using an electrical current to transfer heat from its cool side to be dissipated on its hot side, a thermoelectric module has advantages over fans and heat sinks, including cooling below ambient temperatures. Determining the control voltage and operating current needed to achieve a certain level of cooling requires an understanding of parameters specified on Peltier module datasheets.

This guide provides a detailed introduction to the topic of thermal management in electronics and why it is important, as well as covering the basics of how to choose the right solution for a design and what parameters should be explored during the selection process.

2. INTRODUCTION

No electronic device is 100% efficient, which means that heat is an inescapable by-product of their operation. Bound by upper and lower limits, the clearly defined temperature range within which devices are specified to function is commonly referred to as the Safe Operating Area (SOA). Operating temperatures that deviate outside of this range may cause unpredictable behavior and degraded performance. While some devices can safely withstand small, transient deviations outside of their SOA, this is not guaranteed. Bigger and longer-term temperature deviations increase the probability of sporadic behavior. In some instances, extreme temperatures can cause changes to become permanent, or may even cause total device failure. While excessively low temperatures can be harmful, this book will focus on the negative effects of high temperatures and how to mitigate them. Although temperature control is unnecessary for many applications, it is advisable to address this possibility at the start of the design cycle so that it does not become an issue at a later stage when it may be more difficult to address. A clear understanding of the fundamentals of how heat is created, moved, and removed is essential for creating reliable and effective thermal management solutions. In the first chapter, we will review the theory and terminology of heat transfer and the basic operation of commonly used cooling devices, laying the foundation for a more detailed examination of these topics in later sections.

2.1 MODES OF HEAT TRANSFER

The three common modes of heat transfer are conduction, convection, and radiation. While different combinations of all three are used to cool electronic components, their implementation and effectiveness vary greatly.

Conduction

Conduction is the transfer of thermal energy between two objects in physical contact, where the cooler object draws energy away from the hotter one (Figure 1). This is the most effective method of energy transfer as it requires the least amount of surface area to transfer the largest amount of energy.

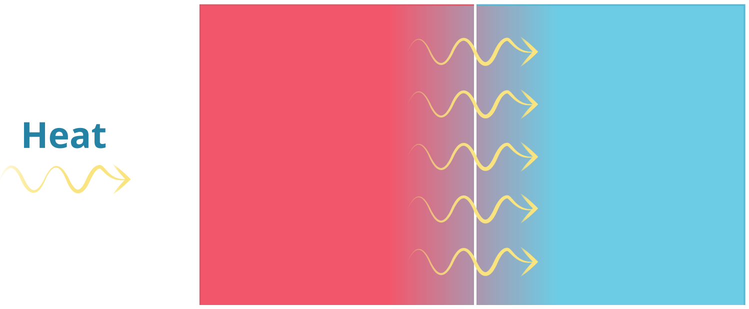


Figure 1: Conduction is the transfer of energy through physical contact

Convection

Convection uses the movement of air to redistribute heat (Figure 2). When cool air passes by a warm body, it draws heat away from the body and rises. More cool air then flows in to replace the risen air and it is this continuous process that reduces the temperature of the body. Air movement can be passive (using only natural airflow, or forced) where a fan speeds up airflow to increase the transfer of thermal energy. Although convection is less efficient than conduction, it is still commonly used as the final stage within a thermal management system.

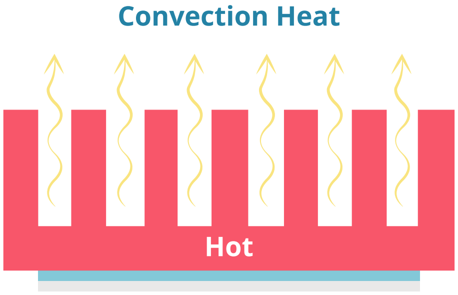


Figure 2: Convection is the movement of heat due to the natural tendency of hot air to rise

Radiation

Radiation is the emission of energy, away from a body, in the form of an electromagnetic wave. The interaction and movement of charged particles in matter generate coupled electric and magnetic fields, converting the thermal kinetic energy into electromagnetic energy that propagates from the source (e.g. the sun). Unlike conduction and convection, radiation does not require a medium for heat transfer. However, because it is less effective, it is only considered in the thermal calculations for applications that are required to operate in a vacuum.

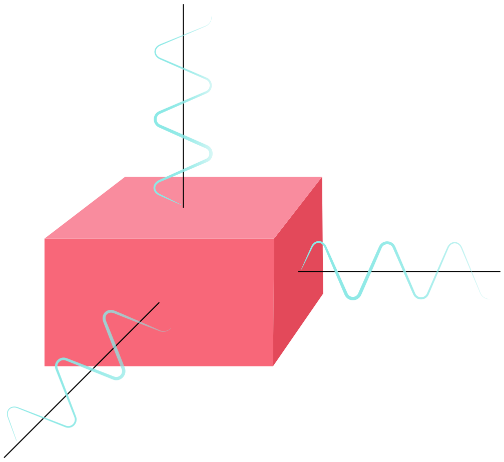


Figure 3: Radiation is the transfer of heat through the electromagnetic waves created when hot particles vibrate

Thermal Impedance

An important concept used to quantify the effectiveness of heat transfer between bodies of different sizes, shapes, and materials is thermal impedance. The lower the thermal impedance of a body, the greater its ability to transfer heat. Using the values for ambient temperature and thermal impedance it is possible to calculate exactly how much power a body can produce before reaching certain temperatures, enabling the design of an appropriate thermal management solution.

2.2 COOLING DEVICES

Combining cost-effectiveness with high-efficiency, heat sinks, fans, and Peltier modules are the three most popular options used to cool electronic devices. While they can be used separately, their effectiveness is greatly enhanced when they are integrated collectively into a composite cooling solution.

Heat Sinks

A heat sink is made from a material with a lower thermal impedance than the electronic device to which it is attached and performs its cooling function by increasing the surface area available for air convection. They are silent, passive, inexpensive components that come in a variety of shapes and sizes and are highly reliable. While larger heat sinks provide better cooling, their increased volume can be problematic in some applications. Alternatively, pairing a smaller heat sink with a cooling fan can be equally or more effective than a larger, passive heat sink.

Fans

Fans (or blowers) work by moving warm air away from the surface of a heat sink or device and quickly replacing it with fresh, cooler air in a continuous process that is more efficient than normal convection. Fans are available in a variety of form factors and operating voltages. The airflow produced is typically measured in cubic feet per minute (CFM) and is determined by the shape and size of the fan. Some fans provide variable speed control that can be used in feedback systems to actively adjust the CFM. While they have the advantage of reducing the size of the heat sink required and are relatively inexpensive, fans have the disadvantage of being active devices that require power. Also, the fact that they use moving parts makes them noisy and subject to mechanical failure.

Peltier Devices

Peltier devices are semiconductor components that use the Peltier effect to transfer heat from one side of a module to another. The cool side is attached to the electronic device requiring cooling and heat is actively moved away from this side to the hot side of the Peltier module. They can be actively controlled to provide precise temperature regulation and can even cool to below ambient temperature – a feat unattainable using fans and heat sinks alone. The cooling function of a Peltier module is based on semiconductor principles that require no moving parts. This means they are robust, flexible, and less prone to failure. However, being active devices that require external power, they have the disadvantage of adding heat and cost to the overall system. They also use more power than a fan or a standalone heat sink. For these reasons they are not ideal for use in all situations – however, they are useful to meet the cooling requirements of more demanding applications.

Chapter Summary

Electronic devices generate heat, which moves from a hot to a cold region by means of conduction, convection, and radiation. The heat movement of a material is quantified by its thermal impedance. Heat sinks, fans, and Peltier modules are cooling devices commonly used in applications that require temperature control. Cost, size, reliability, power consumption, and noise are the design factors that must be traded off in arriving at the appropriate thermal management solution.

3. THERMAL MANAGEMENT IN PRACTICE

3.1 FANS

For many low power electronic systems, conductive cooling using heat sinks is sufficient. However, for applications exceeding 25 Watts that operate in a confined enclosure, forced air cooling is required to prevent overheating. At its simplest, a fan consists of a rotor that spins on a bearing to displace air, but making the appropriate choice of fan for an application warrants further consideration. In this chapter, we review the principles of fan operation and construction. We will also use a practical example to show how to select the correct type of fan for an application, while considering some additional control features that improve fan performance and reliability.

Fan Types

Fans are categorized by how they draw in and expel air, the two most common types being axial and centrifugal. Axial fans draw in air from one side and expel it in the same plane on the opposite side. In centrifugal fans, the air drawn in is expelled in a different direction. This style of fan, which is also known as a blower, is used to compress air that is output at right angles relative to the input. Axial fans are mainly used in low static pressure systems that require a higher level of airflow, while centrifugal fans produce lower levels of airflow in systems with high static pressure. They also differ in how much audible noise they produce with axial fans being quieter than centrifugal. The amount of audible noise a fan produces is proportional to its airflow, so in applications where this is a concern, careful enclosure design is required to minimize the amount of cooling needed. Apart from audible noise, the dc motor in both types of fan produces electrical noise. This unwanted electromagnetic interference (EMI) can affect the operation of sensitive electronic components but can be effectively suppressed using ferrite beads, shielding, or filtering. The features of each type of fan are summarized in Table 1.

Fan Type	Airflow	Application Type	Noise
Axial	Higher	Low Static Pressure	Quieter
Centrifugal	Lower	High Static Pressure	Louder

Table 1: Summary of fan types

Bearings

When selecting a fan for an application, another important consideration is the type of bearing used in its construction. Sleeve and ball bearings are the most common.

Sleeve bearings (Figure 1) are simpler and lower cost, operating as consistently as ball bearing fans at low temperatures. However, at variable or high temperatures, they can degrade more quickly. This results in wobble, noise, and friction-related issues. These problems are magnified in portable applications, where equipment is operated at different angles.

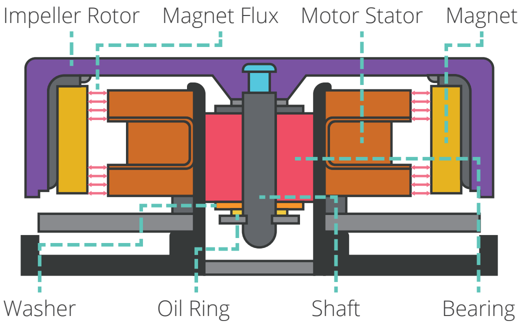


Figure 1: Sleeve bearing

Ball bearings (Figure 2) do not suffer from the problems of uneven wear and friction associated with sleeve bearings, meaning they have a much longer operating life. They can also be operated at any angle, making them suitable for use in portable applications. However, they are less robust (vulnerable to sudden impacts), more complex, and costlier than sleeve bearings.

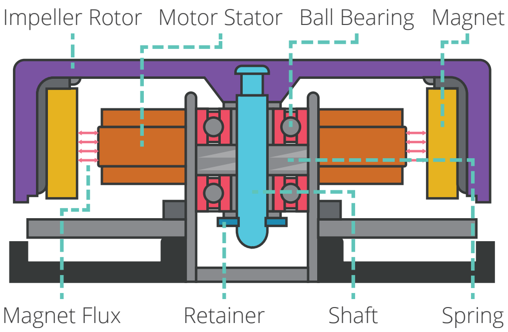


Figure 2: Ball bearing

A third option, developed by CUI Devices, is called the omniCOOL™ system, which promotes extended fan life and performance. Found in our line of advanced sleeve bearing fans, the omniCOOL system incorporates either a magnetic structure (Figure 3) that enables rotor-balancing to minimize tilt, wobble, friction, and allows for operation at any angle, or an enhanced bearing with specialized grooves that improve circulation of lubricant around the shaft. Both technologies lead to a more reliable and cost-effective fan design than traditional bearings.

