Thermal Considerations

Overview

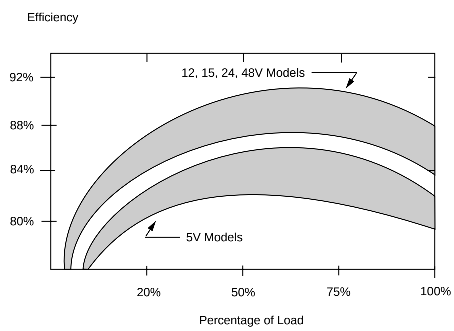
Simplified thermal management is one of the benefits of using Vicor converters. High operating efficiency minimizes heat loss, and the low profile package features an easily accessible, electrically isolated thermal interface surface.

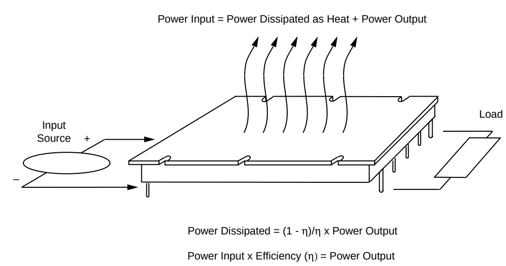
Proper thermal management pays dividends in terms of improved converter and system MTBFs, smaller size and lower product life-cycle costs. The following pages provide guidelines for achieving effective thermal management of Vicor converters.

Efficiency and Dissipated Power

A DC-DC converter takes power from an input source and converts it into regulated output power for delivery to a load. Not all of the input power is converted to output power however; some is dissipated as heat within the converter. The ratio of delivered output power to converter input power is defined as the converter's efficiency. Efficiency is a basic figure of merit that can be used to relate power dissipation directly to converter output power, as illustrated in Figures 1a and 1b.

Figures 1a, 1b.





The first step in evaluating cooling requirements is to calculate worst-case dissipation based on converter efficiency and worst-case anticipated load power. Clearly, higher efficiency will translate into lower power dissipation and simplify the cooling problem. Vicor converters are among the most efficient converters available, with full load efficiencies typically in excess of 80%.

Removing Heat From Vicor Converters

Heat is removed from Vicor converters through the flat metal baseplate on top of the module. The baseplate is thermally coupled to, but electrically isolated from, all internal heat-generating components. The basic thermal design problem is to transfer heat from the baseplate into the surrounding environment as a means of maintaining baseplate temperature at or below rated maximum.

Heat energy is transferred from regions of high temperature to regions of low temperature via three basic mechanisms: radiation, conduction and convection.

Radiation: Electromagnetic transfer of heat between masses at different temperatures.
Conduction: Transfer of heat through a solid medium.
Convection: Transfer of heat through the medium of a fluid; typically air.

Removing Heat From Vicor Converters (cont)

All three of these heat transfer mechanisms are active to some degree in every application. Convection will be the dominant heat transfer mechanism in most applications. Nondominant effects will provide an added contribution to cooling; in some cases, however, they may result in undesirable and unanticipated thermal interactions between components and subassemblies. All three of these mechanisms should be given consideration when developing a successful cooling strategy.

Radiation

Radiant heat transfer occurs continuously between objects at different temperatures that are exposed to each other. The net effect on the temperature of an individual part is dependent on a great many factors, including its temperature relative to other parts, relative part orientations, surface finishes and spacing. The difficulty in quantifying many of these factors, combined with the universal presence of radiant energy exchange, makes calculation of radiational temperature effects both a complex and generally imprecise task.

Temperature differentials encountered in practical applications of Vicor converters are never large enough to cause radiational cooling to be the dominant heat transfer mechanism. Radiation will account for less than 10% of total heat transfer in the majority of cases. For these reasons, the presence of radiant cooling is often assumed to provide safety margins over and above the dominant cooling mechanism, and detailed consideration of its effects are neglected. A valid assumption, in most cases, is that the converter will be warmer than its surroundings and radiant energy transfer will aid cooling. In some cases, however, nearby objects (PC boards, power resistors, etc.) may be much hotter than the converter and net radiant energy transfer may actually increase the converter’s temperature.

