P_d = Temp rise / R_{th} = 5°C/(5.1°C/W) = 0.98 W

Using the 80% efficiency we can calculate the maximum output power:

From $P_I = P_d + P_O$ and $P_I = P_O$/efficiency,
$P_O = P_d$ (efficiency)/(1 - efficiency)
P_O = (0.98)(0.8) / (1 - 0.8) = 3.9 W

Here is a situation where a ‘200 watt’ converter supplies only 4 W, while the 25 W BMPS, designed for free convection, supplies its full rated 25 W. In addition, the ‘200 watt’ converter is larger and more expensive. This example highlights the importance of using a converter in the environment for which it was designed. It also illustrates the benefit of high base plate or case temperature ratings. In the following section an example will be shown where the ‘200 watt’ converter is utilized in an environment more suitable to its design.

4.6.5 Forced Convection Cooling

In principle forced convection cooling is identical to free convection, the difference being that the moving air creates a more rapid interchange of the air at the interface to the body being cooled and that the conduction cooling path is no longer dominant. This interchange results in much greater cooling efficiency, making the convective thermal resistance between the converter or heat sink and the cooling air effectively much lower. This effect increases with increasing air flow, but begins to have diminishing returns at air velocity values above 4 m/s. For example, figure 4.32 shows the effect of air flow on the thermal resistance of the base plate of a ‘200 watt’ converter without additional heat sinking. In many applications, users are utilizing finite element analysis methods to better simulate the thermal behavior of BMPS. In forced convection cooling, it becomes significantly critical to better estimate the airflow around the BMPS and its effect on the cooling of the BMPS. Software packages are readily available for users to estimate the airflow temperature and speed in front of the BMPS which makes the thermal prediction of the thermal behavior much easier to predict.

Even though forced convection and free convection are similar in concept, their practical implementation is significantly different. A fan or blower is needed to create the air movement for forced convection systems. In many systems the power requirements, acoustic noise, and service requirements for fans are significant. The fan or blower also represents a reliability concern since the motor and fan or blower bearings have mechanical wear mechanisms and a finite service lifetime. In return for the above inconveniences, forced convection offers greatly improved thermal performance. In typical systems, for a given board area and environmental temperature, forced convection can cool about 4 times the power per board compared to free convection cooling. Forced convection can also significantly reduce the required size of equipment enclosures.

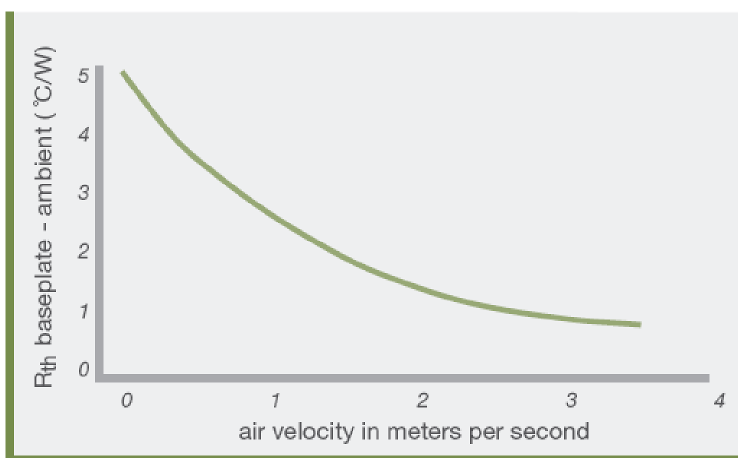

Figure 4-32 Thermal resistance vs. air velocity

As an example of forced convection cooling a power-per-shelf type of telecom system will be used. It is assumed that each shelf contains a ‘200 watt’ BMPS that supplies operating voltage to each board location on the shelf. The system includes a blower that supplies an air velocity of 3.5 m/s through a vertical plenum supplying the area containing the BMPS. A sketch of the system configuration is shown in figure 4.33.

A room environment temperature of +50°C is assumed. With forced convection the temperature

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rise internal to the equipment is typically less than for free convection due to the rapid interchange of cooling air. In this example we assume that the BMPS on each shelf causes a 2°C temperature rise in the cooling air. This will result in slightly different ambient temperatures for the converter in each shelf. The worst case location will be the upper shelf, with a T_A of +56°C. The exhaust air temperature will be +58°C. The DC/DC converter efficiency is 80%, and we will assume an output power from each converter of 150 W. The maximum BMPS base plate temperature is rated at +85°C.