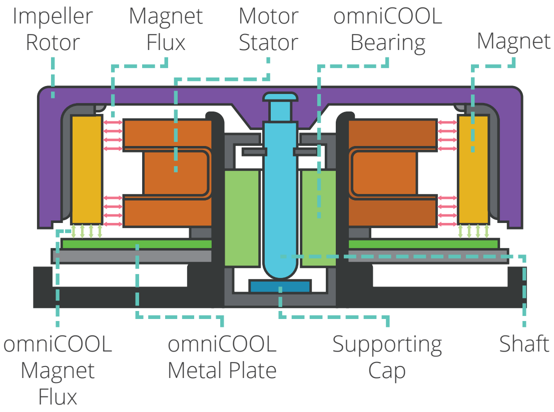


Figure 3: omniCOOL™ System Magnetic Structure

Fan Selection

After weighing the pros and cons of the various bearing types, choosing the most appropriate fan for an application is a multi-step procedure as follows:

System Profiling

The first step is to understand where and how heat is generated in a system. Referred to as "system profiling", data is gathered by placing multiple temperature sensors at different locations around a printed circuit board (PCB), within the system enclosure. It is also necessary to measure the drop in air pressure between the enclosure inlet and outlet (known as the system impedance) before calculating the airflow required from a fan, and hence, the size and type of fan required. This can be done using pressure sensors to measure the pressure drop or by placing the system in an air chamber. For larger applications, such as data centers, system modeling is performed using a computational fluid dynamics (CFD) software package (Figure 4) to provide an accurate profile of the cooling requirements

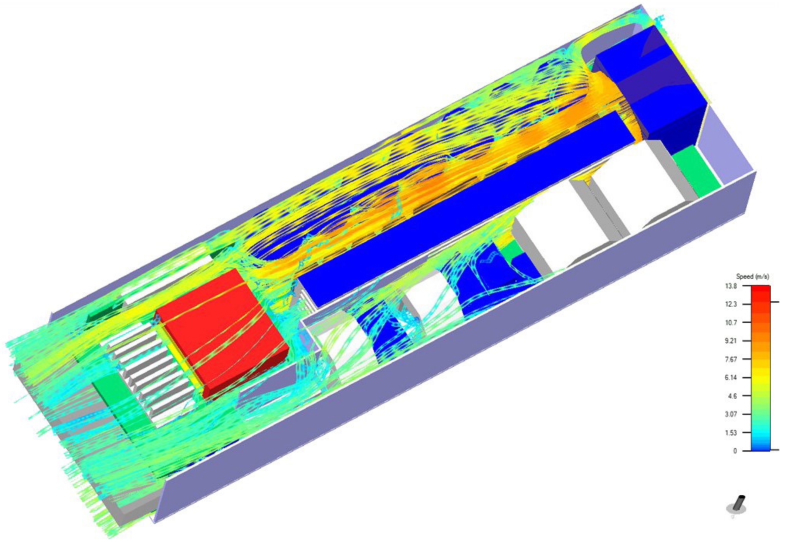


Figure 4: System profiling using CFD software

Setting Temperature Limits

The next step is to determine how much the internal temperature of the system can change without increasing the risk of failure for one or more components. The operating temperature of the "most critical" component sets the maximum allowable ambient temperature, while the total power dissipated in the system is calculated from the cumulative contribution of individual components such as power transistors, microprocessors, amplifiers, and communication interfaces. It is important to know this figure since increased power consumption translates to increased heat dissipation. During system operation, the temperature of the air surrounding the electronic components continues to rise until it reaches a level that inhibits further heat removal. At this point, it becomes necessary to replace the heated air with fresh ambient air using forced air cooling.

Calculating Airflow

Having determined the maximum allowable temperature, the level of airflow required to ensure that the system temperature never exceeds this value must now be calculated. For completeness, the theory underlying these calculations is detailed below, however, CUI Devices provides an online airflow calculator to accelerate this process, by eliminating the need for manual calculations.

Moving air cools a body by absorbing heat and transferring it for dissipation elsewhere. The amount of energy transferred depends on the mass, specific heat capacity, and temperature change of the moving air. The following equation describes this relationship:

$$Q = [q / (\rho * Cp * \Delta T)] * k$$

where:

Q = airflow
q = heat dissipated
ρ = air density
Cp = specific heat capacity of the air
ΔT = temperature rise of the air
k = constant value, dependent upon the units used in the other parameters

The specific heat capacity of dry air is 0.24 Btu/lb °F (1 kJ/kg °C) and the density of dry air at sea level, at 68°F (20°C) is 0.075 lbs/ft3 (1.20 kg/m3). Substituting these values into the above equation simplifies it to:

$$Qf = 1.8q/\Delta TC \text{ (CFM)}$$
$$Qm = 0.05q/\Delta TC \text{ (CMM)}$$

While these equations provide an initial estimate for the required airflow, they assume ideal conditions (i.e. a system with no back pressure and zero system impedance operating at sea level). However, the calculated figure offers a useful starting point for fan selection. Fan manufacturers commonly specify the airflow performance of their products in Cubic Feet per Minute (CFM) or Cubic Meters per Minute (CMM) of airflow delivered versus static pressure. Static pressure is measured in either inches (Inch H_2O) or millimeters of water (mm H_2O). For example, Figure 5 shows the typical airflow vs. static pressure performance curve for a dual ball bearing, 120 mm^2 axial fan (CUI Devices CFM-120 series).

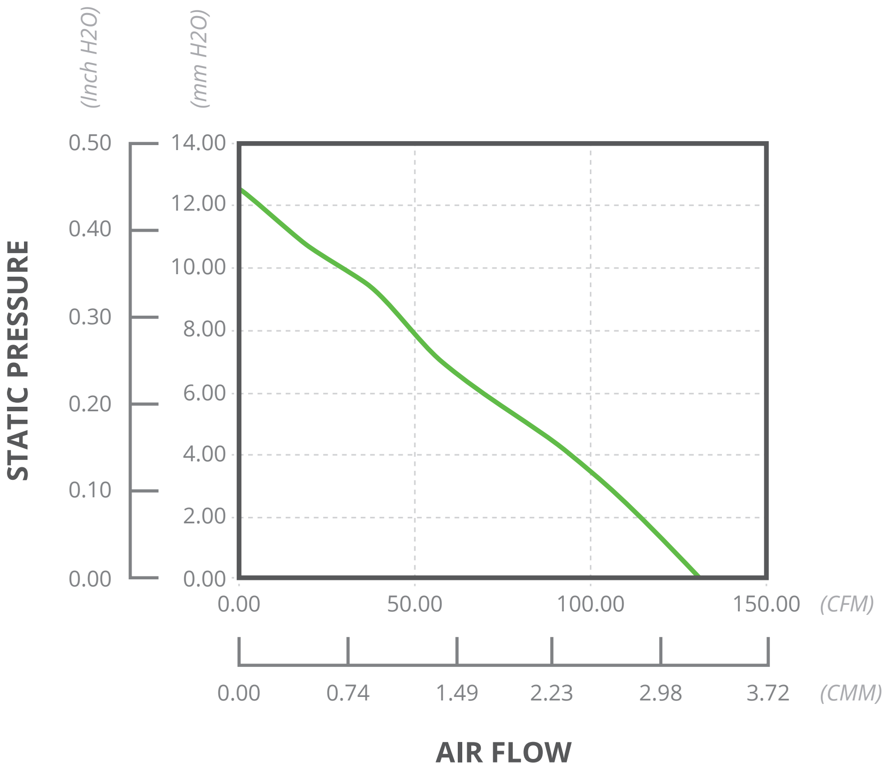


Figure 5: Performance curve of CFM-120 fan

Next, the actual system impedance (previously characterized by system profiling) is overlaid on the fan performance graph and the point at which the curves intersect is the required system operating point (Figure 6).

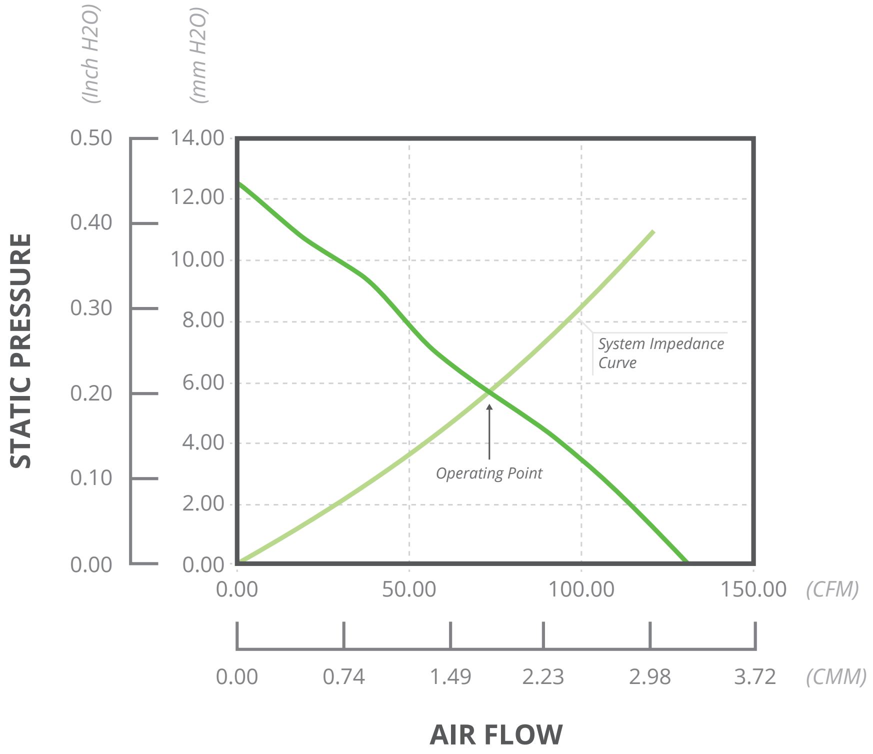


Figure 6: Using system impedance to determine fan operating point

In systems where the airflow cannot be measured, an alternative approach is to specify the fan operating point to be above the idealized figure calculated from the equations. For example, if the required airflow is determined to be 50 CFM (in ideal conditions), a logical approach is to specify a fan with an airflow capacity up to 100 CFM. Operating the fan at 75 CFM provides 50% overhead (enough in most applications) while retaining some spare capacity for increased airflow if operating conditions dictate.

During the design stage, careful board layout and placement of critical components within the enclosure help to minimize system impedance, consequently reducing the power and size of the cooling fan needed. To minimize system impedance, it is critical for air inlets and outlets to be kept free from obstruction while consideration should also be given to the potential impact of air filters. It is also important to note that the density of air falls with altitude. Systems operating above sea level require much more airflow to maintain the same level of cooling. In such applications, it is necessary to revisit the calculations and use the figure for air density at the maximum system operating altitude.

Active Control

Rack-mount enclosures typically use axial fans due to their combination of small size, low power, and high airflow. To help further reduce power consumption, many fans also include additional control features that improve operating efficiency. We have shown how to calculate the minimum airflow rate required to cool a system housed within an enclosure. This allows for the specification of a fan with the capacity to deliver adequate cooling in worst-case conditions (i.e. a system that is constantly operating at full capacity in the most demanding environment). Realistically, this worst-case scenario is unlikely to occur very often, if at all; therefore, continuously operating a fan based on this assumption is inefficient and reduces its operating lifetime.