Surveying the relative positions and estimated temperatures of converters and surrounding parts is advisable as a means of anticipating the potential effects of radiant transfer. In cases where hot components are in close proximity to the converter, the use of interposing barriers can generally moderate undesirable radiational heating effects.

Conduction

In most applications, heat will be conducted from the baseplate into an attached heatsink or heat conducting member. Heat conducted across the interface between the baseplate and mating member will result in a temperature drop which must be controlled. As shown in Figure 2, the interface can be modeled as a “thermal resistance” in series with the dissipated power flow. The baseplate temperature will be the sum of the temperature rise in the interface and the temperature of the member to which the baseplate is attached.

Conduction (cont)

Figure 2.

Temperature rise across a surface interface can be significant if not controlled. The area of the interface should be as large as possible, and the surface flatness of the attached member should be within 5 mils. Thermal compound or a thermal pad should be used to fill surface irregularities. Thermal resistance across surface interfaces can be held to under 0.1˚C/Watt with proper measures.

Many applications require that heat be conducted from the baseplate of the converter to a "remote" dissipative surface via a thermally conductive member. The resulting baseplate temperature will be the sum of the temperature of the dissipative surface, the temperature rise in the heat conducting member, and the rises across the two surface interfaces. The thermal resistance of the conductive member is proportional to its length, and inversely proportional to both its cross-sectional area and thermal conductivity (Figure 3). Minimizing total temperature rise is dependent on controlling interface resistance, as described above, and controlling the thermal resistance of the transfer member through appropriate material selection and dimensioning.

Figure 3.

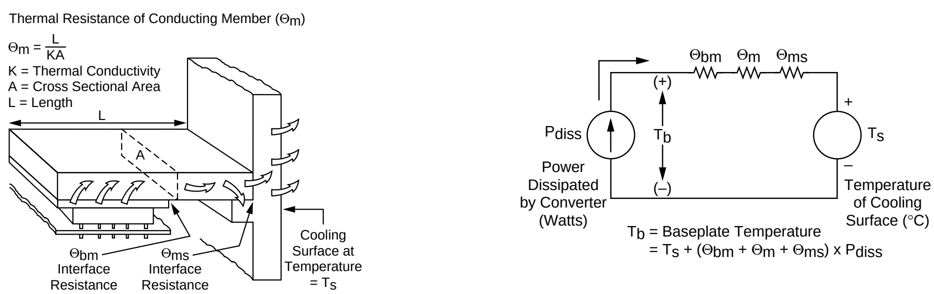
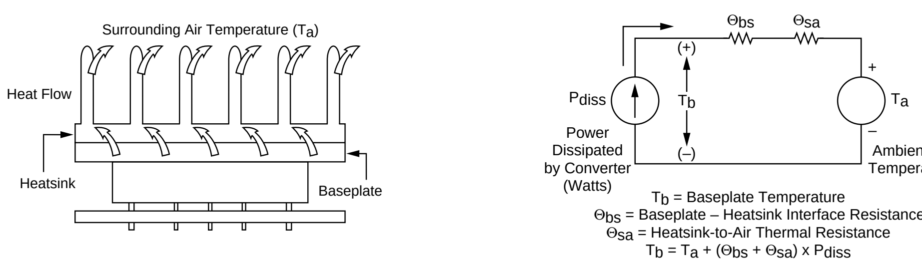


Figure 4.



Convection

Convective heat transfer into air is a common method for cooling Vicor converters. “Free” or “natural” convection refers to heat transfer from a dissipative surface into a cooler surrounding mass of otherwise still air; forced convection refers to heat transfer into a moving air stream.

The convection cooling model is shown in Figure 4, page 23-3. Baseplate temperature depends on the temperature of the air, total dissipated power and the values of two thermal resistances: the thermal resistance of the surface interface between the baseplate and the heatsink, and the heatsink-to-air thermal resistance. Surface interface resistance can be minimized as discussed under Conduction. The heatsink-to-air resistance is dependent on a variety of factors including heatsink material and geometry, air temperature, air density and air flow rate. Fortunately, thermal resistance data is available for a very wide range of standard heatsinks (from Vicor, Wakefield Engineering, Aavid, and others) for use in both free and forced convection applications. The following sections will provide guidelines for both free and forced convection cooling of Vicor converters.