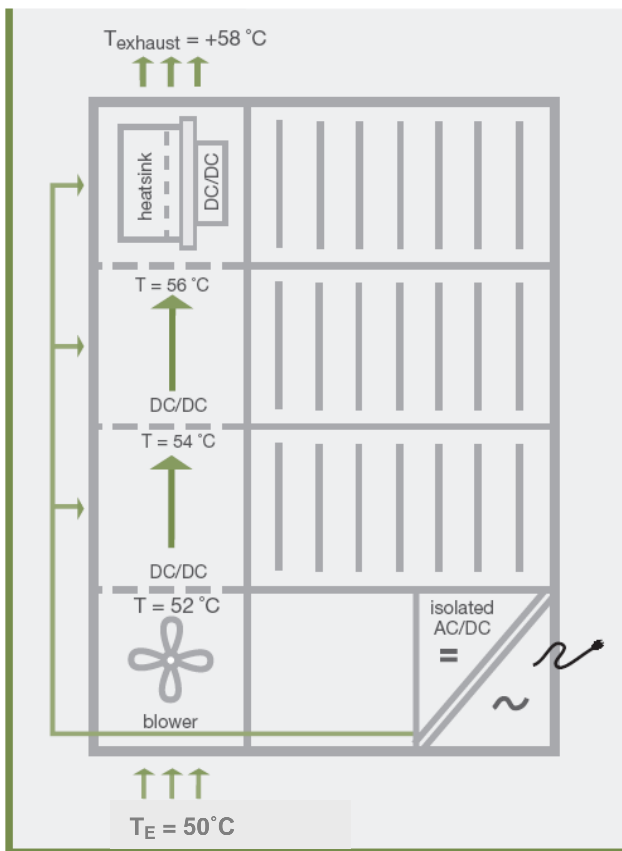
First the thermal performance of the system without any external heat sinks on the BMPS will be checked. Referring to figure 4.32 the base plate to ambient thermal resistance is 1.0°C/W at an air velocity of 3.5 m/s. The power dissipated in the BMPS is next calculated as:

$P_I = P_O$ / efficiency = 150 / 0.8 = 187.5 W
$P_d = P_I - P_O$ = 187.5 - 150 = 37.5 W

Using the above result and the thermal resistance obtained previously, we can determine the temperature rise of the base plate above ambient:

Temperature rise = ΔT = (1.0°C/W) (37.5 W) = 37.5°C

Base plate temperature = 56 + 37.5 = 93.5°C
This is well above the +85°C maximum rating, and the design is unacceptable.



Example of Forced Convection System

Figure 4-33 Example of forced convection cooled system

At this point, we have determined that a heat sink is required to lower the effective thermal resistance from base plate to ambient. We will now calculate how much heat sinking is required. The maximum allowable temperature rise is:

$T_{BASEPLATE} - T_A = 85 - 56 = 29$°C

Using this result along with Pd, we can find the required thermal resistance:

R_{th} = Temp Rise / Pd = 29°C / 37.5 W = 0.77°C/W

The thermal interface between the converter base plate and the heat sink isn't perfect, and has some thermal resistance that is effectively in series with the thermal impedance of the heat sink itself. This interface resistance can be assumed to be in the range of 0.2°C/W. Taking this into account, the required resistance of the heat sink is:

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0.77 - 0.2 = 0.57°C/W

We can then consult heat sink catalogs to find a heat sink that will interface with the BMPS and achieve a heat sink to air thermal resistance of less than 0.57°C/W at an air velocity of 3.5 m/s. There is a commercially available heat sink that is rated at 0.48°C/W with an air velocity of 3.5 m/s. This unit should work, and achieve a slight safety margin, which can now be calculated:

R_{th} = 0.48 + 0.2 = 0.68°C/W

Temperature rise = (0.68°C/W) (37.5 W) = 25.5°C

Base plate temperature = 56 + 25.5 = 81.5°C

We have a 3 or 4°C safety factor, which should be considered barely acceptable. A sketch of the resulting BMPS assembly is shown in figure 4.34.

It should be noted that the heat sink selected above is approximately 3 times the volume of the BMPS itself and provides barely acceptable performance, even with a very high airflow. This is an example of why volumetric density claims for BMPS must be approached cautiously. The system's thermal design, including heat sinks and cooling air requirements, must be understood before deciding on the appropriate BMPS.

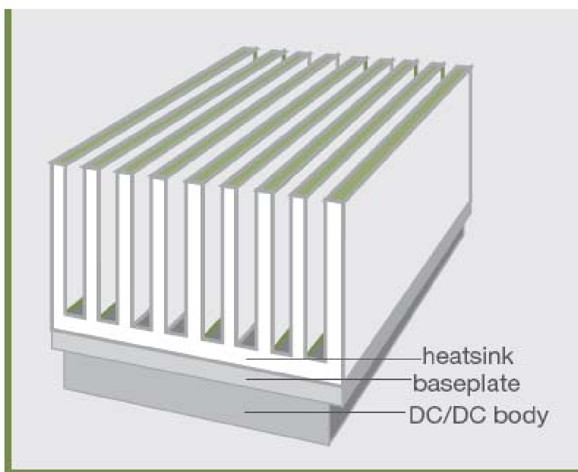

Figure 4-34 Detail of BMPS and heat sink

Indeed, there are many trade-offs to be made in terms of reliability, density, cost, and packaging before a cooling technique and converter technology can be intelligently selected. In the next section, we will explore some of these trade-offs.

4.6.6 Combined Cooling Techniques

There are some applications and converter types that combine both conductive and convection cooling. Using both cooling methods enhances the overall effectiveness of the cooling system at the expense of complicating the analysis required to estimate the thermal performance. Some BMPS have two significant and effective cooling paths: conductive cooling through the pins to the circuit board and convection cooling through the case or auxiliary heat-sink similar to many other DC/DC converters.