Consequently, a more practical approach is to monitor the temperature within the enclosure and only switch on a fan when it is required, leaving it switched off when not in use. While this increases the lifespan of the fan and reduces audible noise, it has the potential to introduce the problem of thermal lag (temperature undershoot and overshoot). This can cause another fault condition to occur if a fan is unable to start due to an obstruction. To address this possibility, modern dc axial fans include a standard protection feature called “auto restart”. If the fan motor is prevented from rotating, this feature automatically cuts the supply current driving the motor to prevent burnout.

Rotation detection, which doubles as a lock sensor, is an additional control feature included in some fans. During normal operation, the sensor output signal is set to a logic high, but if the fan motor stops, the signal is driven low. For fans requiring a more sophisticated level of control, a pulse width modulation (PWM) scheme can be used. The duty cycle (on/off ratio) of the PWM input signal determines the rotational speed of the fan, which is measured using a tachometer. The PWM and tachometer signals (Figure 7) are provided as input to a microcontroller which uses an algorithm to continuously adapt fan operation in response to changes in system conditions, further improving operational efficiency.

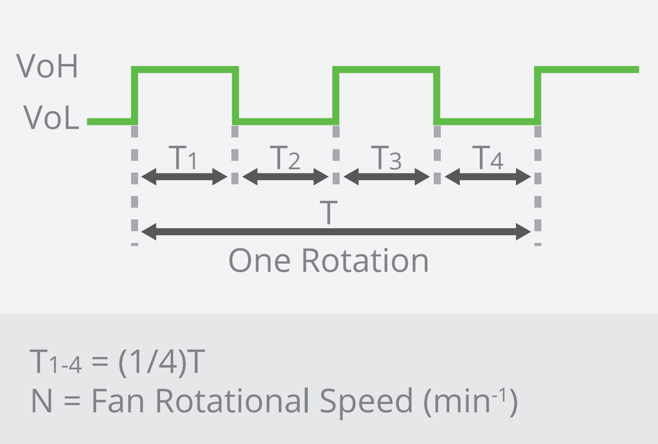


Figure 7: Using a tachometer to detect the rotational speed

CUI Devices Fan Solutions

CUI Devices' provides a portfolio of products that includes dc axial fans and centrifugal blowers with ball bearing, sleeve bearing, and omniCOOL system bearing designs. Auto-restart protection is included as a standard feature on all products while rotation detection, tachometer signal, and PWM control features are optionally available. These fans and blowers have rated speeds between 1500 to 25000 RPM, with noise levels from 10.7 up to 69.9 dBA and static pressures from 0.04 up to 5.22-inch H_2O. Available in frame sizes between 25 mm and 172 mm, they provide airflow levels of up to 382 CFM, making them suitable for use in a multitude of electronic systems that require forced air cooling.

Fan Filters and Guards

An unintentional negative consequence of forced airflow cooling is the potential for increasing the presence of foreign objects and unwanted environmental particles that negatively impact fan and equipment performance. A blocked fan that is prevented from rotating can quickly burn out, leading to system overheating. Fans operating in dusty or polluted environments may require the use of additional filtering and/or guards.

Chapter Summary

As component density increases and enclosures shrink in modern electronic systems, heat sinks cannot always handle the cooling of PCBs alone. Forced air cooling, provided by fans and blowers, is the most common method to prevent overheating. Fans are categorized by airflow direction (axial or centrifugal) as well as bearing type. Selecting the best fan for an application involves system profiling, determining cooling requirements, and performing airflow calculations that can then be used to identify the most appropriate type and size of fan. Additional fan control features are also available that help to increase efficiency and reduce audible noise while maximizing reliability.

3.2. HEAT SINKS

Some electronic systems are simply too small to accommodate a fan for cooling while others cannot economically justify using one. In such scenarios, a heat sink may still be able to provide the required level of cooling. In this chapter, we review the principle operation of heat sinks, show how to determine if one is required, and if so, the steps to follow to select the most appropriate heat sink for a design's specific operating conditions.

Principle of Operation

Heat sinks operate on the basic physical principle that the amount of heat transferred from a hot to a cool region is proportional to the surface area available for heat conduction. They are used to conduct heat away from a critical electronic component so that it always operates within its rated operating temperature range, the safe operating area (SOA). The conducted heat is then removed from the heat sink by natural or forced air convection. While it may be tempting to choose a large heat sink to improve the thermal performance of a system, if a heat sink is comparable in size, or bigger than the component it is intended to protect, its function can become counterproductive. Indeed, some systems may not require any form of additional thermal cooling. In these cases, it is important for circuit designers to determine if a heat sink is required and if so, how to select the smallest heat sink that can provide a safe level of thermal protection, even in worst-case operating conditions.

Do I Need a Heat Sink?

Consider a theoretical application that uses a transistor enclosed in a TO-220 package (Figure 1). Power dissipation caused by switching and other conduction losses are determined to be 2.78 Watts and the maximum expected ambient operating temperature of the application is 50°C. Does this transistor need a heat sink?

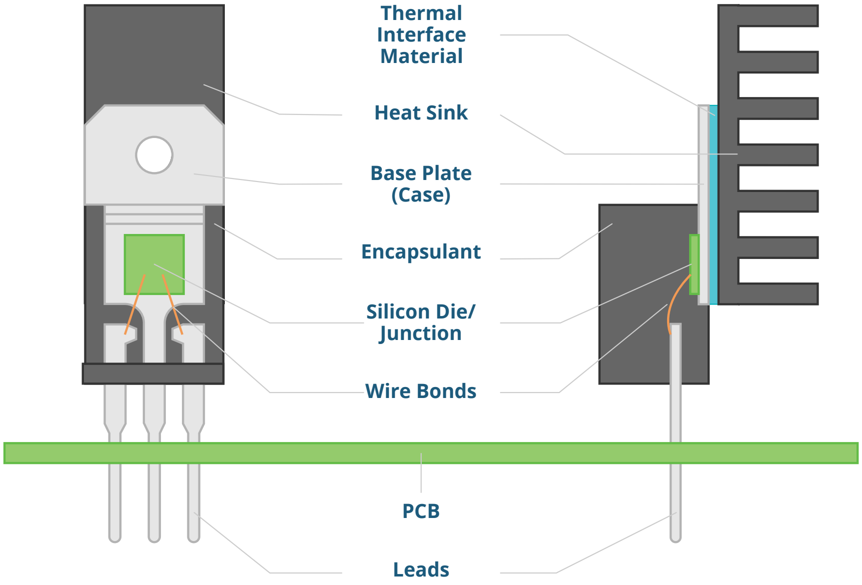


Figure 1: Front and side of a TO-220 packaged transistor with mounted heat sink

Answering this question requires a clear understanding of the thermal impedance pathways that prevent dissipation of the 2.78 Watts of heat into the surrounding air. Transistor datasheets typically specify a “junction-to-ambient” thermal impedance, denoted by the symbol Rθ J-A and expressed in units of °C/W. This figure describes how much the transistor junction temperature climbs above the temperature of the surrounding ambient air, for every Watt of power that the transistor dissipates. For example, the datasheet for the transistor used in this application specifies a junction-to-ambient thermal impedance of 62°C/W. The device dissipates 2.78 W, therefore the rise in junction temperature above the ambient level is:

2.78 W x 62°C = 172°C

The worst-case operating temperature is 50°C. Therefore, the maximum temperature the silicon junction of the transistor will reach is:

50°C + 172°C = 222°C

This figure exceeds the transistor’s rated operating temperature of 125°C and, if achieved, could cause irreversible damage or even destroy the device. Thus, a heat sink is required to sufficiently lower the junction-to-ambient thermal impedance. This will allow heat to be conducted away and maintain the operating temperature of the device within its rated SOA.

Thermal Impedance Calculations

The next step is to determine how low the thermal impedance pathway must be. The highest temperature at which the transistor is specified to safely operate is 125°C and the worst-case ambient temperature is 50°C. Therefore, the largest allowable temperature rise is:

125°C - 50°C = 75°C

The power dissipated by the package is 2.78 W, so the maximum allowable thermal impedance is:

75°C ÷ 2.78 W = 27°C/W

This means that the sum of each component of thermal impedance in the pathway between the silicon junction of the transistor to the surrounding ambient air (Figure 2) must be lower than this value. The individual impedances in this pathway include:

- Junction-to-case
- Case-to-sink
- Sink-to-ambient

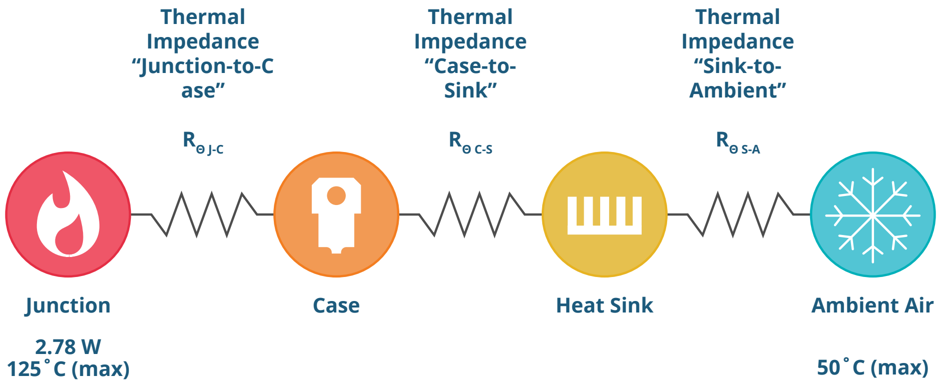


Figure 2: Thermal impedances between the silicon junction of the transistor and ambient air

The “junction-to-case” thermal impedance is denoted by the symbol Rθ J-C and is used to quantify the amount of heat transferred from the silicon junction of the transistor to the surface of the package in which it is housed. Manufacturers typically list this impedance on the device datasheet, alongside the figure for junction-to-ambient impedance. The junction-to-case thermal impedance for the transistor used in this application is specified as 0.5°C/W.

The “case-to-sink” thermal impedance is denoted by the symbol Rθ C-S and is used to quantify the amount of heat transferred from the surface of the device package to the surface of the heat sink. It is important to note that the surface of the TO-220 package is not perfectly smooth (Figure 3), so to ensure that the package and the base of the heat sink are in close thermal contact, it is recommended to use a thermal interface material (TIM), commonly referred to as a “thermal compound” to seal the boundary between them. This enhances heat transfer between the TO-220 case and the heat sink but has the undesirable effect of introducing a small amount of thermal impedance that must also be accounted for in the calculations.