Free Convection

The benefits of free convection include low cost of implementation, no need for fans, and the inherent reliability of the cooling process. Compared to forced air cooling, however, free convection will require more heatsink volume to achieve an equivalent baseplate temperature.

To select a suitable heatsink for free convection cooling, follow these steps:

1. Determine the power to be dissipated by the heatsink. This should be based upon converter efficiency and worst-case converter power output using the formula given in the section on Efficiency and Dissipated Power.

2. Estimate or experimentally determine the surface interface thermal resistance. Use of thermal compound or a thermal pad is recommended to minimize this resistance. An estimate of 0.2˚C/Watt should provide an adequate safety margin.

3. Referencing Figure 4, we can derive the following formula for heatsink-to-air thermal resistance:

$$\theta_{sa} = \left(\frac{T_b - T_a}{P_{diss}}\right) - \theta_{bs}$$

T_a = Worst case anticipated operating ambient air temperature.
θ_{bs} = Surface interface thermal resistance, from Step 2, above.
P_{diss} = Worst-case power dissipation, from Step 1, above.
T_b = Baseplate temperature.

Start with a value of T_b = 85˚C or 100˚C (VI-J00) to determine the maximum acceptable heatsink-to-air thermal resistance.

Free Convection (cont)

4. Select several heatsinks that appear physically acceptable for the application. Using data provided, obtain values for their free convection thermal resistance, preferably at worst-case ambient temperature, T_a. If values obtained are less than the value calculated in Step 3, go on to Step 5. If the values are greater, then either a physically larger heatsink will be required or a different cooling method will need to be used (i.e., forced air, etc.).

5. Select the heatsink with the lowest available thermal resistance consistent with space and cost limits. Keep in mind that small reductions in baseplate temperature produce dramatic improvements in MTBF.

6. Baseplate temperature can be estimated by using the following formula:

$T_b = T_a + P_{diss} \times (\theta_{bs} + \theta_{sa})$

7. Test to verify that performance is in line with expectations.

Keep in mind the following:

Heatsink data is almost always given for vertical fin orientation. Orienting the fins horizontally will reduce cooling effectiveness. If horizontal mounting is mandatory, obtain relevant heatsink performance data or use forced convection cooling.

Free convection depends on air movement caused by heat-induced density changes. Thermal resistance data is dependent on the heatsink fins being completely exposed to the ambient air without any significant interference to air flow at the ends of or along the length of the fins. If packaging will tend to block or baffle air movement over the fins, a larger heatsink might be required. In the worst case, free convection may be ineffective. Make sure that the fins are well exposed to ambient air.

It is not necessary to limit the size of the heatsink to the size of the baseplate. Heatsinks with footprints larger than the baseplate area can often be used to advantage. In the latter case, heat must be conducted along the base surface of the heatsink to get to the outer fins, so don’t count on achieving full cooling capability. Also, several modules can be mounted to a common heatsink, but cooling calculations must now take into account total power dissipation with consideration given to possible localized overheating if worst-case converter power dissipations are greatly imbalanced. When securing a PC board containing two or more converters to a heatsink, it is good practice to use sockets on the converter pins to allow for mechanical alignment. If sockets are not used, be sure to mount the converters first mechanically, then solder the units in place. A fixture should be used to maintain alignment if soldering must be performed before attachment.

When mounting heatsinks to Vicor modules, use #6 screws torqued uniformly through the mounting slots provided. The following tightening sequence should be used:

- Lightly finger-tighten all screws
- Torque screws to 5-7 in.-lbs. per Figure 5, page 23-6.