The combination of the two cooling paths allows for better thermal and reliability performance. We will develop a thermal model for this type of BMPS and show how estimates of thermal performance can be obtained for various application conditions. Figure 4.35 shows the thermal model for this kind of BMPS. The power dissipated by the BMPS, P_d, flows through two parallel thermal resistances. $R_{th\ sub\text{-}P}$ is the thermal resistance from the BMPS ceramic substrate to the module's pins. This thermal resistance is a function of the module's internal components, materials and physical structure, and is not affected by ambient air temperatures or airflow rates. The typical value of $R_{th\ sub\text{-}P}$ is 2.5°C/W.

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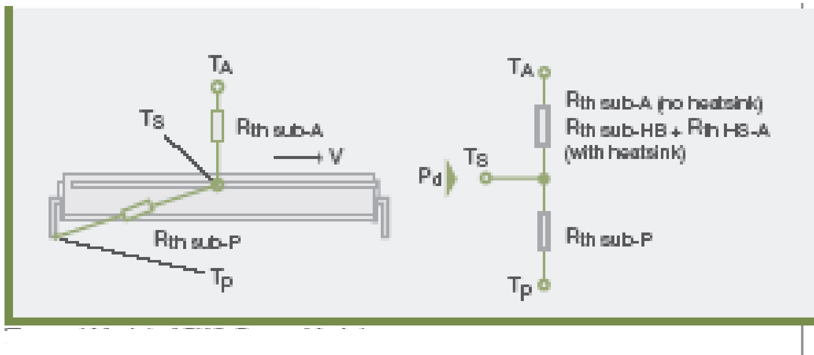

Figure 4-35 Thermal model of BMPS with combined cooling techniques

The thermal path from the power module's ceramic substrate to ambient air is modeled by $R_{th,sub-A}$. This thermal resistance combines the thermal conductivity from the ceramic substrate to the power module's case and the effective thermal resistance from the case to ambient air. $R_{th,sub-A}$ is dependent upon the rate of the airflow across the BMPS. The suppliers usually offer an auxiliary heat sink for such BMPS to further enhance the thermal path to ambient air.

When this heat sink is used the thermal model is modified by including the thermal properties of the heat sink. In this case, the total thermal resistance from the substrate to the ambient air is lower, and is modeled by $R_{th\ sub-HS} + R_{th\ HS-A}$. The dependencies of the thermal resistances on the air velocity with and without the heat sink are shown in figure 4.36.

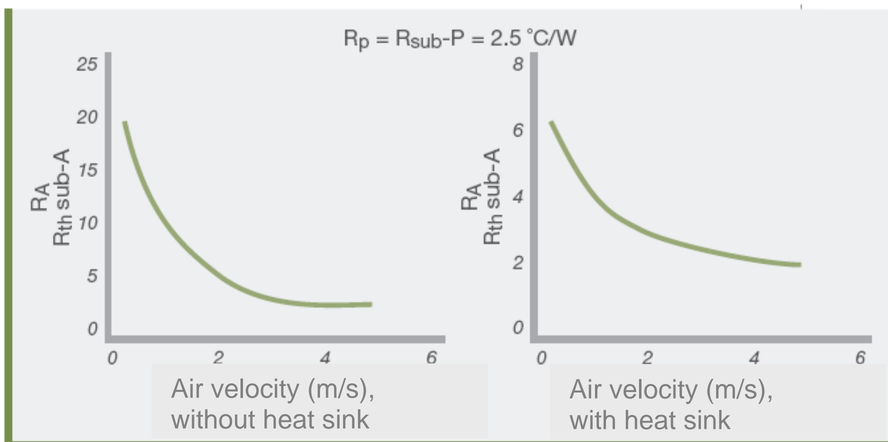

Figure 4-36 Thermal resistance for BMPS with combined cooling techniques

In order to obtain a generalized equation for situations with and without the heat-sink, and to simplify the nomenclature, the term R_A will be used to designate the effective total thermal resistance from the BMPS substrate to ambient air. For a given airflow, the value of R_A will be smaller when the heat sink is used, as shown in figure 4.36. Similarly, the term R_P will be used to designate the thermal resistance $R_{th\ sub-P}$.

Solving the thermal model of figure 4.35 for the BMPS substrate temperature, T_S, yields the following expression:

$$T_S = T_A + \frac{R_A}{R_A + R_P} [T_P - T_A + (P_d)(R_P)]$$

Where:

T_S = BMPS Substrate Temperature
T_A = Ambient Air Temperature
T_P = Module Pin Temperature
P_d = Power Dissipated by the BMPS

Since $R_P = R_{th\ sub-P} = 2.5°C/W$, the expression can be further simplified to:

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$$T_S = T_A + \frac{R_A}{R_A + 2.5}(T_P - T_A + 2.5\,P_d)$$

As an example, we will now use the equation presented above to calculate the substrate temperature of a DC/DC power module for a given set of operating conditions. Assume that:

- Max output power is 60 W
- Actual output power is 50 W
- Power module efficiency is 86%
- Pin temperature is 60°C
- Ambient air temperature is 50°C
- Airflow is 1 m/s
- No heat sink is used

We first calculate the power dissipated as:

$P_d = P_I - P_O = (P_O/\text{efficiency}) - P_O$
$P_d = 50/0.86 - 50 = 8.14$ W

Using the left curve of figure 4.36, we find that R_A at 1 m/s is 10°C/W.