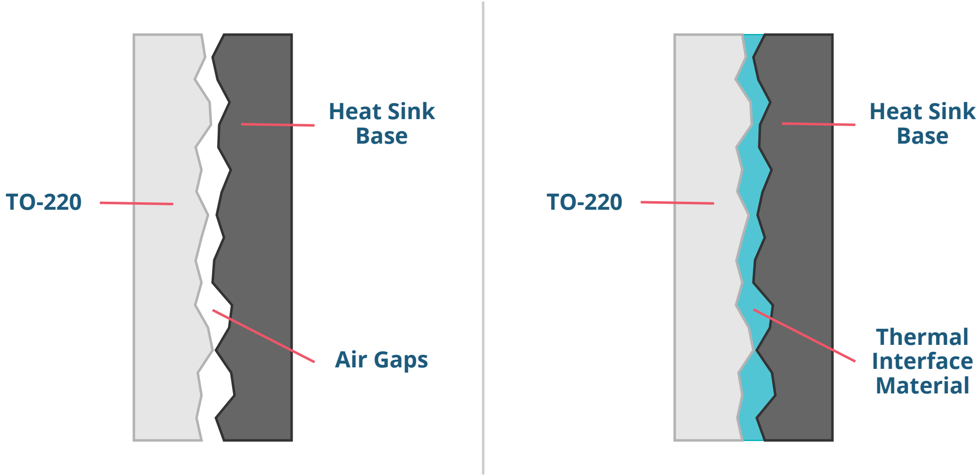


Figure 3: A thermal compound ensures the package and heat sink are in thermal contact

Thermal Impedance of TIM

The conductivity, area, and thickness of application are factors that impact the value of a TIM’s thermal resistance. The value for the conductivity of a TIM is expressed in units of Watts per Meters-Celsius (W/(m °C)). Note that while some datasheets use the Kelvin scale instead of Celsius, this is not significant because 1 unit on the Kelvin scale is equivalent to 1°C and the calculations are only concerned with the relative change in temperature, not absolute values. In this example, a thin layer of the TIM has been applied to the metal tab area of the TO-220 case in the following manner:

TIM’s area of application: = 112 mm2 = 0.000112 m2

TIM’s thickness of application: = 0.04 mm = 0.00004 m

The thermal conductivity of the TIM used in this application is 0.79 W/(m °C) allowing its thermal impedance to be calculated as follows (note that area and thickness are expressed in metric units):

Rθ C-S = (Thickness / Area) / (Conductivity)

Rθ C-S = (0.00004 / 0.000112) / (0.79)

Rθ C-S = 0.45°C/W

Heat Sink Selection

The "sink-to-ambient" thermal impedance, denoted by the symbol Rθ S-A, is the final impedance in the thermal pathway between the silicon junction and the surrounding ambient air. This value is not constant and depends on the ambient airflow and the magnitude of temperature rise. Heat sink manufacturers typically represent this information in a graphical format (Figure 4) to illustrate the amount of heat that can be transferred from the heat sink to the ambient air for different conditions of airflow and changes in temperature.

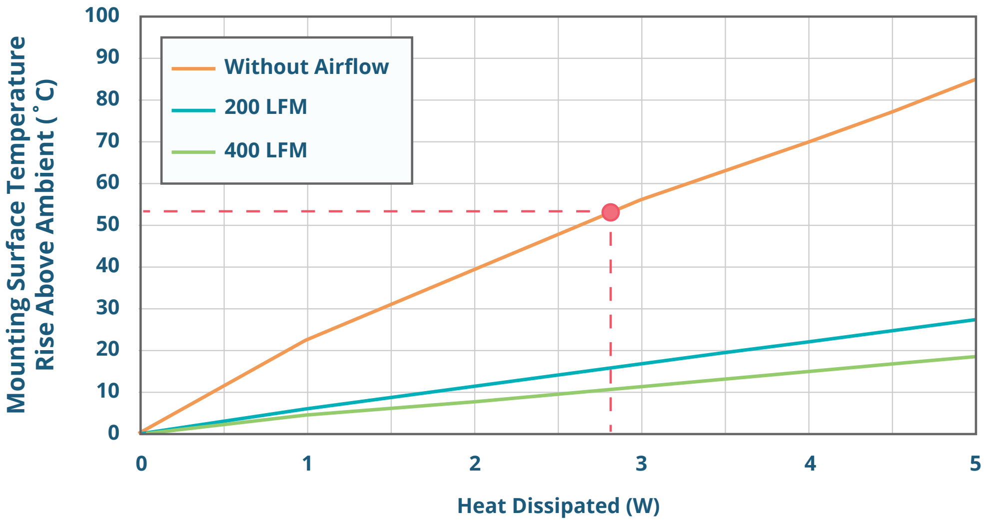


Figure 4: Typical heat sink performance graph

Our example application is assumed to operate in conditions of natural convection without the use of fans to provide additional airflow. This graph allows the calculation of the final thermal impedance (sink-to-ambient) for the required heat sink. The rise in surface temperature (above ambient) and the amount of heat dissipated are used to determine the thermal impedance at the required operating point as follows:

Heat dissipated = 2.78 W

Rise in surface temperature = 53°C.

Sink-to-ambient thermal impedance = 53°C / 2.78 W = 19.1°C/W.

From previous calculations, the maximum impedance allowed between the junction and ambient air is 27°C/W i.e.

Rθ J-C + Rθ C-S + Rθ S-A = 27°C/W

From previous calculations, Rθ J-C = 0.5°C/W and Rθ C-S = 0.45°C/W

Hence

Rθ S-A = 27°C/W - 0.5°C/W - 0.45°C/W = 26.05°C/W

The thermal impedance of 19.1°C/W taken from the heat sink data presented in Figure 4 is well below this value. This ensures an even cooler silicon junction temperature within the TO-220 package and provides extra margin in the thermal design. The maximum junction operating temperature of the junction is estimated as follows:

$$T\ \text{ambient} + \text{Watts} \times (R\theta\ J\text{-}C + R\theta\ C\text{-}S + R\theta\ S\text{-}A) = 50 + 2.78 \times (0.5 + 0.45 + 19.1) = 105.7°C$$

Heat Sink Types

Extruded heat sinks are usually made from aluminum. They are easy to manufacture to custom specifications, with low or high performance, at a relatively low cost. Their main drawback is that their minimum and maximum dimensions are determined by the extrusion widths used in the manufacturing process. BGA heat sinks are another type of simple extrusion where the extruded fins have been crosscut into pins, making them suitable for ball grid array applications.

Stamped heat sinks are usually made from copper or aluminum and have metal fins that are stamped and soldered onto a metal base. These are mainly used in low-power applications. Their main advantage is that they are easy to manufacture, making them low cost but they exhibit lower thermal performance.

CUI Devices provides a range of board level and BGA heat sinks in a variety of shapes and sizes. They are compatible with multiple package types, including the TO-218, TO-220, TO-252, TO-263, and BGA. Manufactured in either aluminum or copper, their thermal resistance is measured under four different conditions. This simplifies the process of selecting the heat sink most appropriate for a natural convection or forced air cooled system.

Clips and Fasteners

It is important that heat sinks always remain securely attached to the component they are being used to cool. In the event of a heat sink becoming loose and detached, a component can quickly overheat, causing damage to or destroying equipment. To prevent this from happening, it is important to use a fastener or clip that matches the form factor of the selected heat sink.

Chapter Summary

Heat sinks are a simple but highly effective thermal management tool, operating on the straightforward physical principle that increased surface area allows for greater conduction of heat away from critical electronic components. They ensure that these parts operate within their rated temperature range, even at worst-case conditions. It is important for circuit designers to be able to calculate if an application requires a heat sink and if so, the minimum size of heat sink needed. This requires an understanding of the contributions to the total thermal impedance between a silicon junction and the surrounding ambient air, a knowledge of the function and nature of the role of TIMs, and the ability to interpret and apply the multiple parameters specified in the datasheets provided by heat sink manufacturers.

3.3. PELTIER MODULES

In some closed electronic systems with no vents, forced air convection using fans is not a viable cooling option. For these systems, thermoelectric cooling modules provide an alternative thermal management solution. In this chapter, we describe the structure and operation of the Peltier thermoelectric module and the benefits it provides. We also explain the procedure to follow when selecting a module to meet the thermal specification for an application, while discussing the features of an innovative construction method that greatly improves module reliability and thermal performance.

What is a Peltier Thermoelectric Module?

The thermocouple operates on the physical principle, discovered by Thomas Seebeck in the 19th century, that a flow of electrical current occurs when a temperature difference exists between two electrical conductors made from different materials. The magnitude of the current flow is proportional to the temperature difference, allowing a temperature scale to be calibrated. The less acclaimed Peltier effect (named after scientist Jean Peltier who later discovered it) is simply the consequence of the Seebeck effect, whereby the application of an electrical current to two different conducting materials causes the movement of heat between them. This discovery had little practical application until the development of semiconductors in the 20th century allowed small, efficient Peltier modules to be manufactured.

A Peltier thermoelectric module consists of P-type and N-Type Bismuth Telluride semiconductor pellets. These are separated by ceramic substrates which are metalized to allow the conduction of heat from the "cool" to the "hot" side of the module when connected to a dc voltage source. Within the module, the pellets are connected electrically in series, but they combine to transfer heat in a parallel manner (Figure 1).

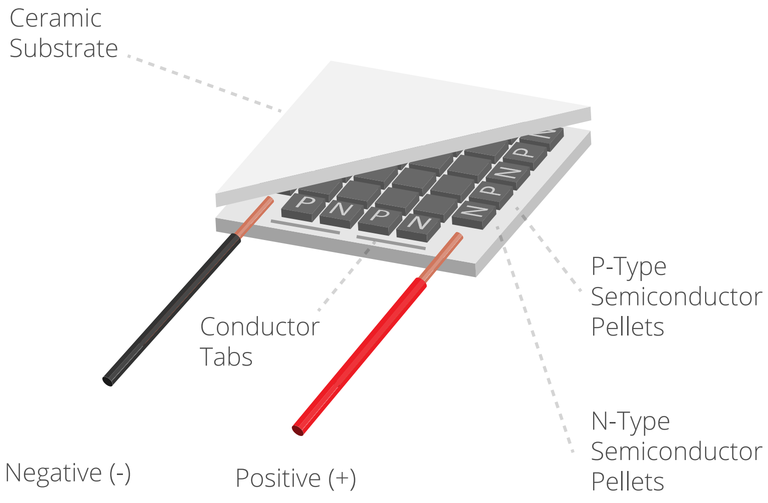


Figure 1: The structure of a Peltier module illustrating multiple semiconductor pellets

The application of a dc voltage causes a flow of positive and negative charge carriers in opposite directions within the module, moving heat from the "cool" side, and transferring it to the surface of the opposite "hot" side to be released (Figure 2). The polarity of the voltage source determines the direction of heat flow, allowing cooling to take place on either side of the module, as required.

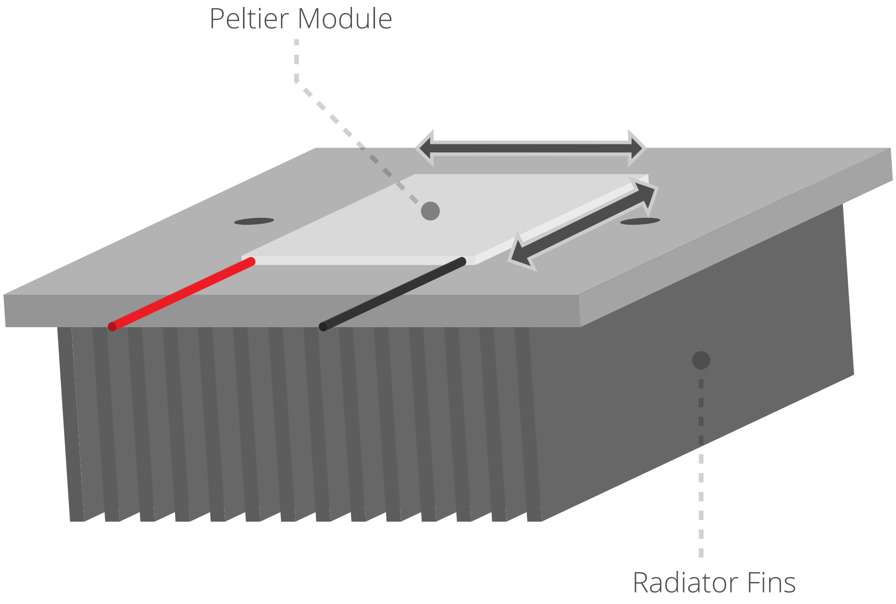


Figure 2:
Flow of charge carriers causing heat transfer in N-Type and P-type Bismuth Telluride semi-conductor

Benefits

Apart from providing a viable cooling solution in closed systems, Peltier modules provide several other advantages. They allow the temperature to be set precisely and changed quickly. Each module design has a defined voltage/temperature profile that allows the amount of heat absorption to be easily calculated. When combined with a feedback control circuit, tight temperature control (to within fractions of a degree) is possible.