Free Convection (cont)

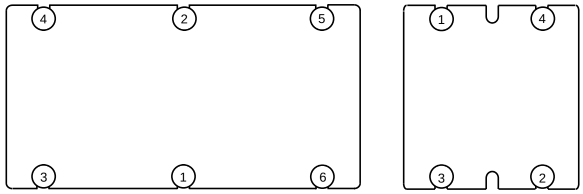


*Figure 5.
Heatsink Torquing
Sequence
VI-200/VI-J00*

Multiple Modules Using Common Fasteners
The following mounting scheme should be used to attach modules to a heatsink for two or more modules. A large, heavy washer should be used on the common fasteners to distribute the mounting force equally between modules. The torquing sequence shown in Figure 6 can easily be expanded from two to any number of modules. An array of three is shown.

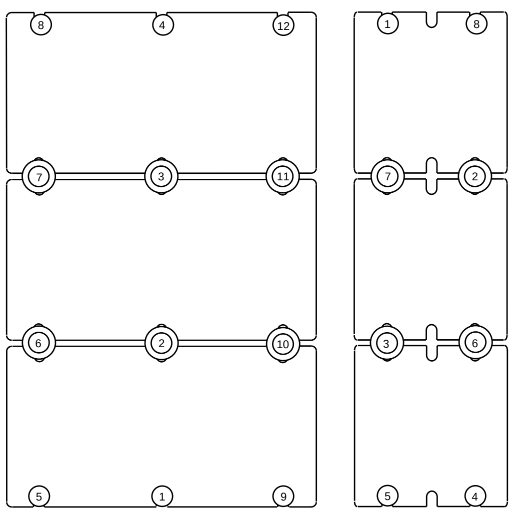


*Figure 6.
Torquing Sequence,
Multiple VI-200/VI-J00
Converters*

Forced Convection

Forced air can make a great difference in cooling effectiveness. Heatsink-to-air thermal resistance can be improved by as much as an order of magnitude when compared to free convection performance, by using suitable heatsinks. Consider the following data for baseplate-to-air thermal resistance (no heatsink) of a VI-200 or VI-J00 module at various air flow rates:

Air Flow	VI-200 Baseplate to Air Thermal Resistance	VI-J00 Baseplate to Air Thermal Resistance
Free Air	5.1˚C/W	8.1˚C/W
200 LFM	2.8˚C/W	5.1˚C/W
400 LFM	1.8˚C/W	2.7˚C/W
600 LFM	1.4˚C/W	2.3˚C/W
800 LFM	1.2˚C/W	1.7˚C/W
1000 LFM	1.0˚C/W	1.4˚C/W

Forced Convection (cont)

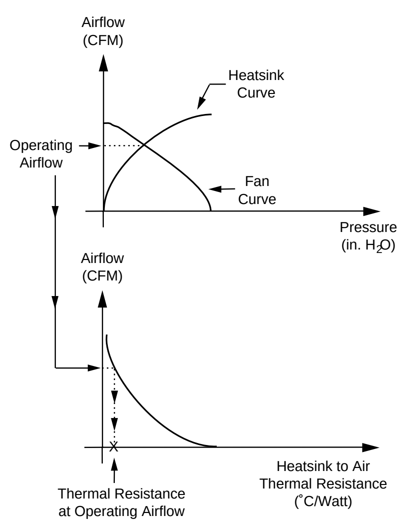
Forced air implies the use of fans. Many applications require that fans be used to achieve some desired combination of overall system reliability and packaging density. In other applications, however, fans are considered taboo. “Dirty” environments will require filters that must be changed regularly to maintain cooling efficiency, and neglecting to change a filter or the failure of the fan could cause the system to shut down or malfunction.

The steps involved in selecting a heatsink/fan combination for forced convection are essentially the same as those followed for free convection, with the additional requirement that the heatsink and fan be matched to achieve desired heatsink-to-air thermal resistance. Attention must also be paid to proper channeling of fan airflow so that maximum utilization of its cooling capability is realized. Selection of a heatsink/fan combination involves the following steps:

1. Determine maximum acceptable heatsink-to-air thermal resistance by following the first three steps of the heatsink selection procedure given in the Free Convection section.