Inserting these numbers into the equation for T_S yields:

$$T_S = 50 + \frac{10}{10 + 2.5}[60 - 50 + 2.5(8.14)] = 74.28\ °C$$

This is below the 100 °C maximum rating, so reliable operation will be achieved.

How much would the addition of the heat sink reduce the substrate temperature? To answer this question, we use a value of R_A obtained from the right hand curve in figure 4.36.

We find that R_A has a value of 4.2°C/W at an air velocity of 1 m/s. Using this value in the equation for T_S results in the following:

$$TS = 50 + \frac{4.2}{4.2+2.5}[60 - 50 + 2.5(8.14)] = 69.03\ °C$$

We find that the addition of the heat-sink reduced the BMPS substrate temperature by about 5°C. This temperature reduction would further enhance the reliability of the BMPS within the application.

4.6.7 Design Trade-offs

As we have seen in the preceding pages, there appears to be no one best cooling method for BMPS. Conduction, free convection, and forced convection all have their place in the power system designer's toolbox, with the best choice dictated by a variety of influences, some under the control of the designer and others imposed by system design constraints. In table 4.9 we have attempted to summarize the typical usage, advantages and disadvantages, and some design trade-offs associated with each cooling methodology.

Perhaps some commentary on the design trade-offs would be useful. Control of temperatures (from room environment to the BMPS interface) is universally helpful in achieving good thermal performance no matter what cooling technique is used. The cooler the thermal interface, whether the circuit board and pin temperature for a conduction cooled BMPS or the ambient air temperature for a convectively cooled BMPS, the lower the internal temperature of the BMPS will be, and the better the reliability of the system will be. Of equal importance is the maximum temperature rating on the BMPS, T_P for conduction cooling and T_C for convection cooling. This should be as high as possible. We saw in a previous example the limitations of using a power converter with +85°C maximum base plate temperature. The object is to maximize the temperature differential between the maximum temperature rating of the BMPS and the source of cooling. The temperature differential will in some cases determine if external heat sinks are required on BMPS, and if so, how large the heat sinks need to be. Maximum pin or case temperature should be a key criterion in the selection of the BMPS.

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Table 4.9 Trade-offs with different cooling techniques

	Conduction	**Free Convection**	**Forced Convection**
Typical Usage	Board Mounted	Low to Medium Power Board Mounted	Medium to High Power Board Mounted or 'Centralized'
Advantages	Low Cost High Reliability Not orientation sensitive	Low Cost High Reliability	Higher Density Ease of Thermal analysis
Disadvantages	Require a low thermal resistance conduction path	More Complexity	Field service required More costly
Design	T_E, T_A, T_P	T_E, T_A	T_E, T_A
Trade -offs	Reliability (T_{CC}) Efficiency Maximum Pin Temperature	Reliability (T_{CC}) Efficiency Board Area Maximum Case Temperature	Reliability (T_{CC}) Efficiency Board Area Air Flow Maximum Case Temperature

In forced convection systems the amount of airflow can be increased to improve the cooling performance. Practical limits are soon approached, however. As shown in figure 4.36 increasing airflow above 4 m/s results in diminishing returns. Also, at high airflow rates the acoustic noise generated by the fans blowers and moving air creates a problem for people in the vicinity of the equipment. Most equipment manufacturers have a maximum sound level that they will accept for the product, and this limit will impose restrictions on the amount of airflow that can actually be accommodated.

Reliability is also a trade-off. The design examples discussed here are predicated upon keeping the semiconductor junction temperatures within the BMPS below +120°C at max ambient temperature. The basis for these kinds of guidelines will be explained in the chapter on Reliability. Even greater reliability can be achieved at lower junction temperatures. So for very critical systems, the designer may choose to operate the BMPS (as well as other electronics) at reduced temperatures to improve reliability. This will need to be done at the expense of at least one of the other variables, such as board area, airflow, or volume needed for heat sinks.

Board area used for circuitry or power conversion functions is a critical factor in system design. For obvious reasons designers want as much density as possible. However, designers must be aware that density generally goes hand-in-hand with higher temperatures and more difficult thermal solutions. For a fixed temperature rise, a given board area and board spacing will only support a certain amount of power dissipation. It is not easy to quantify the amount of power supportable by a convection cooled board due to the large number of variables involved. We have, however, included a rough ‘rule-of-thumb’ estimate based upon the double extended Euroboard used in several telecom type systems. This board is 220 mm deep and 233 mm high, giving a board area of 5.13 dm^2. Figure 4.37 indicates that in typical applications this board supports an average power dissipation of 5 W for free convection cooling and 20 W or more for forced convection. A power dissipation of 5 W per board in free convection corresponds to a temperature rise of 20°C. The amount of power that can be cooled on a given board also depends upon the height of the components and upon the total surface area they expose to the cooling air. Very planar structures will not cool as well as higher components. This estimate assumes a normal mix of surface extensions and building heights.