They are very light and space-efficient (modules with a height profile as low as 1.95 mm are available) making them ideal for small form factor, portable applications. Constructed from solid-state semiconductor material with no moving parts makes them highly robust, with an operating lifetime of up to 100,000 hours when maintaining a constant temperature difference. This is significantly longer than fans, which are constructed using bearings that are prone to failure due to mechanical wear.

The other major advantage of Peltier modules over other thermal management solutions is that they provide the ability to cool an electronic component to below ambient temperature, a feat that is not possible using fans or standalone heat sinks. Unlike refrigerants, they do not use gases that damage the environment. Finally, by simply changing the direction of current flow, they can be used to pump heat into an application if required and they can even be used to generate electricity from processes producing waste heat.

Selecting a Peltier Module

There are several factors to consider when selecting a Peltier module to provide cooling for an application.

Understanding Heat Transfer

For a Peltier module, heat transfer is denoted by the symbol Q and specified in Watts. This figure represents the heat generated by the body to be cooled and also represents the amount of heat the module transfers to the ambient environment. It is important to note that a Peltier module does not absorb heat, it merely transfers heat from the cool to the hot side, from where it is then dissipated.

Temperature Difference

The temperature difference (denoted as ΔT) specified on a Peltier module's datasheet is measured on the outside surface of the module's two ceramic plates. However, during the design process, it is also important to consider any difference in temperature that exists between the surface plates of the module and other areas in the cooling system. There are five regions in which differences in temperature can occur (Figure 3).

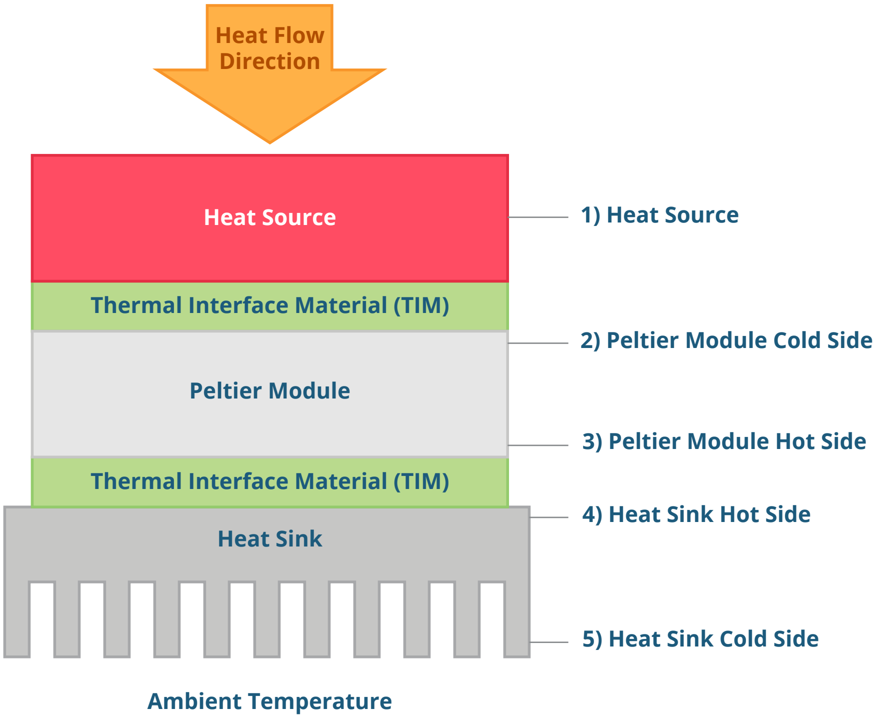


Figure 3:
Five regions of temperature variation in a cooling system

Temperature of Hot Side

The performance characteristics of a Peltier module change in response to its operating temperature. The datasheet may specify module performance at several discrete operating temperatures (e.g., 27°C and 50°C). For systems operating at other temperatures, use the data for the closest temperature specified on the datasheet.

Surface Area

If the surface area of the Peltier module does not exactly match the surface area of the body being cooled, then a low thermal impedance "heat spreader" (Figure 4) can be used to maximize the heat transfer of the module. These are typically manufactured from aluminum or copper.

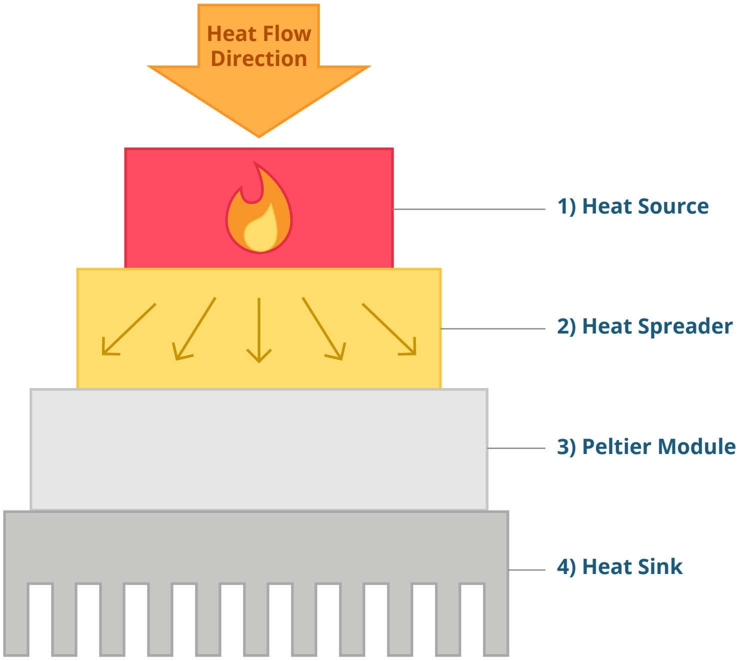


Figure 4: Using a heat spreader to maximize heat transfer

Operating Current

It is easier to control the temperature change provided by a Peltier module using a current source, rather than a voltage source. For this reason, the operating current is specified on the datasheet for a module.

Operating Voltage

The range of voltage over which a current source operates is referred to as its “compliance” and is also typically included on a module datasheet.

System Specifications

The following are the specifications for an example application that requires cooling:

Module Heat transfer: 20 W

Module temperature difference: 20°C

Hot side of module: 30°C

Surface area of the body to be cooled: 30 mm x 30 mm

The performance curves for the CP603315H Peltier module, which is proposed for use in this application is shown in Figure 5

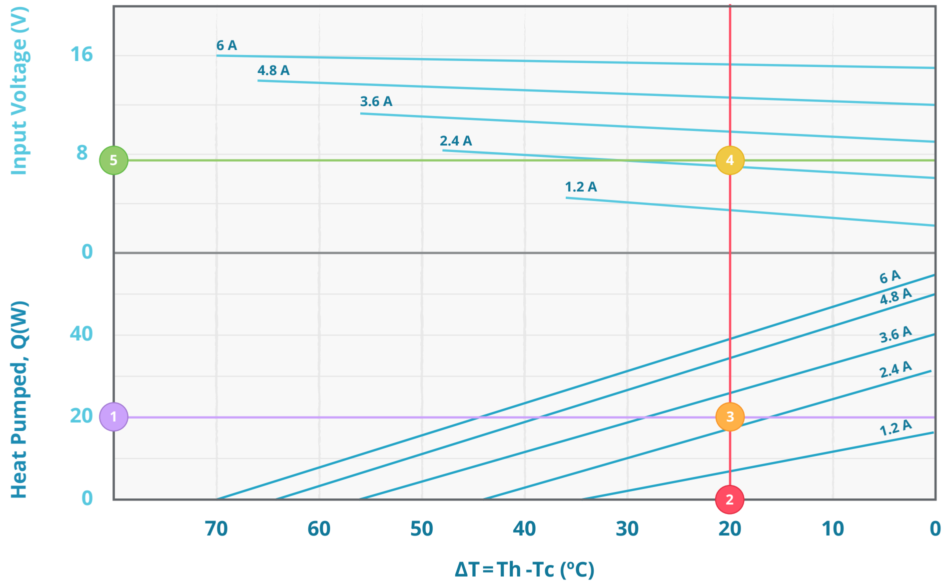


Figure 5: Performance characteristics of CP603315H module

Although it may initially appear to be a single graph, it contains two separate scales:

—the upper half specifies input voltage (V) on the y-axis, versus temperature change (ΔT) on the x-axis. The corresponding curves of the module's operating current also appear on this graph with values between 1.2 A and 6 A.

—the lower half specifies heat transfer (Q) in Watts on the y-axis versus temperature change (ΔT) on the x-axis. This graph also contains the same operating current curves from 1.2 A to 6 A.

The design procedure is as follows:

1. On the lower graph, draw a horizontal line from 20 W on the y-axis, since this is the specified amount of heat that the module must transfer. This is indicated by the purple line.

2. Next, also on the lower graph, draw a vertical line from 20°C on the x-axis, since this is the specified temperature differential that exists across the module. This is indicated by the red line, which extends to intersect with the upper graph.

3. Estimate the required operating current for the module by interpolating the value of the operating current at the point where the purple and red lines intersect. This point lies between the 2.4 A and 3.6 A operating current curves and is indicated in orange at 2.7 A.

4. In the upper half of the graph, mark the point where the red vertical line intersects with an operating current of 2.7 A. Interpolate between the 2.4 A and 3.6 A curves to estimate the location of 2.7 A on the graph.

5. From this point, draw a horizontal line. The point of intersection between this line and the y-axis of the upper graph is the required input voltage to meet the compliance requirement of the 2.7 A current source. In this case, the required input voltage is 7.5 V.

It is important to note that a Peltier module consumes power while transferring heat from the cold to the hot side. The power consumed is described by the following equation:

Power (W) = Voltage (V) * Current (A)

In this example application, the power consumed by the module is 20.25 W (7.5 V x 2.7 A). This also appears as heat, meaning the total heat that must be dissipated by a heat sink at the hot side of the module is 40.25 W (20 + 20.25).

Dynamic Voltage Control

In the previous application, the Peltier module delivered a constant level of cooling, for a fixed temperature difference between its hot and cold sides, which required a fixed control voltage. In some applications, the temperature of the cool side must remain constant even though the temperature of the hot side may change. This requires adapting the control voltage to deliver the required amount of cooling in response to the temperature difference at a given point in time. These applications use a thermal sensor to continuously monitor the temperature of the body being cooled. A thermocouple, an infra-red sensor, or a solid-state temperature sensor provide a choice of options to perform this task.