2. Selection of a heatsink/fan combination requires that forced convection data for both the heatsink and fan be available. Forced convection characteristics for heatsinks define both heatsink-to-air thermal resistance and pressure drop through the heatsink as a function of airflow. Fan characteristics define airflow as a function of pressure drop. The intersection point of the airflow versus pressure curves for the fan and heatsink will define the operating airflow through the heatsink (Figure 7). The heatsink-to-air thermal resistance for this airflow may be read directly off the airflow versus resistance curve for the heatsink.

Figure 7.



Finding and interpreting the operating point requires consideration of the following:

Units of pressure drop are generally given in inches of water. Units of fan airflow are in cubic feet per minute (CFM). Occasionally metric units are used, but conversion is straightforward.

Heatsink airflows may be given either in CFM or LFM (linear feet per minute). The conversion between LFM and CFM is dependent on the cross-sectional area through which air is flowing:

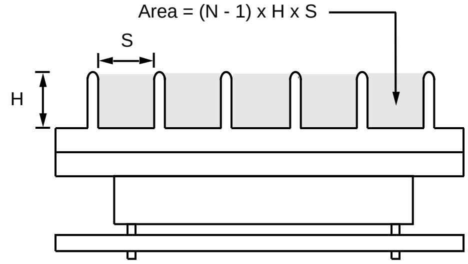
CFM = LFM x Area

Forced Convection (cont)

The cross-sectional area between the fins is the area through which the total airflow must pass (Figure 8). Correct interpretation of heatsink data requires that only the airflow through this area be considered. Simply pointing a fan at a heatsink will clearly not result in all of the flow going through the cooling cross-section of the sink; some channeling of air is usually required to get the full benefit of fan output.

The fan curves give output in CFM versus pressure drop. Fan pressure drop is the total of all drops encountered by the fan airflow. The heatsink, any ducting that is used, and air entry and exit channels all contribute to pressure drop. Pressure drop represents the work done by the fan in moving air through a region, so care should be taken to minimize unproductive pressure losses. Ensure that air entry and exit locations and internal air channels are not unduly constricted, and avoid sharp turns in airflow paths.

Figure 8.



The thermal resistance that was determined by overlapping the fan and heatsink curves will represent an optimistic estimate since it assumes that all the fan output flows through the heatsink cooling cross-section, and that all the pressure drop occurs along the heatsink. If the estimated thermal resistance is close to the minimum value determined in Step 1, then it is likely that a larger fan or different heatsink is required. This will not be a problem in most cases; relatively modest heatsinks and fans usually provide ample cooling.

Careful channeling and ducting of airflow as a means of both maximizing flow through the cooling cross-section of the heatsink and minimizing extraneous flow of air around the sink is well worth the small extra design effort required. Every degree of improvement in baseplate temperature results in significant improvement in MTBF. If you are paying for a fan, you may as well leverage it for all that it is worth.

3. Steps 5 through 7 in the Free Convection section will complete the heatsink selection process. Select the fan/heatsink combination with the lowest thermal resistance consistent with cost and space constraints, calculate the estimated baseplate temperature and test to verify.

DC-DC Converters and Off-Line Power Supplies

These products fall into three categories: full size modules, 4.6" x 2.4" x 0.5"; half size modules, 2.28" x 2.4" x 0.5"; and configurable products. Modules are offered in several different package styles: standard, with mounting flanges; SlimMod, without mounting flanges; and FinMod, flangeless package (Fl/F3, .25" integral heatsink, F2/F4, .50" integral heatsink).

DC-DC Converters and Off-Line Power Supplies (cont)

Consideration should be given to module baseplate temperature during operation. The most common cause of power supply failure is thermal stress beyond maximum rating. Refer to the product data sheet for the maximum baseplate temperature specification. The operating baseplate temperature is the sum of the ambient or environmental temperature and the module temperature rise due to internal power dissipation as given by;

$$Tbp = Ta + \theta Pd \qquad (1)$$

θ is the thermal impedance between the baseplate and the environment to which the heat is transferred (C/W), and is primarily a function of heat sink geometry and air flow rate as illustrated in the tables below. Internal power dissipation depends on conversion efficiency and output power according to the following expression;

$$Pd = Po(1/n-1) \qquad (2)$$

Where n is the converter efficiency which is also available from the product data sheet.