In applications such as certain high-end routers and servers the power dissipation per board can be from 250 to 450 W and up to 850 W or more, in extreme cases. The boards contain several micro processors requiring from about 10 A up to more than 60 A per device at voltage levels of 1.2 V or less. In these applications there are extreme requirements on thermal management and low distribution losses.

The aspect ratio of the board is also a factor in addition to the total area. For a given area, boards with the longer dimension in the direction of the cooling airflow will be hotter than boards extended in the other dimension. This effect is due to the ‘pre-heating’ of the cooling air by components upstream of those being cooled, as is shown in figure 4.37. Components located at the lower edge (air input side) of the board have a better cooling environment than those at the upper edge (air output side). This should be taken into account when doing the board layout, placing components requiring the most cooling lower on the board. Power system designers should be very aware of the location of the BMPS relative to other components on the board. If it is ‘downstream’ from other circuitry, make sure that the preheating effects due to the power

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dissipation of this circuitry is taken into account when defining the ambient temperature for the BMPS.

For systems implemented with BMPS, with the BMPS and load circuitry sharing the same board, it is possible to estimate the amount of board area allocated to the power conversion function by considering the respective thermal performance of the two types of technology. The area power density (W/cm^2) of BMPS is higher than that of logic and load circuitry. For a typical convection cooled telecom BMPS operating at 80% load, for example, the power dissipated by the BMPS per board area is about 0.06 W/cm^2. The figure also includes the additional area required for connections and mounting purposes. If additional filtering is required it will decrease this figure. For the board as a whole, the area power density can be estimated from the values shown in figure 4.37. Using the standard Euro board aspect ratio, we obtain the following estimates for free and forced convection:

Free convection 5 W / 513 cm^2 = 0.01 W/cm^2
Forced convection 20 W / 513 cm^2 = 0.04 W/cm^2

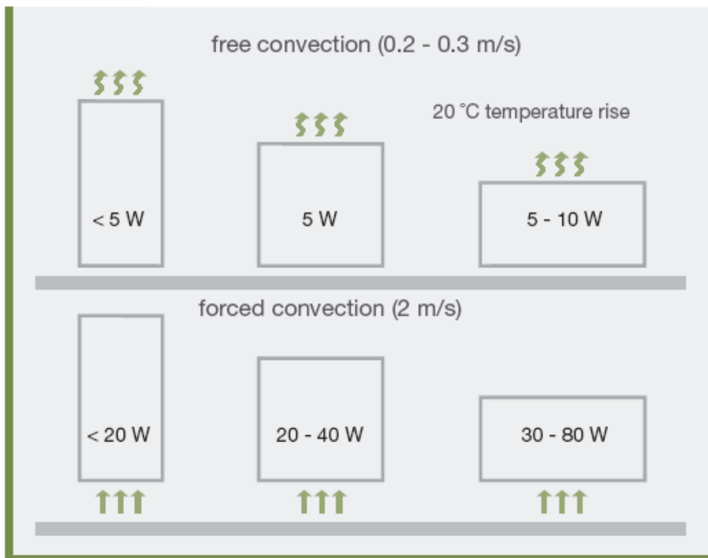

Figure 4-37 Average power per board in typical telecom equipment

We can now compare the power density of the BMPS with the board:

Free convection 0.06 / 0.01 = 6.0
Forced convection 0.06 / 0.04 = 1.5

We have found that the BMPS has between 1.5 and 6.0 times the areal power density of the board as a whole. We must now take into account the percentage of power dissipated in the BMPS. If we assume a BMPS efficiency of 82% for 15 W product and 84% for a 30 W product, then 18% and 16% respectively of the power will be dissipated in the BMPS and the rest in the remainder of the board. Combining this with the power areal density ratios obtained above, we can now estimate the percentage of board area allocated to the power conversion:

Free Convection 18% / 6 = 3%
Forced Convection 16% / 1.5 = 11%

These values can be considered rough 'rules-of-thumb' for use in initial design sizing of board layouts. They indicate that with today's BMPS, a very small percentage of board area is required to provide the benefits of power per board architecture. The final trade-off parameter is efficiency. It is controlled by the BMPS manufacturer, but the system designer must be very aware of the efficiency, and it should be a very important selection criterion when choosing the BMPS to use. Efficiency has a very large impact on all aspects of thermal design. For a 25 W BMPS, the range of available efficiencies is roughly 75% to 90%. At first glance, this may appear to be a small variation. In actuality, it is a very significant difference. Let's calculate the power dissipated by the BMPS, assuming a 25 W output:

for 75%, $P_I = 25 / 0.75 = 33.3$ W
$P_d = 33.3 - 25 = 8.3$ W
for 90%, $P_I = 25 / 0.90 = 27.8$ W
$P_d = 27.8 - 25 = 2.8$ W

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Comparing the two power dissipations,

8.3 / 2.8 = 2.96

The 75% efficient product dissipates 3 times more power than the 90% efficient product!