Using a feedback control loop, temperature readings of the cool side are compared to the desired temperature setting and the control voltage on the Peltier module is dynamically increased or decreased to respond to any difference. Control loops typically use a Pulse Width Modulation (PWM) scheme to adjust the voltage controlling the module (Figure 6). An external PWM controller is required because the output voltage of many power supplies is not adjustable over a large range. The output of the PWM stage also requires additional filtering, to ensure that the ripple on the module control voltage does not exceed 5%. This is important, as larger ripple voltages reduce the performance of the module and induce electrical noise in the body being cooled. Noise is undesirable as it is detrimental to the performance of many electronic components. Thankfully, the design of the thermal control loop is not overly demanding as temperature changes occur slowly, so a fast loop response time is not necessary. However, the design must be able to accommodate changes in the polarity of the control voltage, if the system is needed to both cool and heat the object.

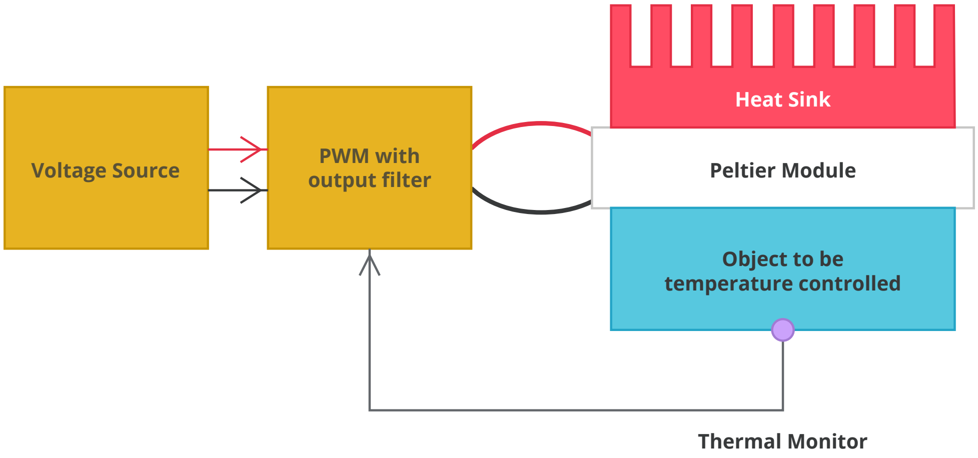


Figure 6: Using a PWM stage to control the voltage of a Peltier module

Improving Reliability of Peltier Modules

Thermal fatigue is a common failure mechanism in many conventionally manufactured thermo-electric modules. This weakens the solder bonds between the copper electrical interconnects and the P/N semiconducting materials. It also impacts the solder and sinter bonds between the metal interconnect and the ceramic substrate (Figure 7). These bonding techniques have the advantage of creating strong mechanical, thermal, and electrical bonds. However, they suffer from the disadvantage of being inflexible, which means, after repeated heating and cooling cycles, their performance degrades slowly and leads to eventual failure.

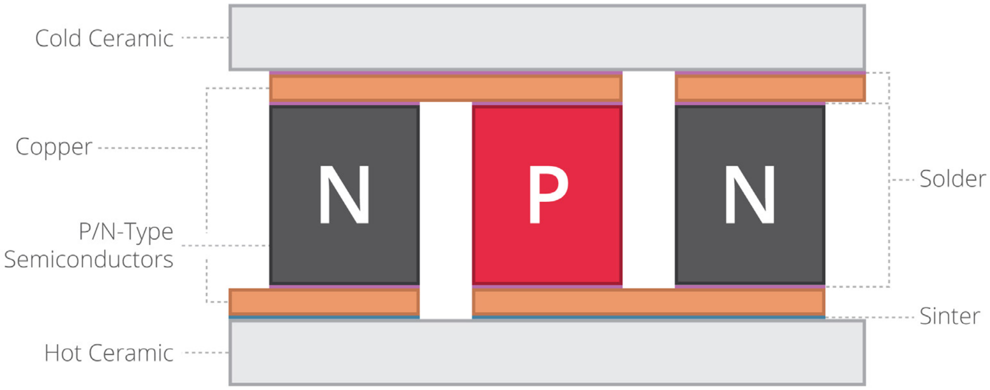


Figure 7: Conventionally manufactured Peltier module

An alternative Peltier module construction technique, the arcTEC™ structure (Figure 8), developed by CUI Devices, is designed to mitigate the negative effects of thermal fatigue. In this structure, a thermally conductive resin replaces the solder bond between the ceramic substrate and the copper electrical interconnect. This resin has elastic properties that allow the bond to expand and contract in response to heating and cooling. This creates a better thermal connection while lowering the stress on the mechanical bond, meaning its performance does not degrade over time.

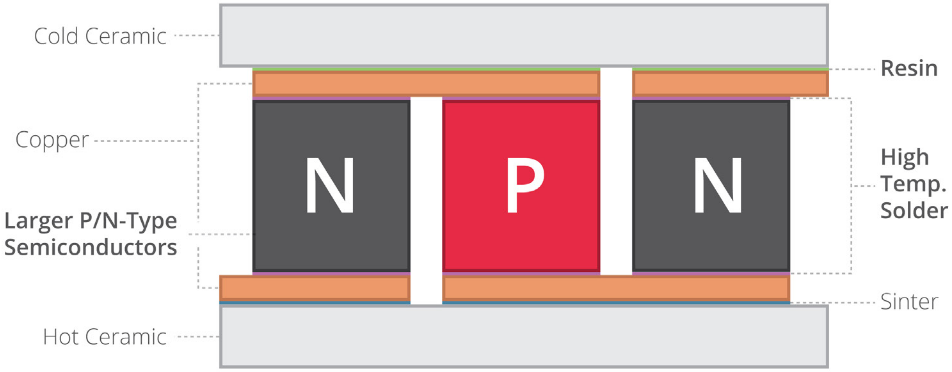


Figure 8: CUI Devices' thermoelectric module with arcTEC structure

Another important feature of this structure is that it uses a different type of solder, SbSn (Antimony/Tin), compared to the BiSn (Bismuth/Tin) solder normally used when joining P/N semiconductors to copper interconnects. This has a much higher melting point of 235°C, compared to 138°C for BiSn, which provides it with better shear strength and higher resistance to thermal fatigue (Figure 9).

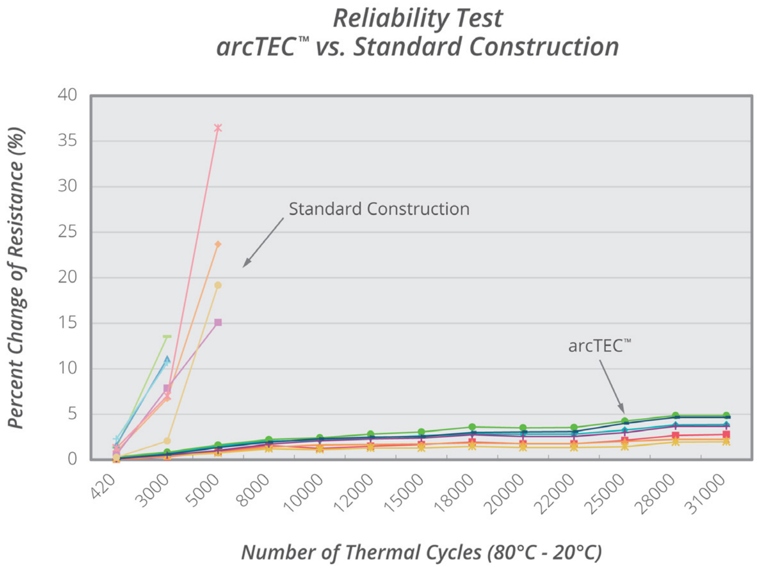


Figure 9: Improved reliability of arcTEC structure vs standard construction

Apart from improved reliability, thermoelectric modules built using the arcTEC structure provide better thermal performance (Figure 10) than modules built using conventional construction methods (Figure 11). This is because the P/N semiconductors are made from blocks of silicon that are up to 2.7 times bigger than those normally used in other products. Larger blocks of silicon allow for faster, more uniform cooling across the surface of the ceramic substrate than conventional modules.

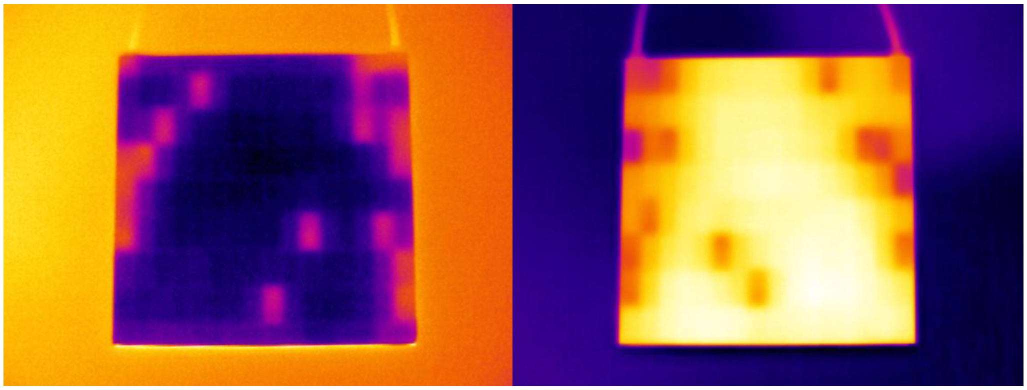


Figure 10: Thermal image showing surface heat distribution for a conventional Peltier module

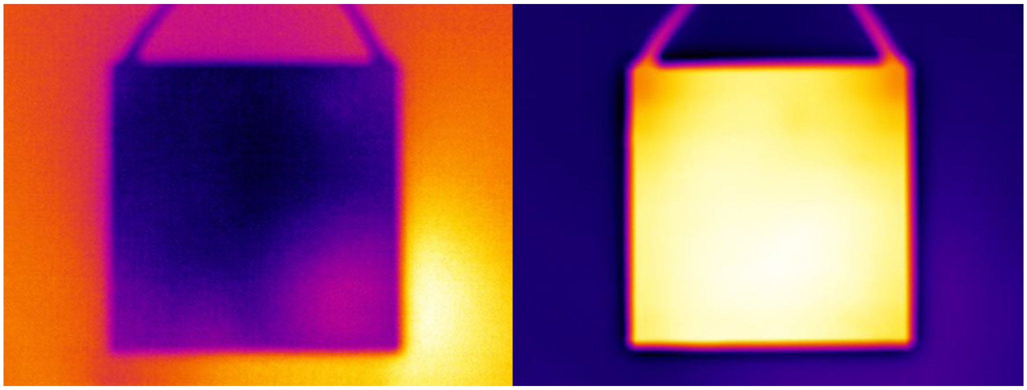


Figure 11: IR image showing heat distribution across the surface of module constructed using arcTEC structure

Thermal Pads

Composite cooling solutions that combine the use of heat sinks and Peltier modules can benefit from the use of a thermal pad. These have high thermal conductivity, are shaped to fit the profile of the thermoelectric module and help to reduce the thermal impedance at the interface between the cooler and the heat sink.