If cooling is by conduction as opposed to convection, the temperature rise is again the product of internal dissipation and the thermal impedance of the member that is in contact with the baseplate.

Thermal Impedance Charts (˚C/W)

VI-200 MI-200 θbm = 0.2	Base-plate	2111 0.9"L Fins	6927 .7"L Fins	2113 .9"T Fins	2092 1.45"L Fins	4431 .7"T Fins	2112 .4"T Fins	Slim-Mod	FinMod -F1/-F3	FinMod -F2/-F4
	θsa	θsa	θsa	θsa	θsa	θsa	θsa	θsa	θsa	θsa
Free Air	5.10	3.40	4.08	2.70	2.60	3.15	3.80	5.40	5.00	3.70
200 LFM	2.80	1.50	1.80	1.10	1.00	1.28	1.55	3.20	2.40	1.80
400 LFM	1.80	1.00	1.20	0.80	0.60	0.93	1.13	2.20	1.50	1.20
600 LFM	1.40	0.80	0.96	0.60	0.50	0.70	0.84	1.60	1.10	0.90
800 LFM	1.20	0.60	0.72	0.50	0.40	0.58	0.70	1.30	0.90	0.70
1000 LFM	1.00	0.50	0.60	0.40	0.30	0.47	0.56	1.20	0.80	0.60

VI-J00 MI-J00 θbm = 0.4	Base-plate	4306 .9" L Fins	4307 .9" T Fins	5738 .4" T Fins	Slim-Mod	FinMod -F1/-F3	FinMod -F2/-F4
	θsa	θsa	θsa	θsa	θsa	θsa	θsa
Free Air (H)	8.10	4.20	4.00	5.63	8.50	8.00	7.00
Free Air (V)	7.60	4.00	3.90	5.49	8.40	7.30	6.70
200 LFM	5.10	1.60	1.60	2.25	5.50	5.00	2.70
400 LFM	2.70	1.30	1.30	1.83	3.60	2.50	1.50
600 LFM	2.30	0.90	0.90	1.27	2.90	2.10	1.20
800 LFM	1.70	0.70	0.70	0.99	2.30	1.30	0.80
1000 LFM	1.40	0.60	0.60	0.84	2.00	1.10	0.70

Configurables (also applies to MI-products)	FlatPAC*			ComPAC*			Mega Module*		
	1 Up	2 Up	3 Up	1 Up	2 Up	3 Up	1 Up	2 Up	3 Up
	θbm	θbm	θbm	θbm	θbm	θbm	θbm	θbm	θbm
	0.1	0.05	0.03	0.1	0.05	0.03	0.1	0.05	0.03
	θsa	θsa	θsa	θsa	θsa	θsa	θsa	θsa	θsa
Free Air	2.1	1.3	1.0	3.6	1.7	1.4	4.4	2.1	1.7
50 LFM	1.5	1.1	0.9	2.7	1.4	1.3	3.3	1.7	1.6
100 LFM	1.2	0.9	0.7	2.3	1.3	1.1	2.8	1.6	1.3
250 LFM	0.7	0.5	0.4	1.6	1.0	0.8	2.0	1.2	1.0
500 LFM	0.4	0.3	0.3	1.2	0.7	0.6	1.5	0.9	0.7
750 LFM	0.3	0.2	0.2	0.9	0.5	0.5	1.1	0.6	0.6
1000 LFM	0.2	0.2	0.2	0.8	0.4	0.4	1.0	0.5	0.5

*Assumes uniform loading of 2- and 3- output units.

Table Usage: The forced convection thermal impedance data shown in the table above assumes airflow through the heatsink fins. Actual airflow through the fins should be verified. For purposes of heatsink calculation, assume efficiencies of 81% for 5V outputs and 85% for 12V and above.

Typical Examples — Thermal Equations

T_{max} = maximum baseplate temperature (From product specifications.)