This 200% increase will have a large impact on requirements for board area, heat sinking, and ultimately on system reliability and cost. The benefits of BMPS efficiency to the system designer cannot be over emphasized. Efficiency, along with reliability, should be at the top of the system designer's priority list. A good BMPS supplier will work with the system designer to help him or her understand the actual efficiencies to be expected from the system implementation and operating conditions.

4.6.8 Cooling considerations for open-frame BMPS

Open-frame or planar BMPS have become popular as their thermal performance has improved and their superior cost structure offers compelling value. However, with open-frame BMPS, traditional methods of relying on a single power module or case temperature are typically not applicable when assessing their thermal performance. This is because all components in an open frame BMPS are not in direct thermal contact with one other. Instead, open-frame BMPS have thermal characteristics that require a different testing and thermal derating process.

We will now describe the issues involved in thermally testing open-frame modules and show how they lead to a thermal derating process. Some key issues to consider are:

- The thermally limiting component varies depending on operating conditions. For example, at low airflow and light load conditions it might be the transformer core, whereas at higher loads the limiting component might be the power MOSFETs in the secondary stage
- Orientation with respect to airflow is more critical. Depending on the layout, any one of the four orientations could be the "best" or "worst" orientation for thermal performance
- Temperature differences among components become larger, and therefore all the important components (those with significant power dissipations and/or sensitivity to higher temperatures) need to be monitored during thermal testing
- Spacing between test boards and wind tunnel configurations play a larger role in influencing thermal testing results
- Component power dissipation ($P_{d,\ comp}$) and component junction-to-case thermal resistance ($R_{th,\ J\text{-}C}$) for each critical component becomes more important in the derating process since they determine the actual junction temperature that limits the BMPS thermal performance. In typical situations, the junction temperature for a typical power semiconductor must not be within 1 or 2°C of the measured component case temperature as widely assumed
- Linear extrapolation based on tests at room ambient temperature often results in inaccuracies for certain types of open frame design at high ambient temperatures when compared to actual measurements done at the elevated temperatures. Thermal performance is generally dependent on the location of both air velocity and ambient temperature sensors.

Prior to the thermal testing, a complete set of efficiency and power dissipation curves of the test module is obtained through electrical testing at various ambient temperatures. Next, the module layout is used to identify critical components and their locations. The critical components are those that limit the thermal performance of the module, such as power MOSFETs, control ICs, magnetic cores, and opto-coupler ICs. The data required for each critical component are the power dissipations ($P_{d,\ comp}$) at various output levels and the junction-to-case (lead) thermal resistance ($R_{th,\ J\text{-}C}$). It should be noted that the actual power dissipation of a component is often a function of the module output. The maximum power dissipation capability given in the component supplier's datasheet is not the actual power dissipation and cannot be used for thermal characterization. Instead, power dissipations at various output current levels are obtained directly from the design engineer.

Due to the distinctive thermal characteristics of open-frame BMPS, thermal testing at room ambient temperature alone is often not sufficient to adequately quantify the thermal performance of an open-frame BMPS. Linear extrapolation based on room ambient temperature tests can cause significant errors at higher ambient temperatures for some of the open frame designs. Therefore it is recommended that tests are conducted in the full ambient temperature range, normally 20-85°C. This task may be accomplished in a closed-loop wind tunnel as shown in figure 4.38. The closed-loop wind tunnel can provide uniformly heated airflow with temperatures ranging from room ambient to about +90°C and air velocities from 0.25 to 4 m/s (50-800 lfm).

An anemometer is used for air velocity measurement. An IR (infra red) camera is used for identifying hot zones and components, and for dynamic assessment of the thermal characteristics of an open-frame BMPS while operating conditions are varied. Thermocouples are preferred for accurately measuring component case (body) or lead temperatures as well as ambient temperatures. A data logger (data

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acquisition unit) and a PC (personal computer) are used for data collection and control. The recorded data should include component, ambient and atmospheric temperatures, BMPS input and output voltages and currents, air velocities and other wind tunnel parameters. A preliminary IR test is used to find out the overall temperature distribution of the BMPS and to determine which components are to be thermo coupled for the actual characterization tests. The module may be operated at half-load under both natural convection and forced convection conditions. At least one IR image should be taken for each of the conditions. Based on the IR images, the critical components are identified and thermo-coupled. These are either the hottest components or those that have lower maximum operating temperatures. The selected components should include at least one component from each of the following key groups: input-side MOSFETs, output-side MOSFETs, transformer/inductor cores, opto couplers and control IC. Depending on the test module, ten to twenty components may need to be thermo coupled. For transformer cores, unleaded semiconductor devices and printed wired boards (PWB), thermocouples are always attached to the hottest part of the body in accordance with the IR images. For leaded semiconductor devices, thermocouples can be placed on the case, lead or tab. However, the point of attachment depends how the manufacturer defines the $R_{th,\ J\text{-}C}$. This is critical to obtaining the correct junction temperature, T_J, from the measured case/lead temperature, T_C. To get the best results, it is strongly recommended that thermocouples be attached to the devices in the same manner as the devices are tested for their $R_{th,\ J\text{-}C}$ value, following the procedure described by the device manufacturer.