Chapter Summary

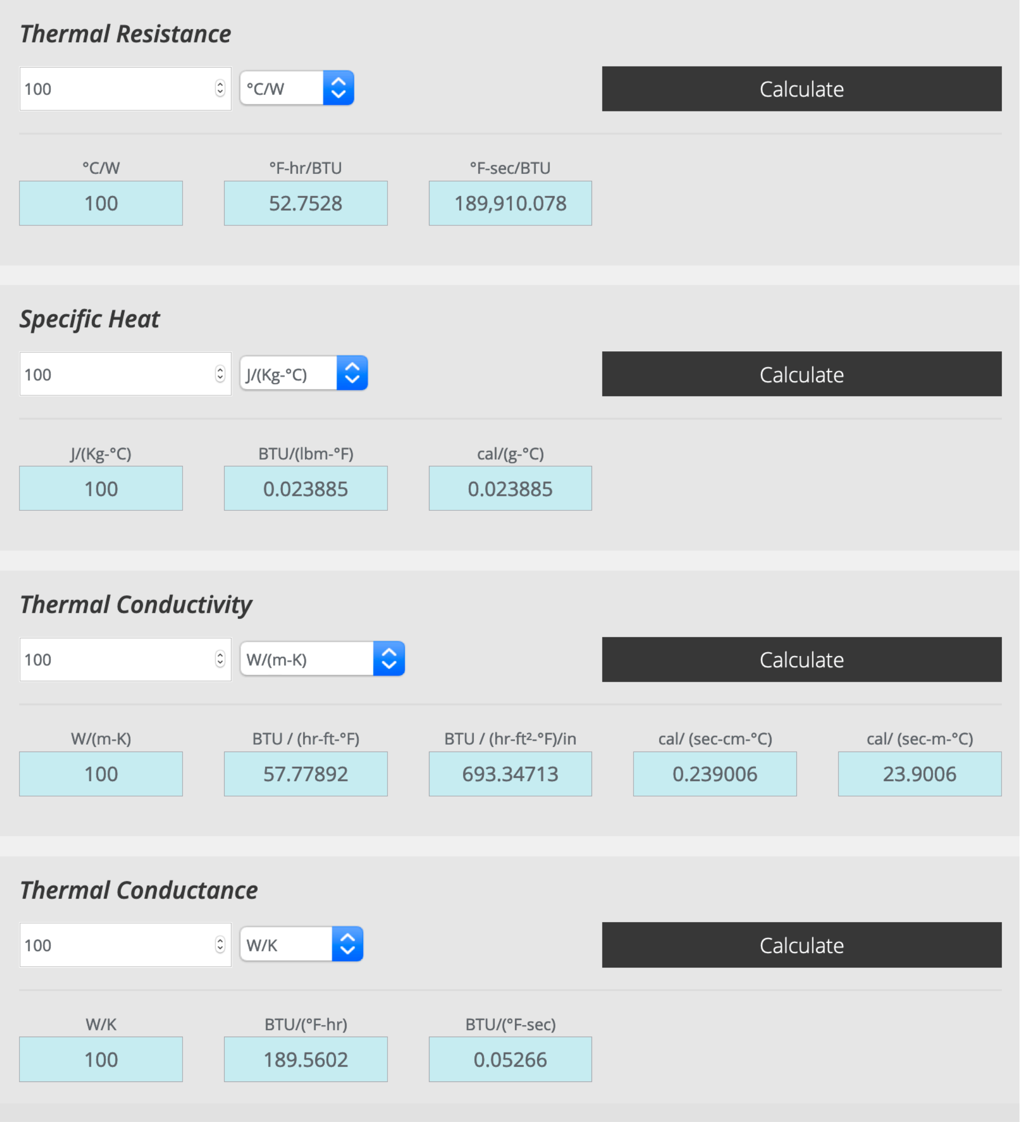
Systems housed in small, sealed environments cannot use forced-air cooling solutions. For these applications, the Peltier module provides a viable alternative. Using an electrical current to transfer heat from its cool side to be dissipated on its hot side, a thermoelectric module has several benefits including a small form factor, precise temperature control, the ability to cool below ambient, and a longer lifespan than fans as it has no moving parts. Determining the control voltage and operating current needed to achieve a certain level of cooling requires an understanding of parameters specified on Peltier module datasheets. Systems that experience continuous temperature variation require the use of feedback control systems to dynamically adjust module cooling. Lastly, the repeated heating and cooling experienced by Peltier modules can cause thermal stress that reduces the lifespan of conventional devices. Thankfully, CUI Devices' arcTEC structure allows for the construction of Peltier modules that exhibit greater reliability, longer life cycles, and more even heat distribution to provide a superior cooling solution.

4. ONLINE CALCULATION TOOLS

The task of designing a suitable thermal management system can be demanding and time-consuming, requiring multiple mathematical calculations. Specifying a fan requires equations that involve the velocity and volume of airflow, while specifying a heat sink uses equations where thermal resistance, temperature, and power dissipation are variables. The task is further complicated by the fact that the variables can be specified in different units of measurement by an application user. To simplify this task, CUI Devices has developed several online calculation tools to assist designers in quickly and accurately specifying the exact cooling requirement of a system. CUI Devices' full suite of calculators can be accessed via the Resource Library.

Thermal Conversion Calculator

A thermal conversion calculator converts between regularly used units for thermal resistance, specific heat, thermal conductivity, and thermal conductance (Figure 1). Enter the value to be converted into the white box, then click the "Calculate" button to see the equivalent values in other scales.



Thermal Resistance

100 °C/W

°C/W	°F-hr/BTU	°F-sec/BTU
100	52.7528	189,910.078

Specific Heat

100 J/(Kg-°C)

J/(Kg-°C)	BTU/(lbm-°F)	cal/(g-°C)
100	0.023885	0.023885

Thermal Conductivity

100 W/(m-K)

W/(m-K)	BTU / (hr-ft-°F)	BTU / (hr-ft^2-°F)/in	cal/ (sec-cm-°C)	cal/ (sec-m-°C)
100	57.77892	693.34713	0.239006	23.9006

Thermal Conductance

100 W/K

W/K	BTU/(°F-hr)	BTU/(°F-sec)
100	189.5602	0.05266

Figure 1: Online thermal conversion calculator

Heat Sink Calculator

This online resource consists of three calculator tools that greatly accelerate the process of heat sink selection.

Thermal Impedance (Sink-to-Ambient) Calculator

Input the values for junction temperature (TJ) in °C, power dissipated (P) in Watts, thermal impedance junction-to-case (RJ-C) and case-to-sink (RC-S) in °C/Watt, and ambient temperature (TA) in °C, then click on “Calculate” to quickly determine the thermal impedance sink-to-ambient (RS-A) in °C/W (Figure 2).

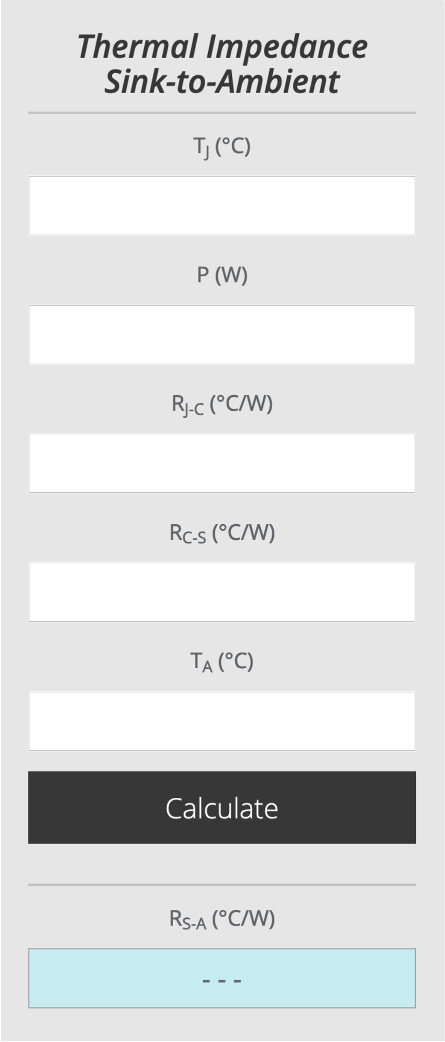


Figure 2: Thermal impedance sink-to-ambient calculator

Junction Temperature Calculator

Input the values for power dissipated (P) in Watts, thermal impedance junction-to-case (RJ-C), case-to-sink (RC-S), and sink-to-ambient (RS-A) in °C/W, and ambient temperature (TA) in °C, then click on “Calculate” to quickly determine the junction temperature (TJ) in °C (Figure 3).

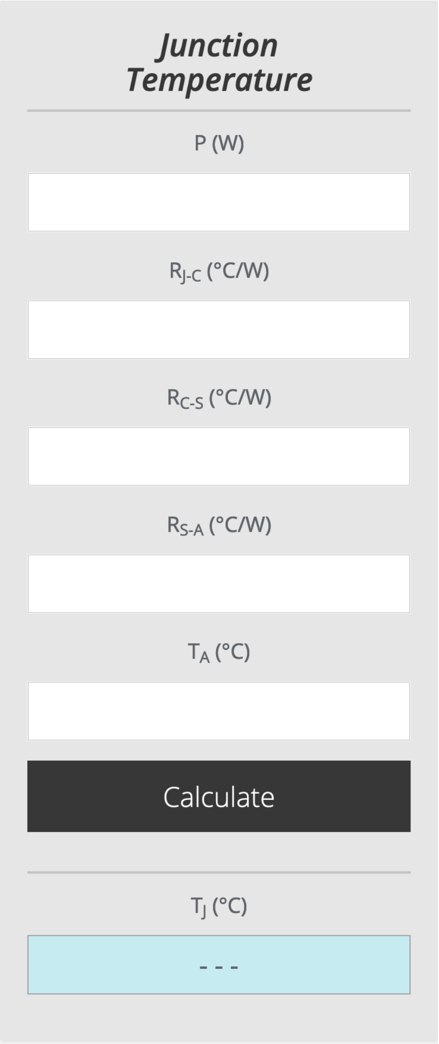


Figure 3: Junction temperature calculator

Power Dissipated Calculator

Input the values for junction temperature(TJ) in °C, thermal impedance junction-to-case (RJ-C), case-to-sink (RC-S), and sink-to-ambient (RS-A) in °C/W, and ambient temperature (TA) in °C, then click on “Calculate” to quickly determine the power dissipated (P) in Watts (Figure 4).

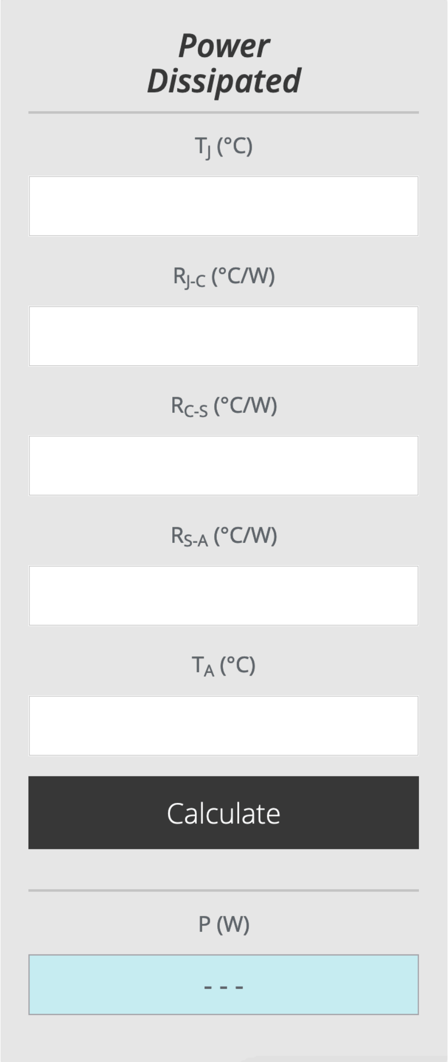
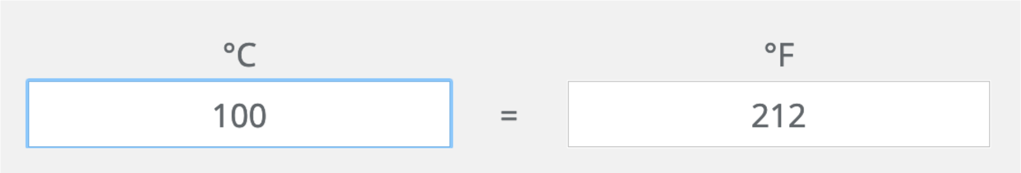


Figure 4: Power dissipated calculator

A convenient Celsius to Fahrenheit calculator is also included (Figure 5).