T_a = ambient temperature

$\eta = \text{efficiency} = \dfrac{P_{out}}{P_{in}}$ (Assume efficiencies of 81% for 5V outputs and 85% for 12V out and above.)

θ_{bm} = baseplate -to-heatsink thermal resistance (From thermal impedance tables in section above)

θ_{sa} = baseplate -to-heatsink thermal resistance (From thermal impedance tables in section above)

$$P_{diss} = \text{dissipated power} = P_{out}\left(\frac{1}{\eta} - 1\right)$$

$$\text{Airflow (LFM)} = \left(\frac{\text{CFM}}{\text{Area}}\right)$$

$$\text{Maximum Output Power} = \frac{T_{max} - T_a}{\theta_{sa}\left(\frac{1}{\eta} - 1\right)}$$

$$\text{Maximum Thermal Impedance} = \frac{T_{max} - T_a}{P_{out}\left(\frac{1}{\eta} - 1\right)}$$

$$\text{Maximum Ambient Temperature} = T_{max} - \theta_{sa} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

$$\text{Temperature Rise} = \theta_{sa} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

$$\text{Thermal Drop} = \theta_{bm} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

Typical Examples — Thermal Equations (cont)

EXAMPLE 1. Determine the maximum output power for a 100W, VI-200 converter, no heat sink, delivering 5V in 400 LFM at a maximum ambient temperature of 45°C.

$$\text{Maximum Output Power} = \frac{T_{max} - T_a}{\theta_{sa}\left(\frac{1}{\eta} - 1\right)}$$

T_{max} = 85°C

T_a = 45°C

θ_{sa} = 1.8°C/W

η = 81% = (.81)

$$\text{Maximum Output Power} = \frac{85 - 45}{1.8\left(\frac{1}{0.81} - 1\right)}$$

= 95W max.

EXAMPLE 2. Determine the **maximum thermal impedance** of a 50W, VI-J00 converter, no heat sink, delivering 24V at 45W in free air convection at 55°C ambient.

$$\text{Maximum Thermal Impedance} = \frac{T_{max} - T_a}{P_{out}\left(\frac{1}{\eta} - 1\right)}$$

T_{max} = 100°C

T_a = 55°C

P_{out} = 45W

η = 85% = (.85)

$$\text{Maximum Thermal Impedance} = \frac{100 - 55}{45\left(\frac{1}{0.85} - 1\right)}$$

= 5.7˚C/W Min.

Typical Examples — Thermal Equations (cont)

EXAMPLE 3. Determine the **maximum ambient temperature** of a 3-up FlatPAC delivering 12V at 600W in 500 LFM with no additional conduction cooling to the chassis.

$$\text{Maximum Ambient Temperature} = T_{max} - \theta_{sa} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

$T_{max} = 85°C$

$\theta_{sa} = 0.3°C/W$

$P_{out} = 600W$

$\eta = 85\% = (.85)$

$$\text{Maximum Ambient Temp.} = 85 - 0.3 \times 600\left(\frac{1}{0.85} - 1\right)$$

$= 53°C$

EXAMPLE 4. Determine the **temperature rise** of a 150W, VI-200 converter delivering 5V at 132W with a 02113 heatsink in 200 LFM.

$$\text{Temperature Rise} = \theta_{sa} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

$\theta_{sa} = 1.1°C/W$

$P_{out} = 132W$

$\eta = 81\% = (0.81)$

$$\text{Temperature Rise} = 1.1 \times 132\left(\frac{1}{0.85} - 1\right)$$

$= 34°C$ Over Ambient Temperature

EXAMPLE 5. Determine the baseplate to coldplate thermal drop for an MI-200 converter delivering 5V at 50W with a thermal pad.

$$\text{Thermal Drop} = \theta_{bm} \times P_{out}\left(\frac{1}{\eta} - 1\right)$$

$\theta_{bm} = 0.2°C/W$

$P_{out} = 50W$

$\eta = 81\% = 0.81$

$$\text{Temperature Rise} = 0.2 \times 50\left(\frac{1}{0.85} - 1\right)$$

$= 2.34°C$