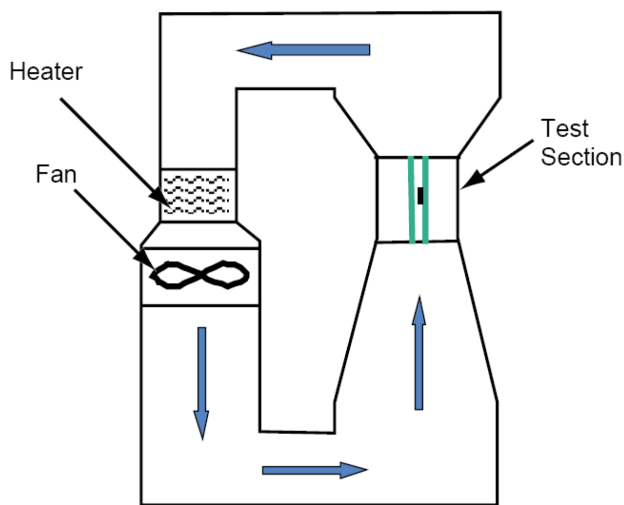

Figure 4-38 Basic closed-loop wind tunnel

The location of the air velocity and ambient temperature sensors should be clearly specified because any variation in sensor locations may cause inconsistency in the test results. When the board spacing is 25 mm (≈ 1 in) or less, we recommend that the sensor be placed in between the two test boards at a distance of 76.2 mm (3.0 in) from the test module and 12.7 mm (0.50 in) away from the test board as shown in figure 4.39. When large heat sinks are used and the board spacing is greater than 25 mm (≈ 1 in), the sensor should be placed in the middle between the two boards.

The actual junction temperature of a semiconductor device depends on the power level as well as the operating environment. Therefore, simply adding a fixed number (whether it is 1~2°C or 10~20°C) to the measured component case temperature to get the junction temperature will lead to significant inaccuracy in the evaluation of the BMPS thermal performance. The essence of the derating method is to obtain accurate estimates of the actual junction temperatures, T_J, of the key components under various conditions. It involves several steps as described below.

1. Establish a non linear characteristic curve as shown in figure 4.40 for each of the critical components based on test data, where component temperature T_C measured is plotted as a function of the output current (or power). For each air flow condition, one set of curves is generated.
2. Based on the data collected from the module designer, define the relationship between the component power dissipation $P_{d,\ comp}$ and module output current I_O for each critical component, $P_{d,\ comp} = f\ (I_O)$, which is typically a nonlinear curve as shown in figure 4.40a. This reflects the fact that component dissipations of some critical components, e.g. the output-side MOSFET switches in the output stage of most low voltage BMPS, vary approximately with the square of the output current.

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3. The temperature difference between the component junction and case can be calculated and plotted as a function of the power dissipation as shown in figure 4.40b, using the following equation

   $\Delta T_{J-C} = P_{d,\ comp} \times R_{th,\ J-C}$,

   where $R_{th,\ J-C}$ is the junction-to-case thermal resistance of the component. By combining the power dissipation curve presented in the last step, it is easy to obtain ΔT_{J-C} as a function of the output current as shown in figure 4.40c.

4. Calculate and plot the actual junction temperature T_J, as shown in figure 4.40d, for each of the critical components based on the measured case temperature T_C, $T_J = T_C + \Delta T_{J-C}$., An example of the junction temperature as a function of the output current in a real BMPS is given in figure 4.41. The measured case temperature is also shown. It is obvious that the temperature difference between T_J and T_C is not a constant, and it is not negligible when the BMPS is operated at high output current level ($\Delta T_{J-C} \approx 15°C$ at $I_O = 35$ A for the particular power device shown in figure 4.41).

5. Apply the proper temperature constraint for each of the critical components. The first component reaching its temperature limit determines the maximum module output current I_O under that particular operating condition. Using the same example given in figure 4.41, the temperature limit for that device is set at $T_{J,\ max} = +125°C$, which results in maximum output current capability of 32 A for this power module under the particular operating condition of 1m/s (200 lfm) airflow and +25°C ambient temperature. If T_C instead of T_J is used, the maximum output current capability would be incorrectly estimated to be 36 A (12.5% larger). However, that would cause the junction temperature to be in excess of +140°C, far above the permitted $T_{J,\ max} = +125°C$.

Steps 1 through 5 are for one particular operating condition. To obtain a complete thermal evaluation of a power module, these steps should be repeated for all operating conditions, which include airflow, ambient temperature, module orientation and test board spacing.