°C 100 = °F 212

Figure 5: Celsius to Fahrenheit calculator

Airflow Conversion Calculator

Use this calculator to calculate the airflow in a duct of a defined shape or volume. Simply enter the value for air velocity (or volume) and the dimensions (or volume) of the duct in your preferred choice of units, then click "Calculate" to see the velocity and volume of airflow in a variety of other measurement units.

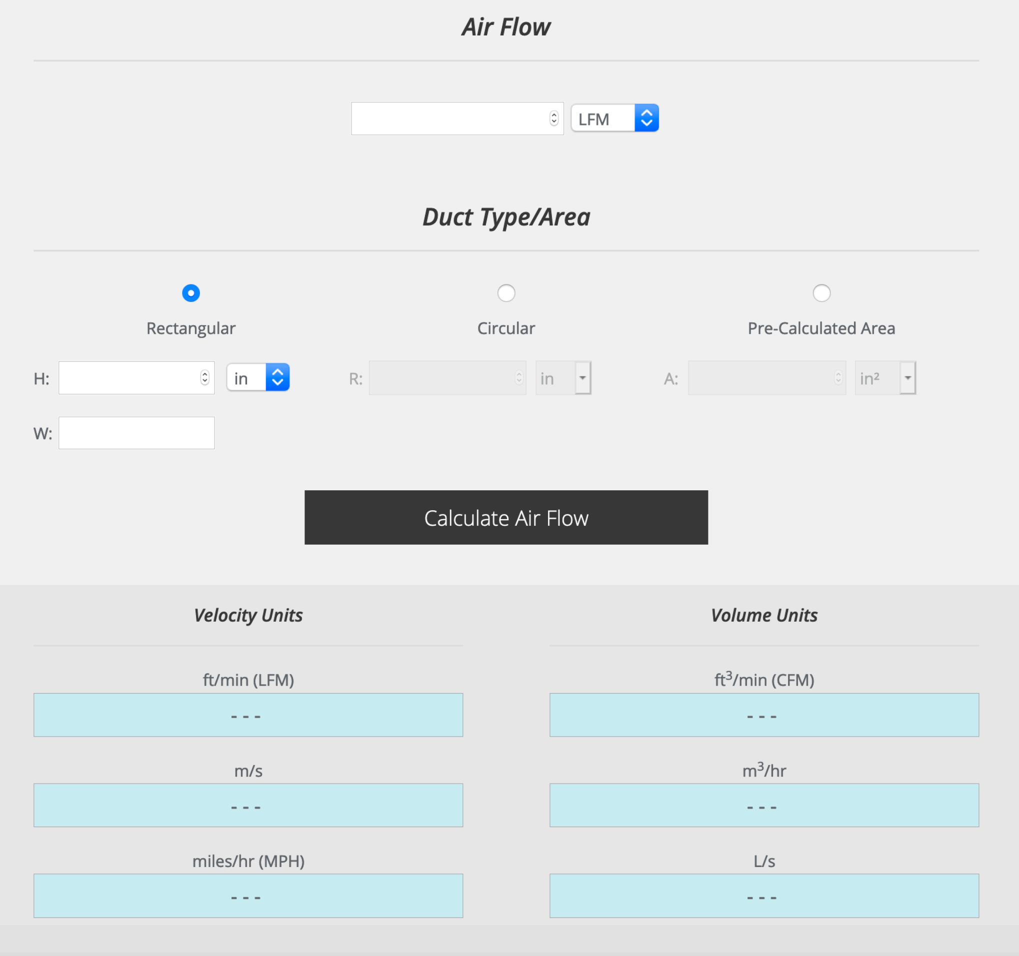


Figure 6: Airflow conversion calculator

GLOSSARY

Active	A cooling device that uses an additional external power source is called an active device.
Axial Fan	A fan that causes air to flow parallel to the shaft about which the blades rotate.
Bearing	The supporting part of a structure that is usually designed to allow the structure to move freely.
Centrifugal Fan	A fan (also referred to as a blower) that outputs air at 90 degrees to the input.
Conduction	The flow of heat from a hot to a cold region within a body without movement of the material within the body. Metals are good conductors of heat.
Convection	The flow of heat from a hot to a cold region within a fluid (liquid or gas) by the movement of molecules within the fluid.
Extrusion	A manufacturing process that creates a device with a defined cross-sectional profile.
Fan	An active cooling device with blades attached to a rotor used for forced-air convection cooling.
Heat Sink	A passive component with a low thermal impedance that conducts heat away from a hot electronic component, to be subsequently removed by natural or forced convection.
Impeller	A rotor that increases the pressure and flow of a fluid.
Junction Temperature	The highest specified operating temperature of an electronic component.
Magnetic Flux	The magnitude of a magnetic field per unit area.
Passive	A cooling device that does not require an additional external power supply is called a passive device (e.g., heat sink).
Peltier Module	An active cooling device that converts electrical energy into thermal energy for cooling purposes.
Power Dissipation	The process by which heat is produced as an unwanted consequence of the flow of electric current.
PWM	Pulse width modulation. A modulation scheme that uses the on/off time ratio of a pulsed electrical signal to control the speed of rotation of a motor.
Radiation	The flow of heat from a hot to a cold region by the emission of electro magnetic waves. Unlike conduction or convection, no medium is required. Radiation is the least efficient cooling mechanism.

Stamping	A manufacturing process to press metal into a variety of different shapes (e.g., heat sinks).
Specific Heat	The amount of energy required to raise the temperature of a substance by 1 degree.
Tachometer	A device that measures the speed of a rotating shaft.
Thermocouple	A thermoelectric device that converts heat energy into electrical energy, allowing the temperature to be measured.
Thermoelectric	The conversion of heat energy into electrical energy and vice versa.
Thermal Conductivity	The ability of a material to conduct heat, measured in Watts per meter Kelvin.
Thermal Impedance	The sum of the thermal resistance of a material and that of its thermal contacts.
Thermal Resistance	The ability of a material to resist the flow of heat. Good conductors have low thermal impedance while insulators have high thermal impedance, measure in degrees Kelvin per Watt.
TIM	Thermal interface material also referred to as a thermal compound. A substance used to create a close thermal connection between two bodies by eliminating air gaps between them.

DEFEAT HEAT WITH THERMAL MANAGEMENT PARTS FROM CUI DEVICES

CUI Devices provides a comprehensive portfolio of cooling products that can be used as standalone components or as a part of a comprehensive thermal management solution. We also offer custom solutions to address the cooling requirements of systems with unique temperature specifications and provides a library of useful engineering resources.

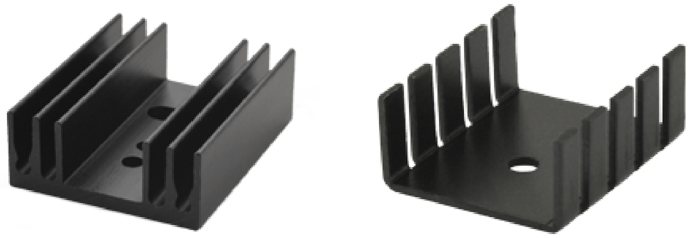
Axial Fans

CUI Devices provides a wide variety of axial fans. For maximum application flexibility, they are available in multiple constructions, including standard ball and sleeve bearing as well as CUI Devices' proprietary omniCOOL™ system bearing design that greatly improves reliability while reducing fan noise. With frame sizes ranging from 25 mm to 172 mm and airflow volumes between 1.35 CFM to 382 CFM, cooling options are available for all types of electronic systems, from those housed in space-limited enclosures to those with the most demanding cooling requirements. All of the most commonly used centrical supply voltages are catered for (5, 12, 24, and 48 Vdc). For applications requiring higher levels of safety and control, the portfolio also includes models with tachometer signal, rotation detector, and PWM control, while all include auto restart as standard. These products are ideal for use in telecommunications equipment, medical devices, industrial applications, and general-purpose IT products.

Centrifugal Fans (Blowers)

CUI Devices offers several centrifugal blowers in frame sizes ranging from 40 mm to 120 mm. Designed to meet the more demanding cooling requirements of industrial and telecommunications equipment, models that operate from 12 V or 24 Vdc with variable speed control, while providing airflow between 1.17 CFM and 54.7 CFM are available.

Heat Sinks



CUI Devices' board level and BGA heat sinks are manufactured using a variety of production methods (stamping, extrusion, die casting, and forging), to ensure that our product offering is suitable for use in the lowest to the highest power circuit board designs. They have been designed for compatibility with TO-218, TO-220, TO-252, and TO-263 transistor packages as well as ball grid array (BGA) package types. Available in a variety of standard form factors, these aluminum and copper heat sinks are specified for thermal resistance under four different operating conditions. This allows for quick selection of the most appropriate heat sink product for use in natural or forced air convection systems.

Peltier Devices

CUI Devices offers a broad selection of single and multi-stage Peltier modules and Peltier cooling units. These thermoelectric devices are perfect to address the cooling requirements of high density, high power systems, in diverse application areas ranging from medical to industrial. They can also be used to provide refrigeration and cooling in sealed environments that cannot facilitate forced air convection. They vary in size from 3.4 mm to 70 mm with profiles down to 1.95 mm, allowing them to be used in space-limited enclosures. CUI Devices' portfolio includes models with current ratings between 0.7 A and 20 A that can provide a temperature difference (ΔTmax) from 70 to 105°C between the hot and cold side of the module. Several models are further constructed using the proprietary arcTEC™ structure that provides higher performance in applications that require enhanced reliability and a longer product life cycle.

Thermal Accessories

Foreign objects can quickly cause a cooling fan to become blocked and burn out, while the increased airflow caused by the fan itself can lead to a buildup of dust particles within a system enclosure. To mitigate against these happening, CUI Devices provides a wide selection fan guards and filters which are constructed from PA707 or steel wire with a nickel chrome finish and are designed to complement their range of dc fans.

CUI Devices also provides a select range of heat sink clips that can be used to ensure heat sinks remain securely fastened throughout the life cycle of a product. This is particularly important for portable and mobile equipment.

The performance of a composite cooling solution, using a heat sink in combination with a thermoelectric cooler, can be further improved by using one of CUI Devices' thermal pads to maximize the thermal conductivity at their interface. Constructed from a choice of non-silicone or silicone elastomers, the pads are shaped to provide easy adhesion to CUI Devices' range of Peltier modules. With the added benefit of also providing electrical isolation, they come with thermal conductivity ratings ranging from 1.0 to 6.0 W/m*K.

Custom Solutions and Engineering Resources

In addition to our standard portfolio of cooling products, CUI Devices offers the customization of their thermal management products to individual system specifications and the ability to integrate a combination of standard or customized products into a comprehensive thermal management solution. Resources including a CAD model library, thermal management blogs, datasheets, calculators, and a parametric search tool are provided on the CUI Devices website to assist with and accelerate the design of thermal management systems.