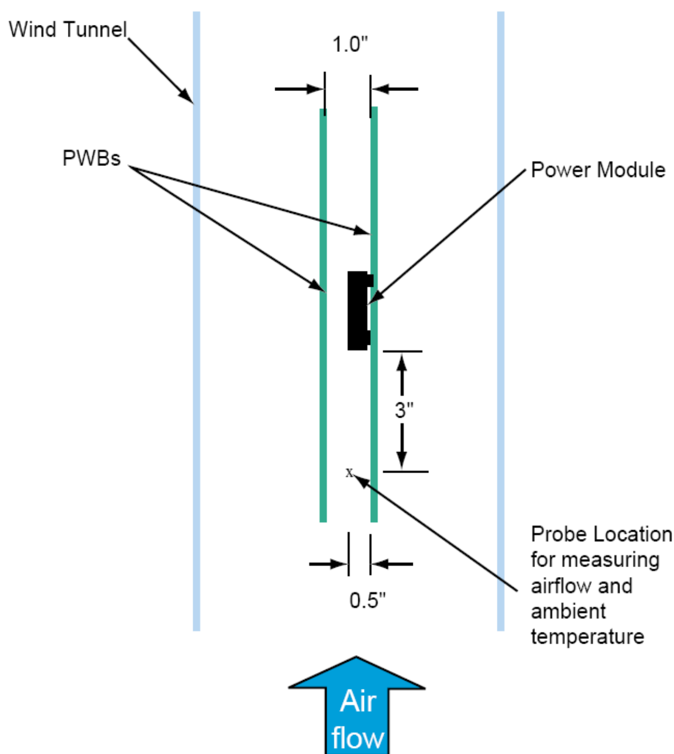

Figure 4-39 Typical test setup and airflow sensor location

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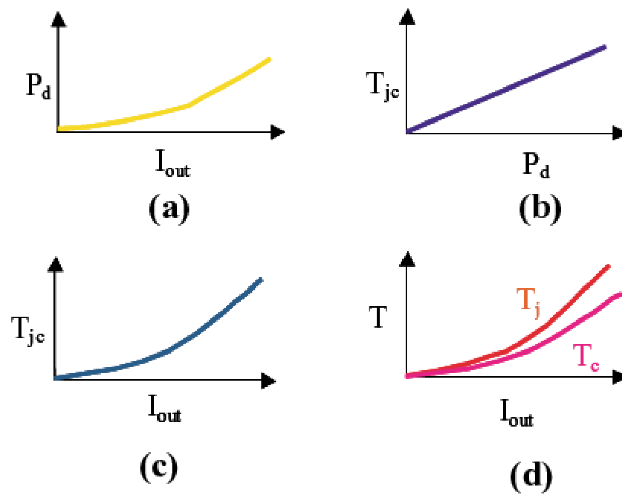

Figure 4-40 Component junction temperature as a function of output current

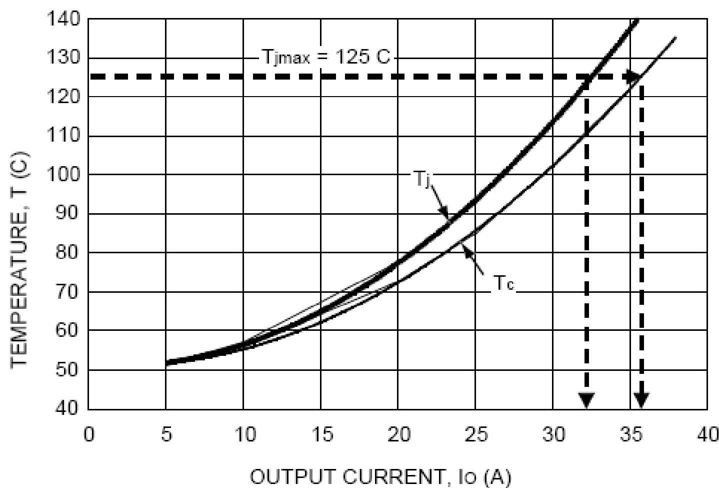

Figure 4-41 Example of junction and case temperatures for a standard SO8 MOSFET

4.6.9 Output Power Derating

Derating constraints are the maximum component temperatures used to determine the BMPS maximum output power or current under a certain operating condition. Semiconductor devices (POWERFET, IC, etc.), are typically specified to $T_{J,max}$ = +150°C (some even up to +175°C). Most BMPS manufacturers, however, are using $T_{J,max}$ = +125°C for their thermal evaluation purposes due to concerns about long-term reliability. One exception to semiconductors is the opto-coupler, which has very small power dissipation but very large junction-to-case thermal resistance. Device manufacturers usually specify a maximum operating ambient temperature of +100°C instead of a maximum junction temperature. Realizing that there is always a certain difference between the body and the ambient temperatures, it is reasonable to use +110°C as the maximum body temperature for thermal derating purposes. FR4 printed circuit boards are limited by their UL ratings, typically +120°C or +130°C, depending on actual material composition and PWB manufacturer. For magnetic cores, the temperature must be limited to +130°C due to concerns about "thermal run-away" at higher temperatures. The temperature values given are typical and actual limiting temperatures may vary depending on device technology and manufacturer, as well as the ultimate application requirements.

Traditionally, BMPS thermal derating charts were presented in the form of power dissipation vs. ambient temperature. To mechanical or thermal designers, it makes no difference whether power dissipation, total output power or output current is used as the independent variable because they are all related to each other. To users of BMPS, however, output current or output power makes more sense than power dissipation. It is recommended that output current be used in the derating chart for single-output voltage BMPS (shown in figure 4.42) and total output power for multiple output BMPS. With the derating method described, tests are conducted across the full ambient temperature range and there is no need for data extrapolation. Furthermore, the thermal performance is judged based on the actual junction temperatures of individual components. As a result, the nonlinear nature of the BMPS power dissipation over ambient

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